Introduction To Chassis Design
Revision 1.0

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Preface

As an undergraduate engineering student attempting to learn about chassis design it became apparent that there was not sufficient information on automotive chassis design readily available. Books that started to explain things lacked important fundamentals specifically in regards to the link with basic mechanical engineering principles. Struggling to gather papers and books gave a clear idea that a comprehensive book detailing theory and following several chassis through the design process could be beneficial.

This book is intended for undergraduate and graduate engineering students who are interested in automotive vehicle engineering. It is intended to give a better understanding of the fundamental requirements of a chassis along with how to start and optomize a design. While the book makes usage of FEA software, the principles of how things work and how to recognize problem areas will not need software, but it will need a good understanding of statics, dynamics, stress, and strain. One of the best authors in the engineering field, R.C. Hibbler, has written two books that should be familar to some people reading this. They are "Statics and Dynamics" and "Mechanics of Solids". They are suggested reads before reading this book or attempting to design an automotive chassis.

Introduction

The automotive chassis is tasked with holding all the components together while driving,and transfering vertical and lateral loads, caused by accelerations, on the chassis through the suspension and two the wheels.

Most engineering students will have an understanding of forces and torques long before they read this. It is suggested that the reader has a good understanding of the concepts of axial forces, shear forces, bending, torsion, angular and normal deflections, and finally mass moment of inertia.

The key to good chassis design is that the further mass is away from the neutral axis the more ridgid it will be.

This one sentence is the basis of automotive chassis design. Some people stress full triangulation and material choice but once you are into these specifics some critical understanding is missed. People familar with space frames may be thinking that full triangulation is the key to a good space frame. While this will make the design better it can still benefit from this more general design principles. The design section of the book will talk more about these items in relation to the types of chassis but the first part is the theory.

Part I

Theory

Chapter 1

Understanding

1.1 Introduction

The perfect chassis is a large diameter thin walled tube.

In order to understand this you should have a solid grasp of statics and deflection. The Automotive chassis has two main goals.

- Hold the weight of the components
- To ridgidly fix the suspension components together when moving

The first item is an easy design solution and is also the basis of the original chassis designs that were taken from horse drawn carriages. One of the most effective shapes for supporting point loads fixed at two ends is an I-Beam, a box tube, or a C-Beam. One beam on either side so that a floor could be attached and even the smallest of I or C beams can hold tremendous weight. Truck frames stil use this construction as it is an easy and effective method of supporting heavy loads.

It didn't take long to find out that once these carriage chassis's has been adapted and speeds increase they would no longer be sufficient to couple suspension components. It was a long time before body on chassis was elimnated in everyday vehicles and happened because of desire to reduce cost and weight in production cars. Long before that the spaceframe was born to fix the problems associated with this type of frame for higher performance vehicles. Space frames did not lend itself to mass production and stayed only in race cars and high performance sports cars.

Space frames gave way to the monocoque chassis as large flat surfaces had more mass consistently further away from the neutral axis. Race cars did this first by skinning a spaceframe to retain a supporting structure. It then eliminated this spaceframe and replaced it with light weight honeycomb material. This was due to the the thin walls being strong in shear but in the compressive direction were unstable and buckled easily. The honeycomb material added a reinforcing structure, and coupling two layers surrounds the driver in a very strong enclosure that is resistant to penatrative loads. Today the focous is on the material of the structure and layering techiniques since the underlying concept is well developed.

When cornering torques are applied to the chassis it causes it to twist. The engineernig solution for this torsion problem is simply a tube. Understanding of basic mechanics, the further the material is away from the center of application of the torque, the more resistive it is to deflections to the power of four. One thing that competition designs normally quote is torsional ridgity in Netwon-Meters/Degree of twist. Not all chassis torsion tests are the same but all give a general idea of how stiff the chassis is. The stiffer the chassis the more cornering torque it can handle with less effect on suspension geometry.

From this principle it is easy to see how a “perfect” chassis is a large diameter tube. It would be very resistant to torsional forces as well as good for holding the heavy components of a vehicle such as an engine and dealing with the lateral loads. But this is an ideal case. In reality loads are distributed over small areas and design elements cause huge stress. For instance an engine could not be mounted to a thin walled tube. It would need some sort of reinforcement to handle the localized bending this imposes.

This brings us to the second problem of design. How do you design a box that people can get in and out of along with mount all the required components and protect the occupants. That is where chassis design becomes complicated. Once a hole for a entrance is created it gets significantly weaker in that area. A window is needed to see through and adds another hole. Soon the perfect chassis is a playground for walls to buckle and less predictable deflections to occur.

As a result of all these holes and component weight is a significant problem and brings up the issue of wall buckling. Applying any load to a thin wall will cause it to buckle before the normal theoretical failure point. Space frames work well because the members are small enough to be self supporting against buckling. Monocoques require a secondary layer and supporting material to solve this problem. This is the where the bulk of design problem solving will take place.

1.1.1 Key Points

- Get mass far away from neutral axis
- Thin wall tube in theory best
- Wall buckling is an issue, must be resolved with something
- Doors and Windows a problem

1.2 Time Constraints

When working on a design their will come a point where the designer runs out of time. It can be increasingly difficult to stop trying to improve a design. When subjected with an open ended design problem all engineers will know that their are many solutions and some will be better than others.

The overall orignal design that will be the topic of the Angular Monocoque Design Walkthrough was decided on, designed and checked after serval iterations which gave the Mark II. Some ideas and dissatisfaction lead to adjustments to the overall shape. The original design was not deemed insufficent nor was a critical flaw discovered nor did design criteria changed. More knowledge was gained throughout the process of writing this book. This resulted in curiosity to explore design changes. After this major adjustment no other changes were looked at because that phase of the design was out of time. The overall shape and construction was determined and only parts related to other problems such as suspension was not incorporated. There are several issues occuring with the design now but they will be solved within the constraints rather than a full redesign.

This highlights a common issue. You will likely find a flaw in your design and wish to fix it. The flaw may be the result of its original architecture, its constrained shape, the engine, suspension location, etc. Time is precious and accepting a flaw may mean meeting a deadline. Do your best to solve it in the time alloted while mitigating it as best you can. At some point the design will be "completed". This becomes easier after completing a few designs but can be initially difficult to accept.

1.3 Suspension

The suspension points of the vehicle for a chassis should be considered before the chassis itself. Designing a perfect suspension for the application after the chassis could cause construction to be impossible or unable to meet the specifications. Suspension and all the chassis requirements will involve much compromise. For this text we are only going to consider the "Double Wishbone" style of suspension.

Double wishbone suspensions can are designed for several different targets. Roll center movement and chamber adjustment in roll are a few of the major goals. A constant roll center will have more predictable handling as the lateral acceleration forces always torque around the same point. If the chassis rolls in a turn the suspension movement can cause chamber change. As a result it puts uneven force on the tire causing a loss of traction. It is possible to setup so that as the chassis rolls the suspension corrects for the chamber. This will cause loss of traction when going over crests, entering a hill, or wheel bump. It is a balance of trading off elements based on the requirement of developing a chassis.

Other things that can be optomized is anti-dive which prevents the car nose diving under braking and anti-squat which prevents the rear from dropping when accelerating.

1.3.1 Key Points

- Only working with Double wishbone suspension
- Several Points can be optomized
- Trade offs for optomizing each point

1.4 Protection

It is difficult to set the next priority of a chassis to be safety when most would say it is most important. Rules for chassis safety provide the best starting point to develop a vehicle. Arguments aside, safety is very important.

Frontal impact protection will require a design that does not have a tendancy to buckle and have a way to dissipate energy. Side impact will require very strong walls surrounding the occupants and a very strong stable linkage from the impact site to the suspension mounts on the opposite side. Rear protection will require a reinforced rear compartment and a way to dissapate energy. Roll over will require very strong supports that can take the impact loading of a rolling car and not deform significantly.

These are just a general overview of protection requirements, but there can be more. The key in designing is to make a chassis as safe as possible but without adding significant weight. Finding ways to incorporate the safety designs into the structural designs is key. The Lotus Elise has done this very effectively. The torsional rigidity of the beam members that run along the sides are also very strong in terms of bending. In a side impact scenario the beam transfers much of the force through to the suspension keeping the chassis from deforming and pushing the car rather allowing intrustion. In most production cars the door is the first line of defense, but for the Elise it is a combination.

1.5 Aerodynamic influence

Aerodynamics will play a role in designing a chassis. It will likely determine the overall shape and area that can be used in design. For race car design there is usually a compromise. If adding something to the chassis goes outside of the aerodynamic envelope it is possible to adjust this envelope without to much affect usually. Sometimes it works the other way as well that aerodynamics forces the chassis to be slightly compromised. It is a balancing act of which is more important.

For lightweight vehicles handling is usually considered more important. The case of the “locost” or Caterham 7 is a good example. The car is intended for handling and not top speed. The Prius is the reverse. Its aerodynamics are very

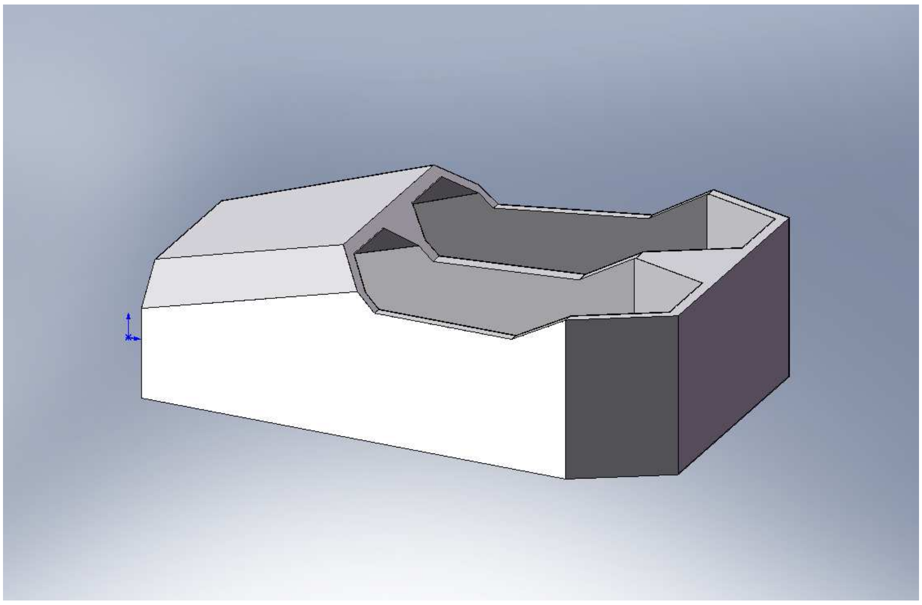

Figure 1.1: FM2 - Mark 2

critical to efficiency so that its chassis must fit in the envelope or else increase drag.

1.6 Tube Theory in practice

In the initial design and developments of a simple two seater monocoque called FM2 (which will be discussed in detail in a latter chapter) put the theory to the test. Not only did it prove the theory but it also showed some very remarkable results.

The most refined designs that looked suitable were Mark II and Mark V. The FM2 Mark V chassis initial design seemed to yeild rather impressive results over the Mark 2 which not make sense considering the surface area were similar. Eventually running more tests after moving to the Mark V proved the initial simulations to be incorrect. While the main driving force behind the alterations to Mark 5 actually came from suspension requirements the design of the vehicle was changed overall along with seating position. This was an initial design compromise.

Taking a look at Figure 1.1 showing the FM2 Mark II chassis and Figure 1.2 showing the FM2 Mark V chassis there are obvious differences. The enclosed nose area of the Mark 5 is longer, the walls are at chamfered at the top and bottom, the cockpit entry area is smaller and less open, the lower sills are gone and extend upwards to a flat area that quickly approaches a large entry hole.

One thing that is easily noticable is that the Mark V does away with the

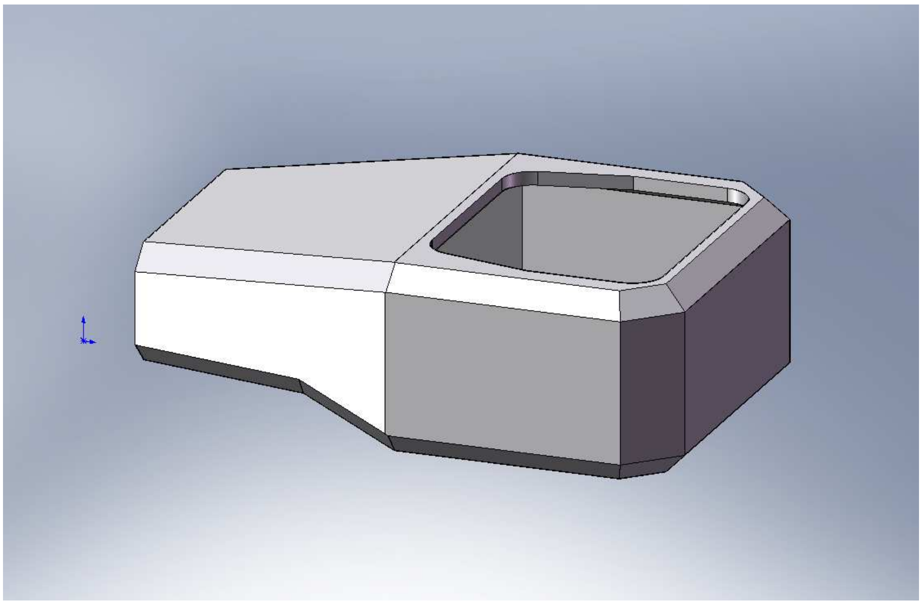

Figure 1.2: FM2 - Mark 5

center column. This adds a sizable chunk of weight to the Mark II. In fact if it was removed it would lighten the Mark II by approximately 8 kg putting it under the weight of the Mark . The tunnel surprisingly added more strength than expected and goes into the backbone theory but the tunnel was not needed because the drivetrain was entirly behind the driver.

To reinforce the tubular theory at this point a simulation was conducted on the Mark V chassis. What would occur if the cockpit opening was enclosed fully. Unfortunately Solidworks does not like having multiple floating bodies when using a shell feature and therefore a small (50mm) hole connected the inner surface to the outer surface but was not significant to provide any load transfer.

The results were more than impressive with a torsional rigidity of 210.6 kN·m/degree and a secondary test of just the outter shell of 132.3 kN·m/degree. This conclusively reinforces the idea that a large tubular structure is deal for torque transfer in a chassis when compared to chassis like the Elise which has a tested value of approximately 11kN·m/degree.

This covers off the starting point which creates the theory for all monocoque and backbone chassis and indirectly the "tub" style (more explanation in the "tub" chapter will explain how) but unfortunately leaves out one of the most versatile frames that will be most common to low volume construction. The spaceframe.

Chapter 2

Suspension

2.1 Introduction to Suspension

There are many different types of suspensions that exsist but the main focus will be on double a-arm suspensions. The reason for this is because they are the most common in the motorsport industry and their versatility.

2.2 Short Long Arm

The arms of the suspension are commonly of two different lengths. The top arm is normally shorter than then lower one. This gives the correct type of chamber correction during body roll from cornering. If they are identical in length then the angle between the wheel and the body would not change and cause an uneven presure distribution on the tire. This gives less area in contact with the ground leading to a loss in lateral grip when turning which is very dangerous.

There are several important points of interest when setting up geometery for short long arm (SLA) suspension. They are the Instantaneous Centers and the Roll Center. The instantaneous center is an imaginary point created from the meeting of coaxial lines extended from the suspension geometry in the frontal view. The roll center is the point of intersection of two lines extended from the contact patch to each respective instantaneous center. The roll center is the point that the car torques about when in a turn.

There are two goals that are drawn from all of this. They are correct chamber control and stable roll center. Both aspects increase the predictability of a vehicle.

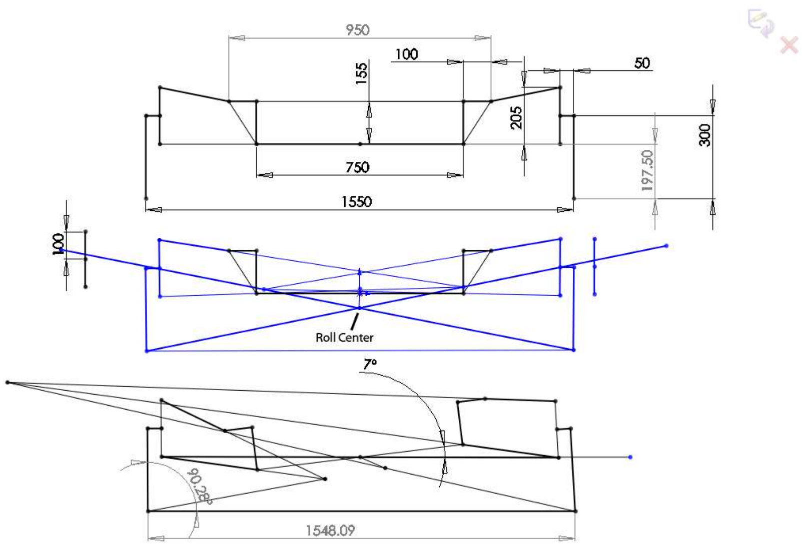

Figure 2.1: String Calculator

2.3 Computer String Calculator

The string calculator is a great tool, but in the age of computers it is quicker to be able to edit a few numbers and see the results visually in a CAD application. It allows you to check the chamber control, roll center movement, tire scrubbing, etc.

A Solidworks string calculator is shown in figure 2.1. There are three parts to it. The top section is for setting up basic geometry. Setting the track width, the attachment points, and the offset are done here.

The middle section of the string calculator shows the instant center and roll center. The colinear lines that extend from the suspension arms will cross at a point. This point is known as the instantaneous center. A line can be drawn from the instantaneous center to the wheels edge touching the ground. The interesction of each of these lines is the roll center. The roll center is the center about while the car will roll given a lateral force at any given time. If you move the suspension by grabing any point in the drawing the roll center will move. By tuning the suspension arm geometry it is possible to make this point fairly stable.

The bottom section shows a simple roll scenario. After adjusting to stabalize the roll center the geometry can be further adjusted so that as the car rolls the chamber is corrected. As seen in the picture a roll of 7 degrees causes a 0.28 degree roll on the wheels.

Chapter 3

Impact protection

3.1 Introduction

The scenario which everyone trys to avoid is having an accident. During a car accident on a road there is more emphasis put on decelerating a vehicle through structural deformation absorbing the impact with crumble zones. An accident on the track is more concerned with having a very rigid enclosure with devices attached to dissapate the energy. A driver is also very securely connected to the chassis through multipoint harnesses and head restraints like the Hans Device. There is a difference in philosphy and the focus here will be on the latter.

Static force simulations can be used to understand how something may be affected in an impact. Simulations can show how an area will deform and reinforcements can be added as a result. Real impact simulations are possible but require significant computing power and setup times. Small variances such as how a wall will buckle or material definition in the plastic deformation range will have major impact on the results. As a result there is no substitute for impact testing but work can be done to mitigate it as a requirement.

Unfortunately without the aid of costly destructive testing it is can be a difficult task to determine the desired safety. Even with physical testing there is only so many scenarios that can be tested but they can validate impact simulation. The focus here is on understanding how to make the safest enclosure possible for the occupants.

In Formula One and Lemans the requirements focus on the survival cell being rigid enough to prevent intrustions. The physical testing, if passed, should have no impact or very little on the chassis. If possible, conducting these tests or similar ones should be beneficial. It should be noted that Formula One and Lemans vehicles likely achieve significantly higher speeds and some of these tests can be toned back as a result.

3.2 Sancationed Rules

Considering motorsport has been around for many years the easiest way to determine safety of a chassis is to start with accepted testing methods. Formula One and Lemans technical regulations are freely available for viewing. The tests have not changed from year to year so they are a good benchmark. They perscribe several impact simulations which should only damage impact attenuators and not the chassis. The static testing should not affect the chassis structure permanently either.

Formula one perscribes several different requirements for the chassis in article 15.5 of the F1 Technical Regulations. 15.5.4 describes the five separate static load tests to subject the chassis too. This is a good starting point and refers to article 18.2 for details. The cell is subjected to static loads on:

1. Vertical plane passing through the centre of the fuel tank
2. Vertical plane where the wheel would hit
3. Vertical plane 375mm forward of the rear cockpit entry
4. Beneath the fuel tank
5. Side of the cockpit opening

Section 15.5.5 refers to static loading tests for the impact structures which are described in articles 18.5, 18.7, and 18.8.2.

In the Lemans prototype regulations under Appendix J - Article 258A - Appendix 2 describes the safety procedure. Section 2.1 states that the survival cell is subjected to four separate static loadings tests.

1. Vertical plane passing between front axle and top of roll structure
2. Vertical plane at seat lap belt area
3. Fuel tank area
4. Fuel tank floor

3.3 Impact Simulations

3.3.1 Formula One Testing

Formula one perscribes several impact tests to be carried out with the survival cell and impact attenuators with a dummy of 75kg and total test trolly weight of 780kg. Frontal impact test occurs at 15 m/s with several acceleration requirements to be met. The survival cell, along with mounting points for the safety belts or fire extingishers, should not sustain any damaged. Further detail is perscribed in article 16.2.

The Formula one side impact test is a similar setup to the front impact test but at 10 m/s. Again there should be no damage to the survival cell. Further information is available in article 16.3.

The rear test is conducted at 11 m/s with no damage requirements as well. Again further infromation available in article 16.4.

The attenuators should be the only part sustaining damage while the survival cell or chassis should remain intact and usable.

3.3.2 Lemans Testing

Lemans testing indicates a 75kg dummy and loaded to the perscribed weight of the class with an additional 150kg and an impact velocity of 14 m/s. During the test the maximum deceleration should be less than 25g. There should be no structural damage to the survival cell. It also perscribes the impact energy to be disappated for LMP1 of 102.9kJ and LMP2 of 95.55kJ. This information can be used to determine if the attenuator is of sufficient strength though other types of testing.

3.3.3 Recommended Tests

The development of a chassis or survival cell for a motorsport application is a complicated endeavour. While computer simulation is getting more and more powerful, the case of "impact" is where destructive testing is the only way to get the right results or at least determine if simulation results are reliable. A chassis with its impact attenuators should be built and put on a rig and tested in the impact scenarios if possible. If one chassis does not pass the test then it could easily be considered unsafe.

A better alternative is to conduct the static tests described in the next section and do an impact test with just the attenuator. This can be conducted in several ways such as logging the force data as an equivalent weight is dropped from a sufficient height for perscribe energy onto an attenuator. Another way is to attach accelerometers to a large mass attached to the the attenuator and drop it from a sufficient height. The ideal is also logging transfered forces because this can latter be easily used in a dynamic load simulation (which should not be confused with a dynamic impact situation).

The problem with simulation is with the attenuator. There is 88kJ of energy to be absorbed in this impact that must all be handled by the attenuator. It is therefore very difficult to simulate due to the complexity of an attenuator device and a chassis in an impact scenario. However, impact testing on the attenuator or available information may allow for a simple overall structure such as a box to replace the real attenuator during impact simulation. If this information is available or tests have been conducted and determined the overall properties forces can be determined on the chassis and used for static simulation or dynamic simulation.

3.4 Static Tests

3.4.1 Formula One Testing

Formula One technical regulations have a limited time of application to the perscribed load less than 3 minutes and held for 30 seconds. The load is released and any failure is determined as greater than 1.00mm of permanent deflection which for most cases will constitute the failure scenario.

Roll Structure Testing

In Article 15.2 titled "Roll structures" of the F1 Technical Regulations states that all cars must have two roll structures. The rear must be at least 940mm above the reference plane (ground) and 30mm behind the cockpit opening while the front should be no more than 250mm forward of the steering wheel. The drivers helmet has to be 70mm perpendicularly below the line drawn between these points and the steering wheel has to be below 50mm.

The main roll structure is submitted to a 50kN lateral, 60kN logitundinal, and 90kN vertical downward load on a 200mm diameter pad that is perpendicular to the loaded axis. Deformation must be less than 50mm along the loaded axis and less than 100mm vertically. The front roll structure has a 75kN load applied through a 100mm pad vertically downward. During the tests the survival cell should be secured on a horizontal plate so all loads are being resisted by the entire undercarriage area.

This is a very good test because in a roll situation the driver's head should not impact anything on flat ground and the roll structure must be sufficiently strong to protect the occupant. The static testing has to be robust enough to deal with the impact and rolling.

This test can be conducted in Ansys with a simple static simulation. Create a solid pad and mate it to the roll structure. Apply the loading to this pad and a fixed support to the floor of the chassis. Mating a pad to a roll structure can be difficult if round tube is used. In this case if there is a small radius bend at the top of the roll structure this surface can be used to apply the directional loads. If possible apply them as a bearing load, this will mean only compressive force is applied. Tensional forces would be created if pulling the roll bar which is less accurate.

Survival Cell Side Tests

There are three individual tests. The first test has a 100mm x 300mm (W x H) pad conforming to the shape of the survival cell. It is placed on a vertical plane passing through the centerline of the fuel tank with the bottom at the lower edge of the survival cell. An identical pad should be placed on the opposite side and used as a fixed support while a 25kN force is applied laterally to squeeze the structure. Failure is any permanent deformation greater than 1.00mm.

The second test has 200mm diameter circular pads placed on either side of the survival cell where the wheel would strike as a result of swinging on the safety cable if it had become detached from the suspension. One pad is used as a fixed support while the other is subjected to a 30kN force. Failure is 1.00mm of permanent deformation or 15mm of total deflection under loaded condition.

The third test has 200mm pads placed 375mm forward from the rear edge of the cockpit entry on either side and 350mm above the reference plane being the ground. One side is a fixed support again while the other has a lateral force of 30kN applied. Failure is again more than 1.00mm of permanent deflection or 15mm of total deflection under loaded condition.

These three tests are all very good tests to perform because they stress the structure surrounding the occupant. The first test is useful for fuel tank safety but depending on the type of chassis being simulated may need to have positions adjusted. The second test is more Formula one specific but still a good test if uprights have a safety cable. The third is occupant safety and the most important to be performed since it directly reflects the weakest area of the chassis.

Fuel tank Floor Test

The fuel tank floor test has a 200mm pad applied to the center area of the fuel tank while a 12.5kN force is applied. No specific supports are listed so this is assumed to be at the discretion of the tester. Failure is more than 1.00mm of permanent deformation.

Again this is a good test to perform in order to determine fuel tank safety and is easy to simulate. It may require being modified to be simulated for specific chassis types.

Cockpit Rim Test

Two pads of 100mm diameter placed on the edge of the cockpit 250mm forward of the rear edge with a 15kN force applied. Failure is 20mm of deflection during loading or 1.00mm of permanent deflectoin. This is also a good test in determining occupant safety. Even in a fully triangulated frame this is going to impose difficult bending loads to the safety structure which are difficult for a chassis to deal with. The test might need to be modified if the cockpit entry area is significantly different from a area of a Formula One cockpit.

Nose Push Off Test

Survival cell secured so that the nose's strength is not affected. A 40kN load is applied to a 100mm x 300mm (W x H) pad at a point 550mm forward of the the axis of the front wheel on the impact attenuator. Failure is any structural deformation greater than 1mm after the force is released.

It is likely that the design of a non-Formula One style vehicle will not have these exact dimensions, but a 40kN load applied latterally though the perscribed pad to the impact absorbing structure would be effective in determining the safety of the front structure. If no impact attenutator structure is simulated appling the forces to the front most structure under the same requirements would be a good test.

Side Intrustion Test

Side intrustion test involves a 500mm x 500mm test panel that is truncated witha a cone at a rate of 2mm per second until it has displaced 150mm. During the first 100mm the load should exceed 250kN and the energy absorbed should exceed 6000 joules. To Pass this test there should be no failure of the structure at the fixtures edges.

This is a good test for safety against intrusion but cannot be easily simulated and even simulation would require accurate wall construction knowledge. Normally a panel is easy to create to test but the required fixture and speed control is more difficult. This type of test is really only applicable to a honeycomb cored composite structure.

Rear Impact Structure Push Off Test

The rear drivetrain such as gearbox and engine are attached to the survival cell and all held in such a way to not increase the strength of the cell. Like the nose push off test a 40kN force applied to a 100mm x 300mm pad 400mm behind the axle to the rear impact structure with similar failure requirements of 1.00mm of permanent deflection after forces released.

Side Impact Structure Push Off Test

The survival cell must be secured to a flat plate while 20.0kN horizontal loads are applied to a ball jointed pad measuring 550mm x 100mm (h x w) at a point 600mm from the centerline line of the car. Pad center should be placed 300mm above the refeerence plane which is the ground. The force must be applied in a forward and rearward direction.

A 10kN force applied both upwards and downwards to the side impact structure though a pad measuring 400mm x 100mm (L x W) 600mm from the centerline of the car and 500mm forwad of the rear edge of the cockpit entry. The failure requirements is again no more than 1.00mm of permanent deflection.

3.4.2 Lemans Testing

Static Side Load Test

A 30kN force is applied through a ball jointed structure to a 100mm x 300mm (W x H) pad on a vertical plane passing through three areas. On a vertical plane halfway between the front axle and the front rollover structure. On a vertical plane through the center line of the seat belt lap strap fixture. On a plane passing through the center of the fuel tank is the side elevation view.

The test have similar requirements to the Formula One technical regulations of applied in less than 3 minutes and held for 30 seconds and failure defined as any permanent deformation greater than 1.00mm.

Static Vertical Load Tests on Fuel Tank Floor

A 17kN load is applied to a 200mm diameter circular pad to the the center area of the fuel tank floor. There cannot be any structural damage to the inner or outer surface in addition to the 1.00mm permanent deformation restriction.

Static Frontal Impact Absorbing Structure

A 40kN lateral force is applied to the frontal crash absorbing structure 500mm forward of the front axle centerline with a 100mm x 300mm (L x H) pad. Again the failure criteria is defined as 1.00mm of permanent deformation.

Rollover Structure

The front roll structure is subjected to a 75kN vertical downward load. The rear is subjected to 60kN rearward, 50kN transversly inward, and 90kN downward. However the 60kN rearward can also be tested in the forward direction during technical scurtinization. Loads should be applied with a 200mm diameter pad positioned perpendicular to axis of force. Deformation is limited to 50mm measured along the axis and 100mm vertical below the top of the roll structure.

3.4.3 Recommended Tests

The following is a description of static tests a chassis should be subjected to which are relatively simple to conduct in most finite element analysis software packages. It is recommended to do the following tests:

- Survial Cell Squeeze Test
- Cockpit Rim Test
- Roll Structure Test
- Survival Cell Fuel Tank Test
- Fuel Floor Test
- Nose Push Off Test
- Rear Push Off Test
- Wheel Swing Test (If Applicable)

Survial Cell Squeeze Test

The side of a race vehicle cockpit is likely the weakest due to the lack of reinforcing structure above. The forces perscribed in the Formula One rules seem to indicate this test would be the resultant forces of another F1 type vehicle impacting directly into the side. It is therefore recommended to conduct this test.

Two 200mm circular pads should be placed on the weakest mid section area where the driver would be seated. Set one side to a fixed support and the other to a 30kN force acting to squeeze the chassis directly. Failure criteria should be judged on an indivivdual basis but it is suggest to have a safety factor of 1.5 to 2 to account for inaccuracies in building and failure to be 1.00mm of permanent deformation when load is released or 15.00mm of deflection when loaded

Cockpit Rim Test

This is similar to the survival cell squeeze test but depending on the chassis may indicate that the topmost structure is significantly weaker than the side impact area.

Place two 100mm circular pads on the mid point of the cockpit openings rim and apply a 15kN horizontal force to one and a fixed support to the other. Use Formula One criteria of 20.00mm of loaded deformation or 1.00mm of unloaded permanent deformation.

Roll Structure Test

The Formula One and Lemans testing for these are identical so should be carried out on any type of race vechile. The frontal roll structure should be subjected to 75kN of downward load and the rear should be subjected to 90kN down, 60kN fore and aft (requiring two simulations) and 50kN laterally. Deformation should be limited to 50mm along the axis of loading and 100mm vertically.

Considering that the line between the top of these structures should have both the steering wheel and helmet beneath by 50mm to 75mm. In loaded conditions there still should be a gap between the steering wheel and helment and this line.

Survival Cell Test Fuel Tank

Setup a 100mm x 300mm (W x H) pad on both sides of the chassis surrounding the fuel tank area. A 25kN to 30kN lateral force should be applied to one while the other is used as a fix support. Failure criteria is that of the Formula One regulations of 1.00mm of permanent deformation.

Fuel Floor Test

The Formula One and Lemans differ on the amount of force required. Lemans applies a 17kN force to a 200mm pad in the mid section of the fuel tank while

Formula One only perscribes a 12.5kN force. Lemans failure is any structural damage to the inside or outside of the structure while Formula One perscribes the normal 1.00mm of permanent deformation. Either test should be acceptable to be carried out, but considering that simulation only requires computing time both are recommnded. Conduct the 17kN force first and determine if there is no structural deformation. If there is structural deformation but deformation is below 1.00mm when the force is released based on best known material properties then conduct a 12.5kN test. After this test take some time to analyze the area for maximum shear stress and ensure it is well below the yeild point.

Nose Push Off Test

Use a 100mm x 300mm (W x H) pad on the very front of the chassis structure and apply a 40kN lateral load. The fixed support should be either the rear of the chassis such as around the suspension points or the rear firewall. Again 1.00mm of permanent deformation is considered failure.

Rear Push Off Test

Same setup as the nose push off test but place the 100mm x 300mm (W x H) pad on the rearmost structure with a fixed support on the front sturcture such as around the suspension points. Force is again 40kN laterally and failure is 1.00mm of permanent deformation.

Wheel Test (If Applicable)

If the wheel or upright has a safety cable, which is recommended, there should be a wheel swing test conducted. The point where the wheel would impact if swung should be approximated and 200mm diameter pad placed on either side of this point. One pad should be used as a fixed support while the other pad has a 30kN force applied to squeeze the chassis. Failure is again 1.00mm of permanent deformation or 15mm of loaded deformation.

Part II

Design Reference

Introduction

This part of the book is broken up into descriptions several different chassis designs. Most information is derived from design exercises and simulations of tens of Formula SAE Chassis for Space Frames, the K1 Design project for "tub" and some monocoque understanding, the FM2 project for Angular Monocoque. Eventually the design walkthroughs may be expanded to include more designs.

The Following sections are a quick overview of the type of chassis's. Refer to relevant introduction chapter for a picture of the chassis.

Ladder Frame

Two long beams that run the length of the vehicle and provide a strong support for weight and originally based on a carriage design. Body on frame achitecture is a good example of this type of chassis.

Space Frame

A nodal triangulated truss network that attempts to distribute all loads into axial directions so that no part of the frame is subjected to the harsher bending forces. A good example of this type of chassis is most Formula SAE chassis or a Lamborgini Countach.

Audi Aluminum Space Frame

A technology that blends mass manufactured monocoque design with large cross section aluminum members. The Audi R8 or the Lamborgini Gallardo is a good example of this type of chassis.

Skinned Space Frame

Rather than triangulate all members, a sheet of metal is either welded or rivited to the area. This acts as a multidirectional axial member in the tensile directions. It provides little compressive resistance due to its ease of buckling but by the nature of the space frame design one primary direction is always in tension. Formula One transition vehciles are a good example of this type of chassis. The Ferrari 126c introduced in the early 80's is of this type but was not sufficient to compete against the composite chassis at the time.

Backbone Chassis

Lotus developed a different kind of chassis for its Elan sports car. It ran a fully enclosed tubular member through the center of the vehicle. Though this method definetly is trying to make a fully enclosed tubular member which directly relates to underlying theory, but because of the small size it makes it difficult to create a very ridgid chassis by todays standards.

Lotus Tub

The Lotus Tub is a development which progressed from the backbone chassis. Though not a direct evolution it is related by Colin Chapman's development into light weight and is also a rather unconventional chassis. It takes many small cross sectional extrustions and glues them together to create large beams that run the length of the vehicle. Unlike Ladder Frame design the passenger actually sits between these large beam members providing a strong passenger compartment protecting against impact. The weaker passenger compartment is stabalized by the front and rear area which heavily connects the sides. The Lotus Elise and variants such as the Vauxall VX220 are a good example of this type of vehicle. It should be noted that this platform has become very common for startup companies to base a sports car on. Notable's include the Tesla Roadster, Venturi Fetish, Dodge EV, Zytek Elise, and several others. It has evolved into the 2 + 2 called the Evora.

Monocoque

A monocoque is similar to that of a skinned space frame but witout a any underlying support through the monocoque area. It may built up of a material reinforcing the skin or more commonly using double wall honeycomb techniques. Monocoques use the outter body as a load bearing structure but in some cases it refers more to that its constructed of continous panels. In the case of aluminum chassis one can be constructed by rivits, glue, spot welding, or seam welding, and in the case of a fiber composite it can be glued or rivited.

Angular Monocoque

The Angular Monocoque is a full monocoque but uses flat panels constructed out of sheet metal. The easiest way to turn an edge is with a hard corner with flat sections. Curvatures are difficult to build in low volumes repeatably without a press and die. One aspect to watch for is stress concentrations when simulating as these bends and edges are stress risers. The simulation software is going to assume that these have similar strength attributes but in reality this may not be the case as the metal would need to be have been either annealed or normalized. The forced bending with strengthen the material but bring it closer breaking and less resistant to fatigue. Welding will also cause differening behaviour based on the type of weld.

Carbon Fiber Monocoque

Carbon fiber monocoques are similar to angular monocoques but have very little compressive strength but high tensile strength. The carbon fiber techniques can be used for glass fiber and kevlar based monocoques as well. The emphasis is on carbon fiber in the industry now as it is stronger and more ridgid than kevlar and glass fiber and in this respect designs can be made stronger and lighter than any other. Using a fiber composite allows for low volume repeatability of designs but simulation is difficult as layup technique and directionality of the material changes the overall properties in different directions.

Chapter 4

Project Description

Log Book

At most University bookstores or office supply stores have black log books available for purchase. These little hardcover books should be familar to most science or engineering students. Pick one up for each project you start. Log everything. If you talk to someone bring it with you and take notes. Never rely on your memory for important information that you may only get access to once. A persons time is valuable so if someone is willing to share some experience don't waste it and write it down.

4.1 Describe your project

It is best to know in a concrete fashion what it is you are working on. Normally a person has a concept but making it concrete and communicable is necessary. Using words describe in a run on sentence or with jot notes what your project is. Describe as much as you can. You can stop and go back to it, but try and keep it flowing as much as possible. Below is a quote from the logbook for FM2.

> A roadgoing lemans style chassis midrear engined RWD 2 Seater, small luggaged, low aerodynamic drag, medium down forced car, similar in size to the lotus elise, low center of gravity, modifable rear bolt on end, small diameter tires and wheels for reduced weight and mass moment, minimalist interior, aluminum chassis monocoque, double A-arm suspension with anti-roll bars in both the front and rear, outboard suspension components such as shocks (if permissable), fiberglass body work, single vehicle road compliant, scca autoX compliant (unless to difficult)

The goal is to figure out what you are building in words. If a person was to wade through all this and visualize what was being described it would be a combination of a Lotus Elise and a Lemans prototype that was small but simple with a little luggage compartment somewhere. So why even bother with this considering this visualization is still a rather vague outline. It will provide the basis for your target specifications and also likely give you some reference points.

At this point most engineering students and even engineers will lack sufficient knowledge to design and understand everything. A person will learn more from seeing (and visualizing) than they will from reading. More is further accomplished by doing rather than either.

What is being proposed is to "cheat" a little. Whatever type of vehicle you are designing, someone will have likely designed something similar before you (unless you are perhaps designing a vehicle for planet exploration). Since a vehicle exists somewhere at sometime similar to what you will be designing, getting as much information about that vehicle will prove to be a valuable starting point.

While FM2 never described its weight, it sounds minimalist but similar to the Elise so the Elise weight and specifications will be a good starting point. Braking requirements may sound simple but they can easily get very complicated. Possibly more costly in the long run, what will be proposed will help cut out design time. See what people say about the handling of the vehicle that your design is closely related and judge its components from there. If people say that the brakes are lacking then you can use the rotor size and make some rough approximations to increase the size and use a larger braking system or different materials. However, in an ideal situation the materials will be analyzed and calculated, the approximate amount of braking during an event will be figured out, the heat generation, required cooling, type of airflow, etc. Sometimes the best starting point will be to copy others, make some educated guess's, and then build – all depending on team size and money.

However for the chassis, since that will be the primary focus, the engineer is encouraged to figure out as much as possible, design, simulate and test, but all within your alloted timeline.

4.2 Specifications

Now the run on sentence or jot notes have to be translated to actual specifications. A tabular program such as Excel should be sufficient.

Translate the words to specifications. The more you research and progress the more accurate you can be and the more you can refine the specification and allowable variance. The Elise was referenced in relation to the FM2 so its track of 1450mm and wheelbase of 2300mm can be used as a starting point with some variance. Looking at other similar sized vehicles such as the Mazda Miata and the Pontiac Solstice can also give a good indication of dimensions but since these are front engined vehicles keep in mind that other physical proportions will be harder to use. Specifications such as the chassis type is up to the designer. Something like the Elise could have a carbon fiber monocoque, an angular aluminum monocoque, a spaceframe, or even a ladder frame. Physical proportions will decide a lot of factors but for the most part a cars looks does not have to be defined by the frame – unless the frame is designed first.

Chapter 5

Ladder Frame

5.1 Introduction to Ladder Frame Design

A ladder frame is the simplest and oldest frame used in modern vehicular construction. It was orginally adapted from "horse and buggy" style carriages as it provided sufficient strength for holding the weight of the components. If a higher weight holding capacity was required then larger beams could be used. It was comprised of two beams that ran the entire length of the vehicle. A motor placed in the front (or rear sometimes) and supported at suspension points. Add the passenger compartment and a trunk with a load and it becomes a simple indeterminate beam. Those familiar with Hibbler's books will find solving this easy for the carrying capacity.

However this type of frame provides very little support for a performance automobile. Many people have heard stories of how an engine was so power that it twisted the chassis of a "pony car" or american muscle car. This is actually a matter of perspective. What it really comes down to, from this books point of view, is that the chassis' were so underdesigned and insufficient for the task that mating such power to that chassis was an amature mistake made by people who have no understanding of chassis design.

5.2 Ladder Frame torsional ridgitity

A ladder frame has several members that cross link to hold the frame rails together. A simple design of two rails connected by a simple span and simulated provides a very good indication of how a ladder frame is useful in regards to performance auto design.

Using Aluminum, so that a basis of comparison can be made to other chassis in this book, a simple ladder chassis weighted only 13.85kg and had a torsional rigidity of 522.6 N·m/degree. Steel at 39.25kg had a torsional rigidity of 1424 N·m/degree. Note the units. These are two orders of magnitude less than monocoque chassis and at least one order less than other construction tech-

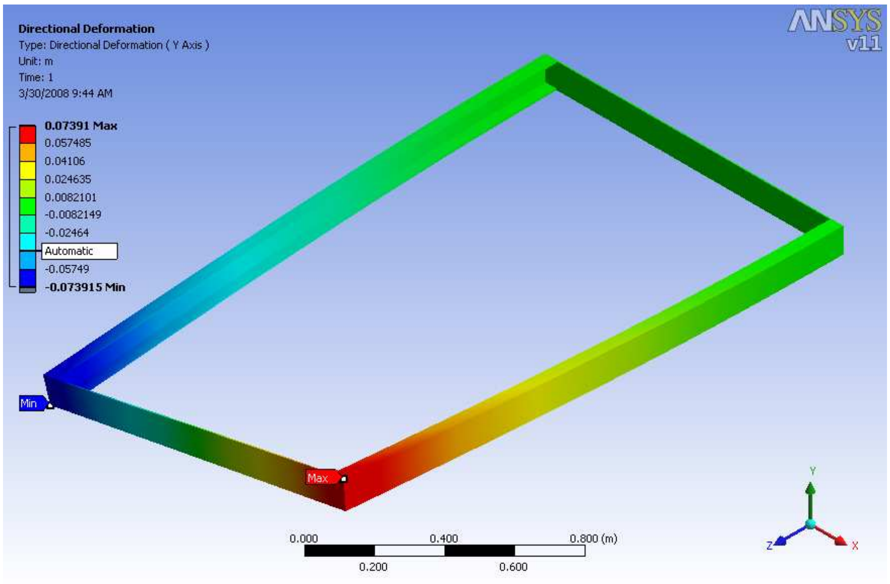

Figure 5.1: Ansys Simulation of Steel Ladder frame

niques. Figure 5.1 shows a simple chassis with a fixed support at one end and a 10kN·m torque applied at the other end.

Figure 5.2 shows the stress distribution at the fixed support in the rear is twenty orders of magnitude different than the moment applied to the front. This is the scenario of a motor “twisting” the chassis. Realistically the chassis has no significant rigidity. Figure 5.3 shows how the front and rear cross beams have no apperciable influence on the strength of the chassis. Since they are not continous they provide very little means of transfering torque uniformly through the chassis and only effectively provide the little strength required to hold the rails together.

For these reasons no “performance” vehicle should ever utilize a ladder frame. The only exception is that of large heavy vehicles that are specifically designed to go at slow speeds, and not to corner at significant speed, hold very heavy loads or for towing. Essentially all the ladder frame is good for in todays world of automotive design is large trucks and transport trailer vehicles.

5.3 X bracing

Many cars from the era used braces between the sides. Does this add a significant amount of strength to the ladder chassis?

In fact it does, but first lets look at what is happening. When torque is applied to a ladder chassis it deflects each beam independantly as if it was

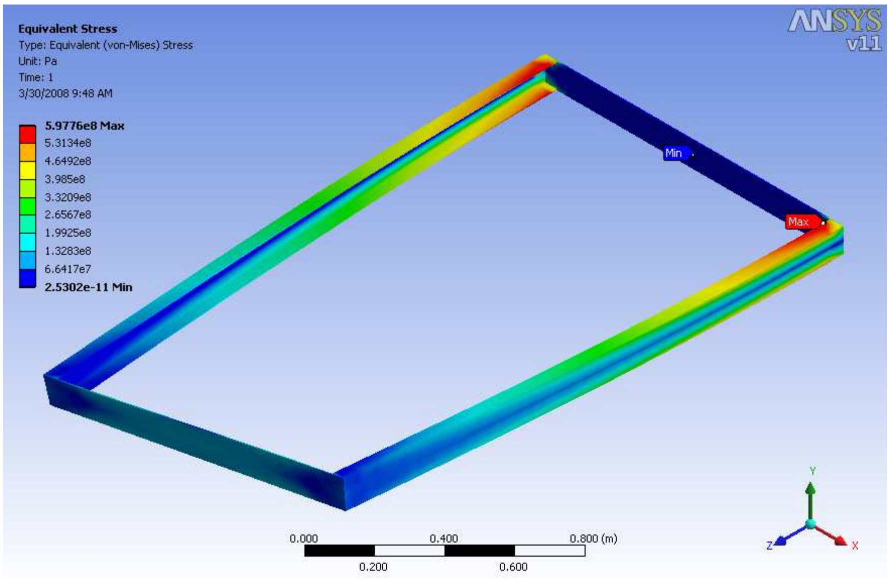

Figure 5.2: Ladder frame stress distribution

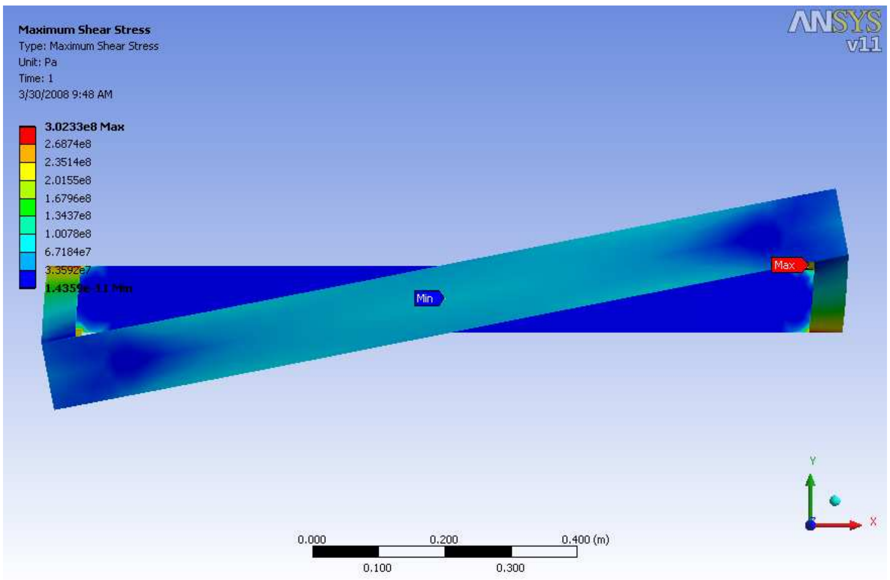

Figure 5.3: Ladder frame stress frontal view

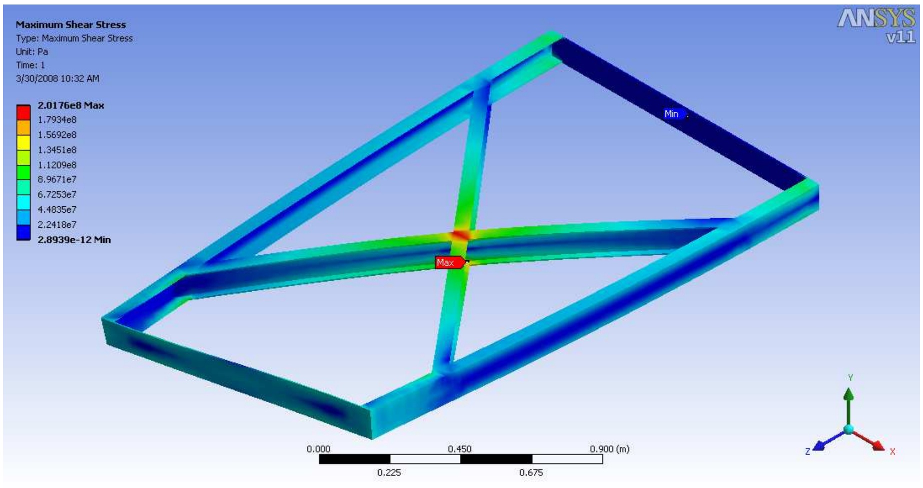

Figure 5.4: Large X-Bracing Shear

held rigidty at a wall with a point force at the end. Both rails are deflecting in different directions. Since they deflect in different directions they could be utilized to reapply that bending load to stretch material on the top or the bottom of the chassis.

Having long X-member in the aluminum chassis as show in figure 5.4 gives realivity improved torsion numbers of 1843 N·m/degree at 23kg for aluminum and 5178 N·m/degree at 65kg for steel. This is because the material at the top and bottom reaches close to the ends and provides a continous amount of material to transfer the shear forces created by the torque.

What would happen if this material was shortened and did not span as long an area. Figure 5.5 shows the maximum shear forces for a smaller X-bracing. this only achieved 1172 N·m/degree at 20.5kg in aluminum and 3287 N·m/degree at 58.1kg for steel. An improvement over the originals but close to proportional to mass. So cross bracing is an effective means of strengthing a ladder frame but an estimate to reach the stiffness of a 40kg monocoque in aluminum would require a 650kg ladder frame of steel or 500kg aluminum ladder frame.

5.4 Evolution

If an engineer would keep evolving the ladder frame would find that having a continous panel on the bottom would increase strength. As well to make the sides taller, then reinforce against buckling. Eventually would reach a point where it is better to put a person between the rails rather than on top of them. This would lead to the Lotus "tub" chassis.

If this approach was taken even further so as to fill in the areas around the person as much as possible and reinforce against buckling then it would

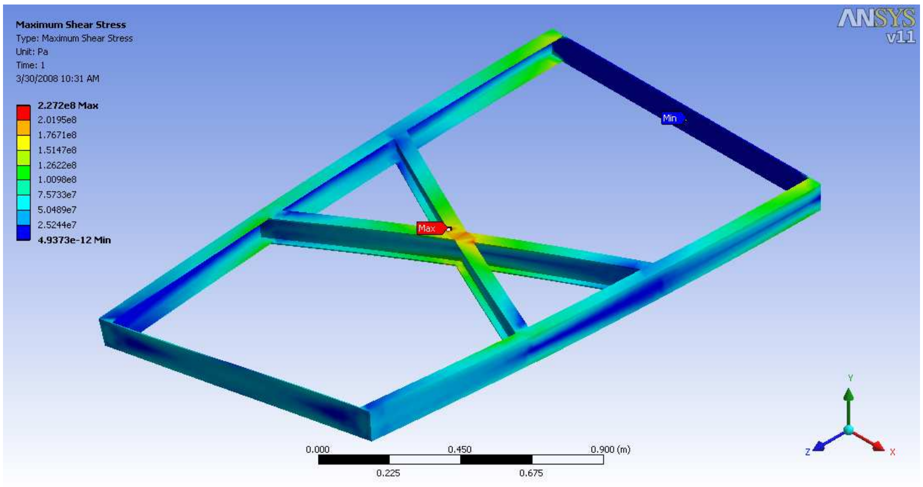

Figure 5.5: Small X-Bracing Shear

eventually turn into a monocoque.

It may be hard to imagine but once the new requirements were put on ladder frames and with a little understanding of engineering the monocoque could easily be evolved. It however sidetracked. Space frames replaced it for performance due to the self supporting nature of tubes. Skinned spaceframes would evolve so as to put mass far away but the tubes were still used to support against buckling and impact. Finally honeycomb monocoques would evolve by replacing the tubular structure and the area filled with a weak coupling material.

While ladder frames have been dismissed they provide a good thinking exercise to figuring out the tube theory.

Chapter 6

Space Frame

6.1 Introduction to Space Frame Design

Considered to be one of the best chassis methods that can yeild very good results for torsional ridgity, weight holding, and impact protection it is also simple to design and only moderate in difficulty to build. This makes it perfect for many applications from Formula Sae competitions to project cars and even low volume sports cars. An example is shown in figure 6.1.

Anyone who has ever designed a spaceframe will know that triangulation is very important as well as making sure that it is comprised of nodes where the tube ends meet and not to have parts subjected to bending loads. This seems like a tall order but the first thing to understand is that even though these aspects are important it is still subjected to tubular theory that was presented earlier. Therefore making it as wide as possible with make the chassis more rigid. This is normally difficult to do but through making side pods structural it is possible to addd strength.

The biggest problem of any design is that it will require openings for entry and exit from the cockpit area and these will not be filly triangulated. This will be the weak spot for the chassis and care must be taken to ensure this area is of sufficient strength.

6.2 Audi Aluminum Space Frame

Somewhere between a monocoque and a spaceframe lies Audi's Aluminum spaceframe as shown in Figure 6.2. It doesn't necessarily follow the same rules that most spaceframes are subjected to such as full triangulation and having no bending moments on any beams. In fact if you look at the Audi R8 chassis you will notice that the suspension points are very much subjected to bending forces.

The Audi Aluminum Space Frame is a combinations of stamped or hydroformed parts, tubular extrustions, and other panels which can bee seen in Figure 6.3. They are connected through spot welding, seam welding and riveting. Uti-

Figure 6.1: Space Frame

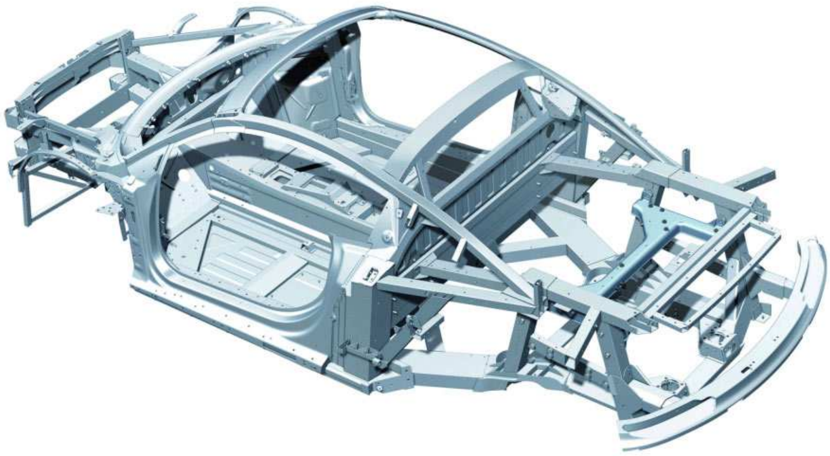

Figure 6.2: Audi R8 ASF

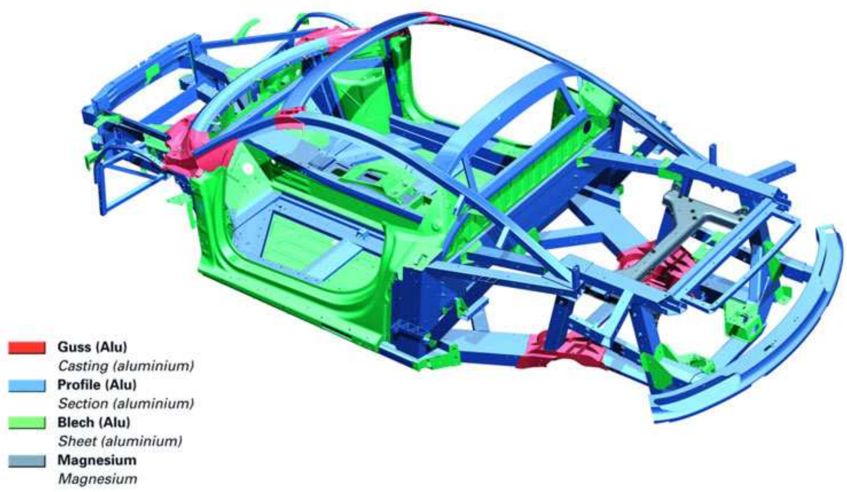

Figure 6.3: Audi R8 ASF parts

lizing aluminum correctly can lead to similar stiffness and strength compared to a steel chassis but at significant weight savings. It is however easy to jump to the conclusion that Aluminum will always yeild a lighter frame for the weight but in simulation later it will be proved to be only minimally.

Since the R8 is formed of many different types of parts it is expensive to assemble. The idea is to abandon triangulation and replace it with large cross section tubular members of aluminum. As a result the wall thickness is fairly high and buckling becomes less of an issue. They put bending moments on these members without worrying of this failure mode. One prime example is the suspension mounts which are in the middle of a beam.

Due to this being a production method and incorporating unibody architecture which requires pressing materials it will not be explored in the design walkthrough.

6.3 Skinned Space Frame

Skinned space frame is a techinque that is used to transition from space frame to monocoque. It is exactly as it sounds. A sheet metal skin is laid on top of the tubular spaceframe and welded or riveted on. This adds material away from the neutral axis very easily. Advances in torsional stiffness can be made easily at the cost of weight. It is a quick way to increase performance at slight cost of weight but it can be optomized by removing certain triangulation members and leaving only safety oriented members in place.

Chapter 7

"Backbone"

7.1 Introduction to Backbone

This is a direct application of the tube theory. The idea is to create a front and rear structure that connect to a tube that runs the entire lenght of the car. Unlike a transmission tunnel the backbone is fully enclosed to be a ridgid structure and handle all loads. It is normally very continous with few holes. Since it is so narraw the wall is generally thicker.

Some chassis intergrate this type of design into the primary structure such as cars like the "locost". Others build on this, relying on the backbone but adding additional structure to stiffen the backbone such as the DP1 from dpcars.net.

It should be noted that the backbone can be created through many types of construction. Triangulated space frame, angular monocoque, or continous tube. All been used in production cars. Almost all are rear wheel drive and front engine allowing the backbone to double as a transmission and drive shaft tunnel.

7.2 Hybird Backbone Spaceframe

The Dp1 uses a spaceframe to create the backbone structure. There is also an engine compartment and a cockpit compartment on the sides. Normally these are not structural but because of the intergrated nature of the Dp1 and the triangulation this stiffens the backbone.

The Locost transmission tunnel can also be considered a backbone spaceframe hybird as the tunnel if triangulated can have significant torsional load bearing.

Both of these chassis gain significantly from the structure for the cockpit or engine bay (DP1) because these are futher from the neutral axis.

Figure 7.1: Delorean backbone chassis

Chapter 8

"Tub"

8.1 Introduction to "Tub" Design

Lotus was the first to utilize the "Tub" approach to build a chassis for the Elise as seen in figure 8.1. Its design elements can be seen to come from the original tube theory for torisional stiffness but may be difficult to rationalize. The best chassis has been emphasized to be a large diameter thin walled tube, but what if you take a modified approach where you cut the tube in half. This is exactly what has been done but way back in Chapter 1 we saw that disjointed torque transfer makes for a much weaker chassis. So what is going on here exactly?

Lotus needed a chassis that could do several tasks but would not require major redesign to become many different sports cars so they look at what happens when you cut the tube in half. The failure mode relates to walls buckling. If you cut a tube in half and apply a torque the solution for deflection is not accurate if it is a thin walled tube because buckling will be very prevalant. The solution was to remove buckling from the equation by reinforcing the walls that were left over.

Lotus did this by using extrusions glued together. The K1 did this by many layers of honeycomb and sheet metal. Any way it is done it mitagates the buckling criterion and thus idealizes the solution.

It is like cutting a cardboard tube in half and twisting it. It fails by being crushed in the weak sections, but take that same half tube and hold it to a sturdy pipe and twist it appears to be much stronger. Failure in this instance may be buckling outward now but if small forces that pushed out could also hold in it would be even stronger still. The same can be said if it buckles inward. It is therefore self supporting.

Rather than go with the initial and simple design theory, Lotus designed a chassis that meant not using a roof structure to make an open topped vehicle very strong.

If the chassis of K1 was compared to FM2 seen in Figure 8.2 and Figure 8.3 FM2 has significantly more area away from the neutral axis. Reinforcing

Figure 8.1: Elise Chassis

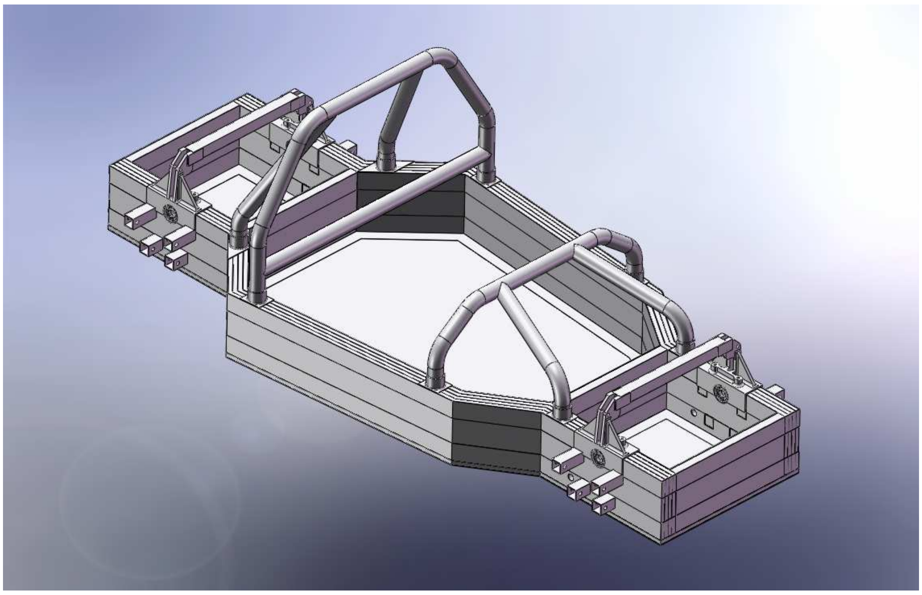

Figure 8.2: K1 Chassis

against buckling is likely a weaker method compared to monocoque as it limits some material to areas that are not useful such as the floor. Even though it is transfering the torque it is not significantly far away from teh axis of applied torque due the restrictions placed on the design for being able to enter the vehicle through a door. This means wide sills are required for strength.

In the case of K1, additional walls shown in Figure 8.4 yeild deminishing returns compared to weight and wall thickness which limits accessibility to the vehicle. This type of chassis is ideal for the open top sports car variey compared to the production monocoque chassis that exsist due to its better ability to transfer loads from the front to rear suspension.

A surprising benefit is that during a frontal impact the sills are interally supported against buckling provide a very ridgid enclosure. The significant width of the beams provide phenominal side impact protection as well due to their required thickness and internal support mechanism providing that the beam is designed to be at least as high as the point of impact with a similar car.

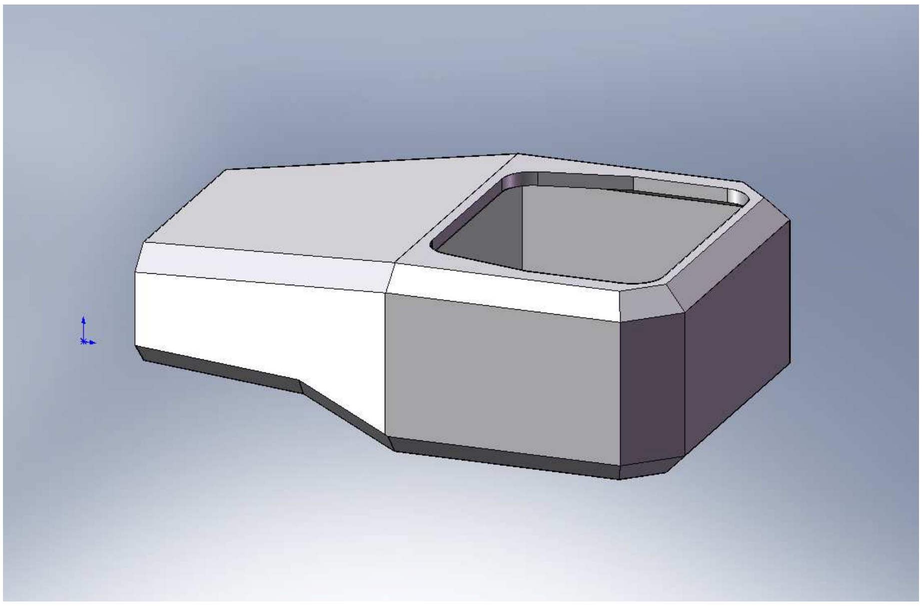

Figure 8.3: FM2 Chassis

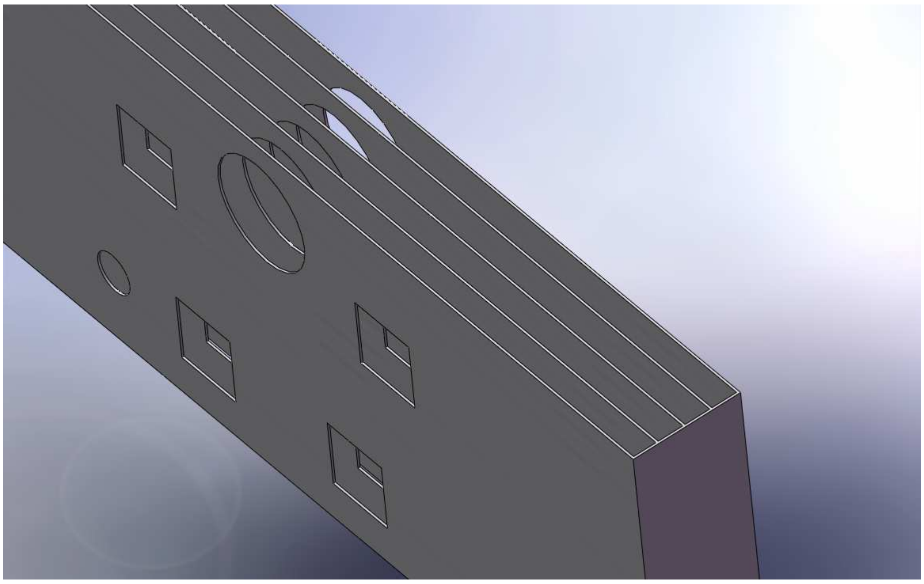

Figure 8.4: K1 wall structure

Chapter 9

Monocoque

9.1 Introduction to General Monocoque Design

According to Wikipedia a short description of a monocoque is:

> Monocoque (French for "single"(mono) and "shell" (coque)) is a construction technique that supports structural load using an object's external skin. This stands in contrast with using an internal framework (or truss) that is then covered with a non-load-bearing skin. *Wikipedia*

A monocoque chassis can therefore be taken to mean a vehicle where the external body is load bearing. While this is the technical definition, accepted usage will differ. A vehicle like the Koenigsegg ccx is considered a monocoque but it still has bodywork and non of the actual load bearing skin is actually on the outside of the vehicle except the bottom. In the ideal sense this is not really a monocoque as the outer shell is not stressed of the vehicle - however it is still a shell like chassis that has a stressed surface.

Most commercial vehicles today are of the monocoque variety but they generally will differ from the shape implied by road racing vehicle structure. Common vehicles such as the Honda Civic and Chev Impala are stamped from steel panels, these panels are then assembled and spot resistance welded together to build the cars structure. Like the Koenigsegg it is also not a true monocoque but for different reasons. It is made up of continous panels but there are large holes along with structures being created resembeling tubular members.

This type of architecture is refered to as a unibody but is still referred to as monocoque. A distinctiction can be made but has not been commonly done. The reason for this is that a mass produced vehicle today transfers stress throughout the unibody surface like a monocoque, the difference is that it still has body panels. Some of the outer surface is load bearing like the pillars and the roof, and some may not be such as the quater panels.

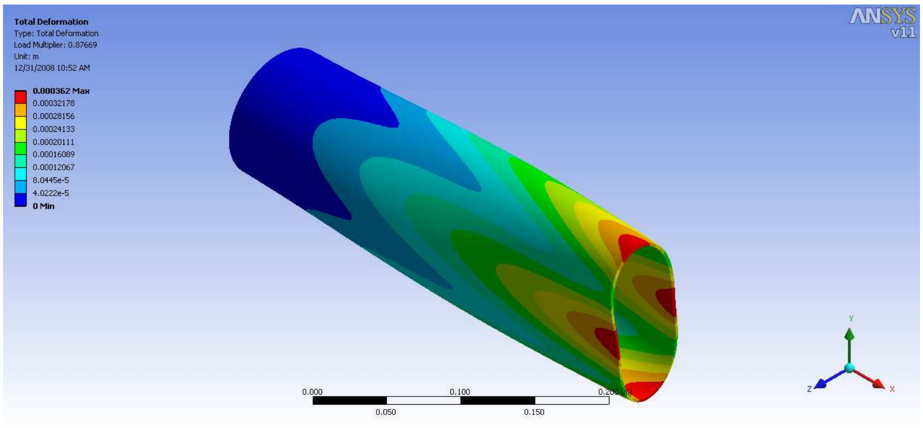

Figure 9.1: Lowest bucking mode of tube

The unibody architecture is a mass market architecture which is not being catered to in this book. This chapter will continue more in regards to the monocoque designs of formula style vehicles and low volume production vehicles.

Since some or all of the monocoque is exposed to the air, aerodynamics will play a very key role in defining the shape of the vehicle. From this the structural design will take place, but this is a cyclic matter. Weak areas structurally may require reinforcement which will result in poor localized aerodynamics. This will mean continously fighting for compromise until the designer is statisfied.

9.2 Wall buckling

A problem exsists concerning the original theory. Thin walls far away from the neutral axis will yeild the strongest stiffest chassic for bending and torque. Due to the size limitation a single wall car chassis is subjected to a torque will cause wall buckling.

If the original tubular theory is tested on a small scale with a torque applied at one end and a fixed support at the other. An arbitray value of 20kN·m is chosen as the torque for this test. The safety factor for the 90mm tube with 2mm walls which is 300mm long is at approximately 0.16238 which is significantly below failure. The buckling mode multiplier is 0.87669. So this means the tube would fail in buckling at about 88 percent loading. The first buckling mode is shown in figure 9.1 and the 3rd buckling mode is shown in figure 9.2. Notice that they are deforming in different ways. The third mode takes more load than the first but given the right level of imperfections this mode may occur.

In order to examine what happens at the larger scale a flat sheet is used. Figure 9.3 shows the shear force setup for 1000N on a 300mm x 300mm x 1mm plate. In this case the software predicts that it is perfect and therefore will figure give a fairly predictable result which is shown in figure 9.4 as very slight

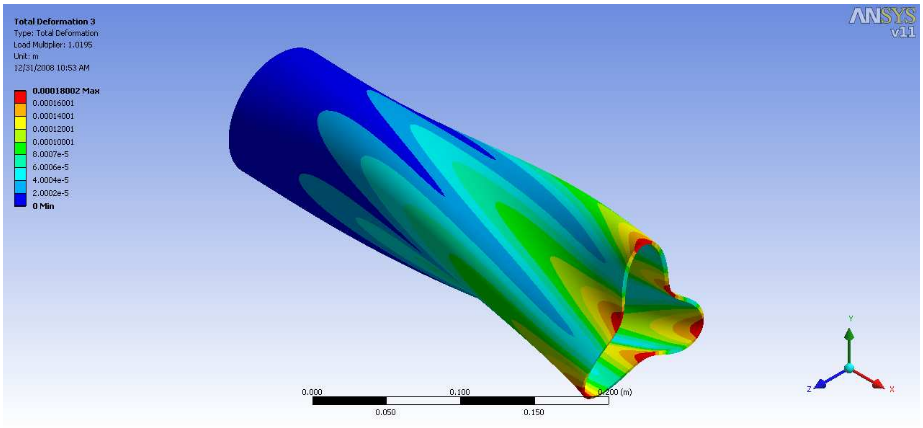

Figure 9.2: 3rd Lowest bucking mode of tube

Z direction deformation.

However when we impose the linear buckling solver there is an interesting result. Figure 9.5 shows a significant increase in deflection. Dividing this up to its two major components of the Y direction and the Z direction shown respectively in figure 9.6 and figure 9.7, it can be seen that Z direction is still insignificant while most of the deflection is in the Y direction.

Given the moment of inertia being very small for a thin plate, a large deflection at the plates end in the Y direction would take very little force to stabalize. Stabalizing the plate with a small continous force will bring it closer to the original ideal result with a safety factor of over 7. The lowest buckling mode has a load factor of 0.47814. Any load therefore greater than approximately 478N in shear would cause this plate to buckle in a distributed load which is significantly less than the ideal load.

This is the basis of why stabalization is required for monocoque designs. The normal construction techinque lends itself to making bending resistant panels as well as shear resistant making them function as the safety structure as well.

9.3 Angular Monocoque

The angular monocoque is more of a way of differentiating metal and composite monocoques. Hydroforming, pressing, and manual shaping are required to make curvatures. Normally in low volume production for race vehicles this is not done. Faceted monocoque construction is employed. Flat sheets of metal either welded along the seam or with a tab folded and glued or rivetted or both. It will usually employ a double layer technique with a coupling material such as aluminum honeycomb to provide the stabilizing structure as well as provide impact protection. A simple angular monocoque is shown in figure 9.8

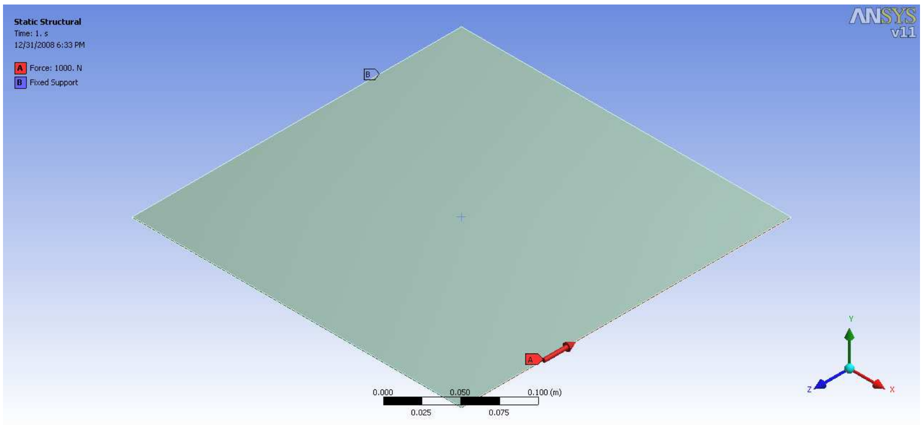

Figure 9.3: Sheet Shear Setup

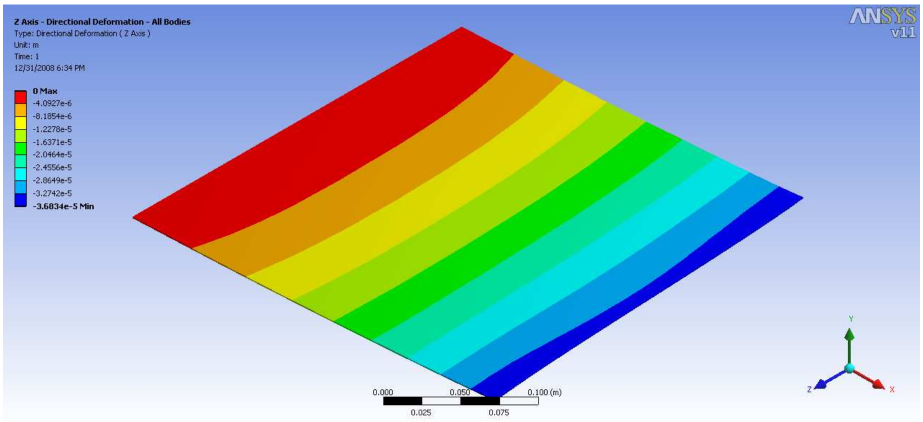

Figure 9.4: Ideal Z axis deformation

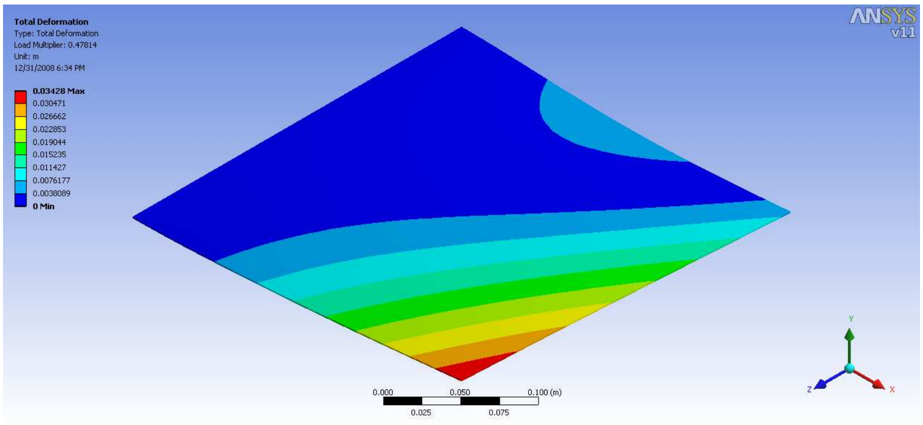

Figure 9.5: Buckling mode total deformation

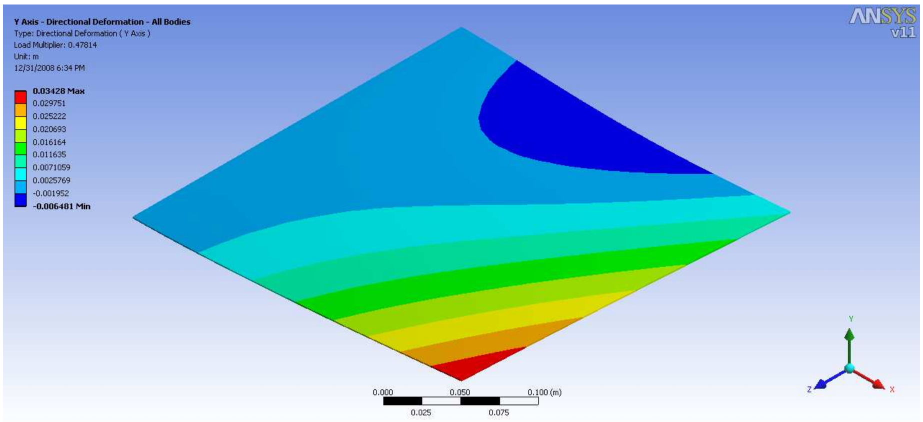

Figure 9.6: Buckling mode Y direction

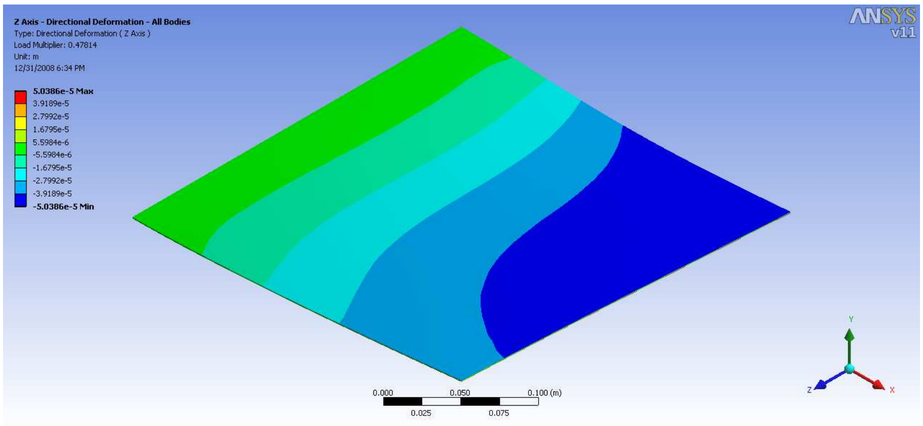

Figure 9.7: Buckling mode Z direction

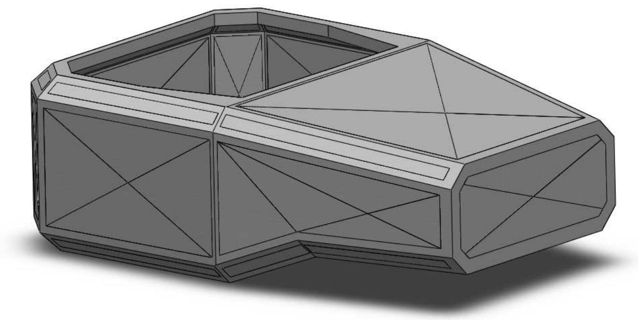

Figure 9.8: FM2 Angular Monocoque chassis

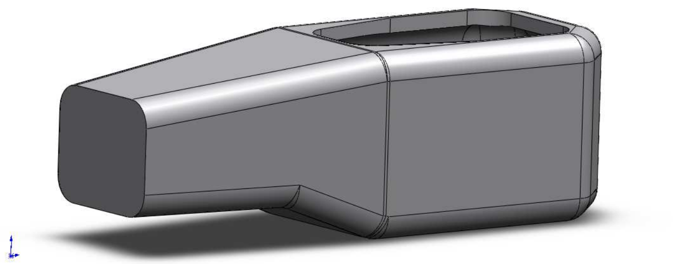

Figure 9.9: Modified single seat FM2 for composite

9.4 Carbon Fiber Monocoque

Carbon Fiber monocoques use a woven fabric covering the entire structure of a vehicle. It has a coupling structure between the inner and outter layer which is bonded to the carbon fiber. The epoxy provides stability and load distribution for attachement points as well as compressive strength.

The main benefites of carbon fiber is that in tension the elastic modulus is such that deformations are kept to a minimum which makes for a very rigid design. The downside is that metal absorbes a huge amount of energy in the plastic deformation region where carbon fiber is closer to glass or elastic and will fracture. The epoxy is also brittle so while the chassis is very rigid and strong there is very little room for error when on the edge of the design such as crash situations.

An intial single seat modification of the angualar monocoque chassis is shown in figure 9.9. It still would need optomization of the edges and development of the layering of the carbon fiber. The fillets may need to be reduced in size as well. The major thing to notice is that it is a more fluid and organic shape which helps ease the loadings.

9.4.1 Orthotropic Elasticity

Carbon fiber is unlike steel or aluminum or any other metal material. It is a composite of "strings" and a holding agent. If you pull on a piece of rope it is very strong in tension, but try to push the ends of the rope together and it has no holding strength. The same can be said about carbon fiber. The epoxy resin holds the strands of carbon fiber together and without it the part would have no compressive strength. With the epoxy resin it has some compressive strength, but not a significant amount.

This brings us to the Orthotropic Elasticity. We can no longer deal with just the elastic modulus and the poissons ratio to deliever the results we need. This is what causes difficulties in simulating carbon fiber and requires some expertise. Layering techiniques will affect it's strength, along with number of layers, and how much epoxy is used and what type. There are many variables and they usually must be tested to yeild an equivalent result.

Part III

Design Walkthrough

Introduction

Its very difficult to say where to start a vehicle design for a production enviroment. For mass marketing the design can be seam to be backwards. This section is going to take the engineering approach for performance vehicles but first will take a quick glance at the production enviroment.

The Vehicle Industry Approach

The Car manufacturing industry takes a very different approach to designing a car. The biggest issue they start with is aesthtics. Some of the steps are forward and backward so this is just a rough overview of how it goes.

1. Generate concepts on paper
2. Choose a concept
3. Create and refine that concept in clay at scale
4. Larger more refined concept generated
5. Concept adjusted to fit people and parts
6. Shown and approved it passes to engineering
7. Adjusts to fit chassis platform and suspention
8. Body changes for Aerodynamics
9. Prototypes built and tested with compromises
10. Chassis and body refined and tested
11. Production readying

If an F1 car started by defining its overall apperance and then attempting to fit the components to it the vehicle would not perform well. This industry process is much more detailed and refined and not accurate for all companies and is just to give an indication that the engineering is a much more constraint area.

The Performance Approach

The approach that will be taken by this book is that of defining initial parameters of the vehicle, setting up supension, and designing the chassis to fit these required tasks. The next chapter will detail this more fully.

Chapter 10

Design Process overview

Introduction

To take a fully utilitarian approach to design, the application must first be chosen. This can range from anything from commuter vehicle like a Smart Car, offroad vehicle such as the HMMVEE, racing vehicles such as an open wheel race car like F1 or closed wheel like LeMans Prototype. By chosing the specific application that the vehicle is design for will give a better understanding of the loads on the suspension points and chassis. An offroad vehicle is going to need to be designed to handle high levels of impact loading while a race vehicle is going to be designed close to the engineering edge with a desire to know accurately the loads and utilize low safety factors.

10.1 Design Steps

The first set of steps is that of general car design overview.

1. Application Definition
2. Suspsension Design
3. Chassis Design
4. Aero Design
5. Cockpit Design

Most of the focus of this text will be on the first 3 steps and can be broken down into the following.

1. Application Definition
2. Wheel layout - Track and Wheelbase

3. Suspension Definition and setup
4. Chassis requirements
5. Prelim chassis design
6. Chassis refinement
7. Chassis checks
8. Chassis simulation
9. Chassis Redesign, check, simulation, repeat
10. Final Chassis planning
11. Refinements for other requirements

This is not a linear process. The initial application definition should be a complete list of metrics and result in a definition of what the vehicle should be in respect to suspension, chassis, aerodynamics, interior, and user friendliness. A perfectly design chassis with no consideration for aerodynamics is not going to make an effective high speed race vehicle while a good aero design may not lend itself to a good cockpit. The entire process is about making trade offs and learning what is important for a given application.

Chapter 11

Two Seat Sports car "Tub" Frame

11.1 "Tub" Introduction: K1

K1 was a project initiated to study the design of an electric supercar. The Chassis went through a total of eleven major revisions. It started with the intention of following the "Tub" design but diviated to exploring skinned space frame, space frame, and angular monocoque. In the tenth revision the cockpit area of the chassis was settled on. The eleventh would see the main side rails extended to house the 4 custom axial gap motors.

Most of the specifications that were developed for the K1 were based off the Lotus Elise. Elements such as wheelbase targets, weight targets, power output, and more were to be copied from the Elise to the K1. The major differences were the following

- Direct drive pancake motors
- No differential, each wheel has its own motor
- Inboard braking to reduce unsprung weight on suspension
- Direct push suspension designed for common coilover
- Chassis stiffness similar to Elise
- All wheel drive

11.2 Ideas

The first process is generating ideas. Lotus uses glued extrustions. The project limited itself to off the shelve materials so the special glue used by Louts was

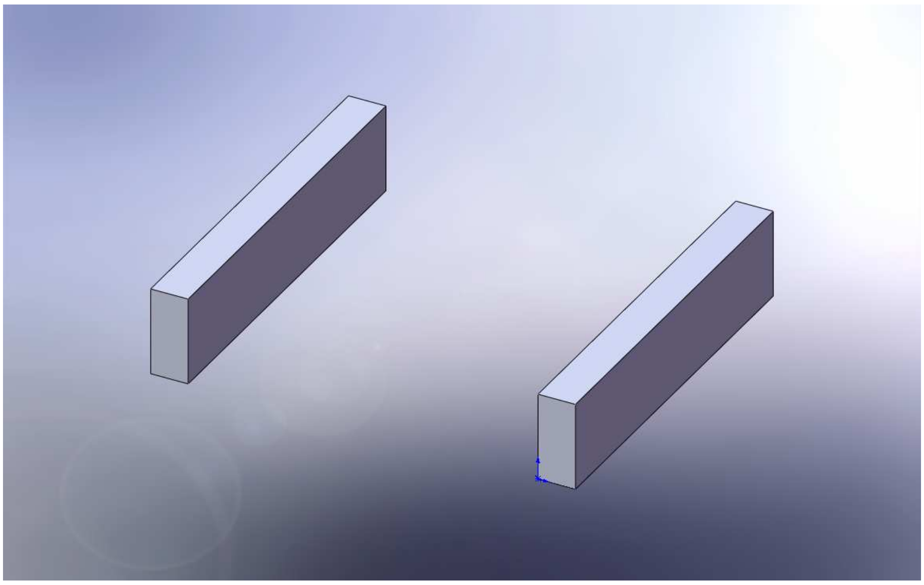

Figure 11.1: K1 Idea 001

out of the question but it was accepted that there was other methods of creating the longerons.

The first idea was to look at simple large box sections as shown in Figure 11.1. It was a simple idea. It was mainly for layout to see the sizes required for the 95 percentile male.

Once the length was determined this evolved into looking at how the motors would mount. An initial idea of having octagonal motors that could just slip into the sides was concieved. A solid model mocking up this concept was developed and is shown in Figure 11.2. It was believe that the wall buckling on such front and rear structures would be so great that the idea was revised.

The next concept was to taper the sides of the chassis similar to the Elise which is shown in Figure 11.3. Surprisingly this idea would be dropped at some point but make it to the final design in a variation. The idea was to hollow the center for seating but as a concept was never fully explored at this point.

11.3 Mark I

The K1 Mark I chassis was the first attempt to start developing the longeron sturcture. The initial attempt shown in Figure 11.4 is of the simple sheet steel cross section of the longeron. While this looked to be a good design and followed Lotus's idea of filling the cross section with material to couple the inside and outside it was reasoned that there was no direct way to create this shape easily. The requirement was that this project had to be realistic and this created

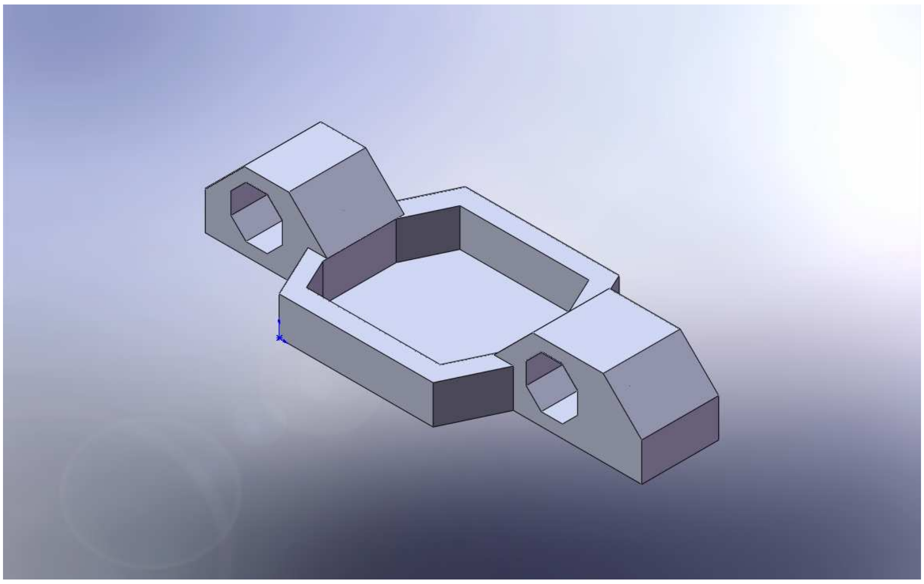

Figure 11.2: K1 Idea 002

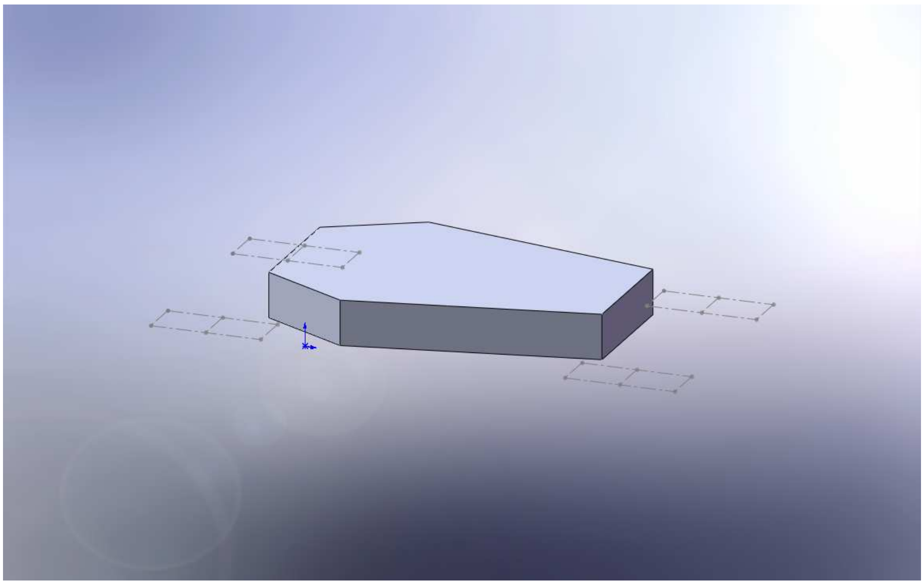

Figure 11.3: K1 Idea 003

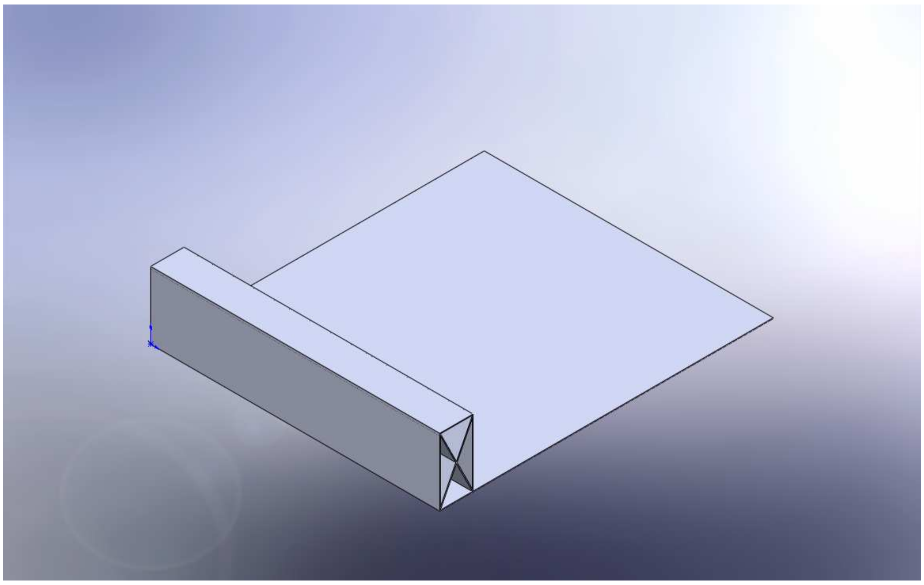

Figure 11.4: K1 Mark I

problems for welding the internal structure. As a result it was abandoned.

11.4 Mark II and Mark III

After serveral attempts to create easy to build structures from sheet aluminum it was decided to go after a skinned space frame approach and combine it with a simple bulkhead monocoque. Mark II in Figure 11.5 shows two vertical members at the front and rear on the inside. Sheet metal was going to connect these to create the longerons but it was determined that they did not add significantly to the strength and caused concern that if weight was placed on these they would easily buckle. Without a support structure it was determined that this would not be a suitable design.

The Mark III then eliminated the skinning and the project started heading towards a space frame. The removed sheet metal panels leaving just the space frame is visible in Figure 11.6. This went against the philosphy of the original project and was therefore dropped. While this does not seem to warrent a full major revision it was a major deviation in idea even though no real design was completed.

11.5 Mark IV and Mark V

The Mark IV was a major change from the skinned spaceframe and spaceframe versions of the chassis. The final product is shown in figure 11.7 and is a nearly

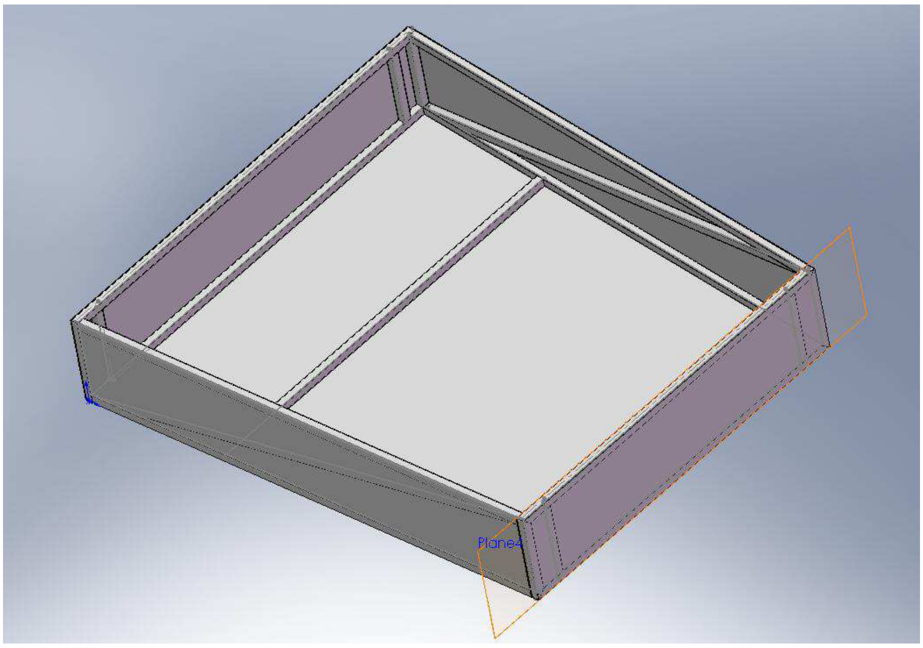

Figure 11.5: K1 Mark II

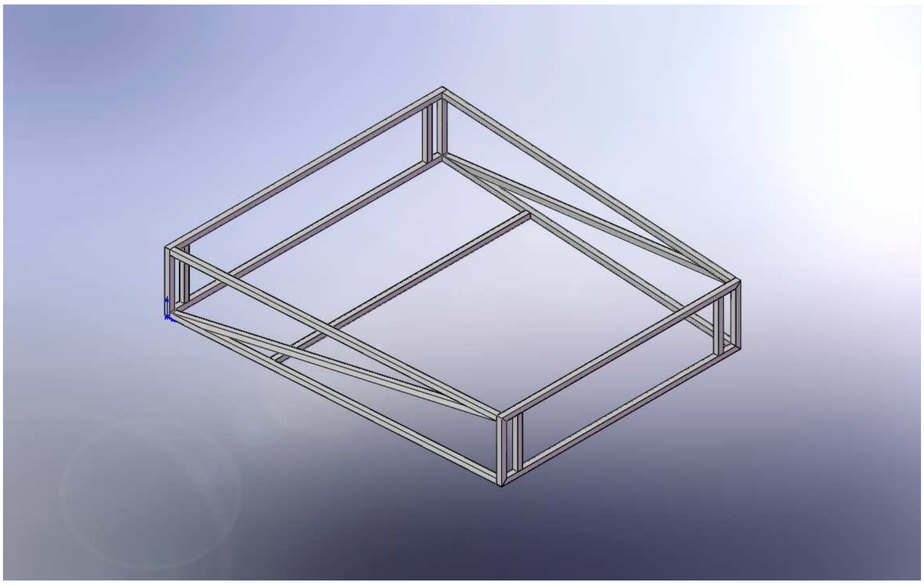

Figure 11.6: K1 Mark III without skinning

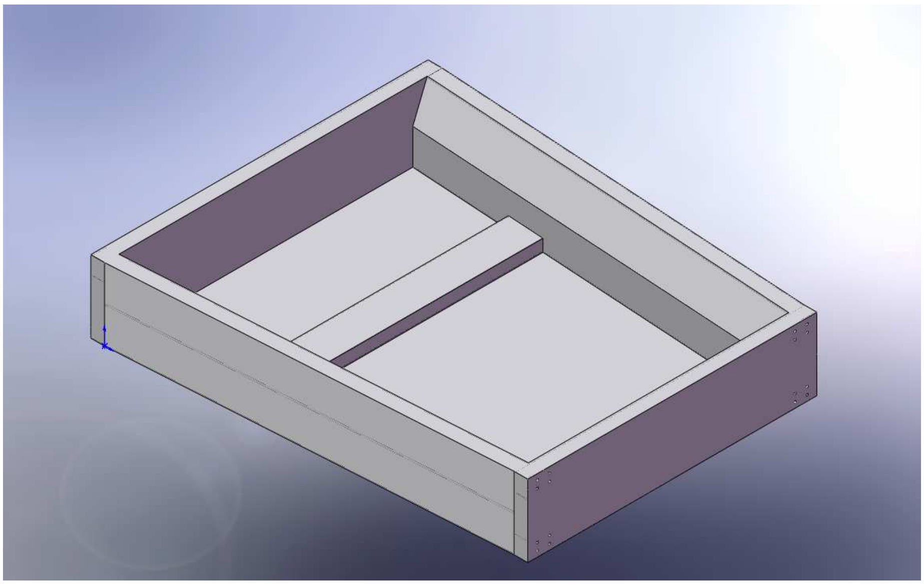

Figure 11.7: K1 Mark IV

completed chassis. It had well reinforced longerons shown in figure 11.8 with significant aluminum wall thickness which appeared good in regards to wall buckling.

The front and rear structure consisted of two tubular members that ran horizontally, shown in figure 11.9, skinned with aluminum sheet metal. There were holes in the front and rear for mounting seperate structures which would hold the motors and the suspension mounts. This was an idea taken from Koenigsegg as they use a central carbon tub with front and rear structures for housing the drive train.

A close up can be seen of how the front structure was developed in Solidworks in figure 11.10 as one continous solid. This made it easier to test but did not accurately acount for the bonding strength in this area.

Mark V was just minior adjustments to positioning of this chassis. The overall original design of the Mark IV was intended to be kept intact so a new revision was created incase the design had to back track to the original Mark IV.

11.6 Mark VI and Mark VII

Mentioned in the previous section was the Koenigsegg car. The idea then developed that the chassis could be made stronger by covering the frontal area and by expanding up the rear of the chassis. This would provide a better system to mount the drivetrain to as well. The inital concept can be seen in figure 11.11.

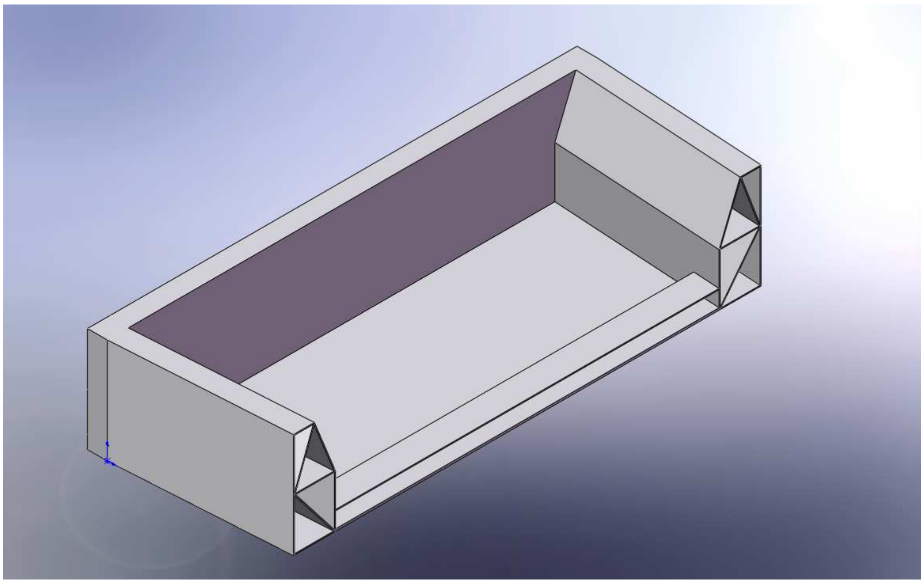

Figure 11.8: K1 Mark IV longeron cross section

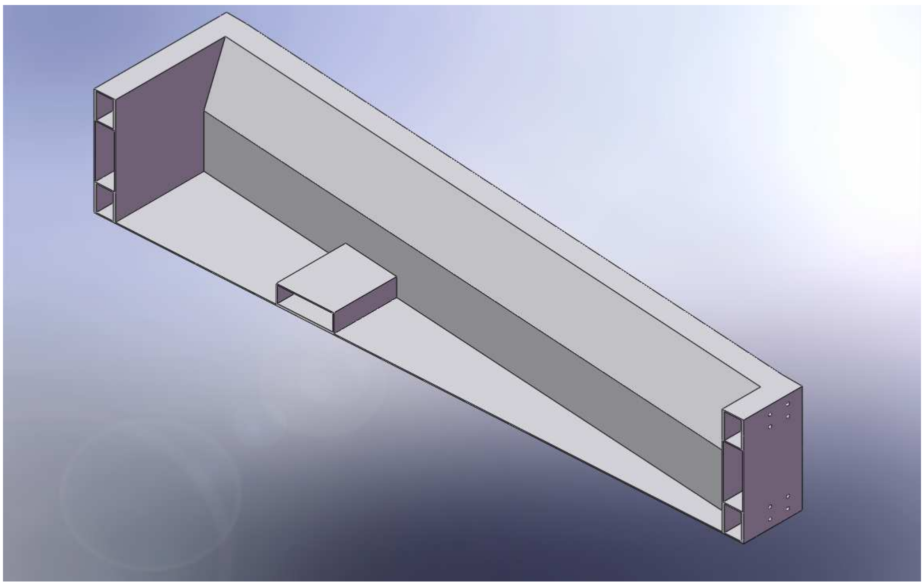

Figure 11.9: K1 Mark IV front and rear cross section

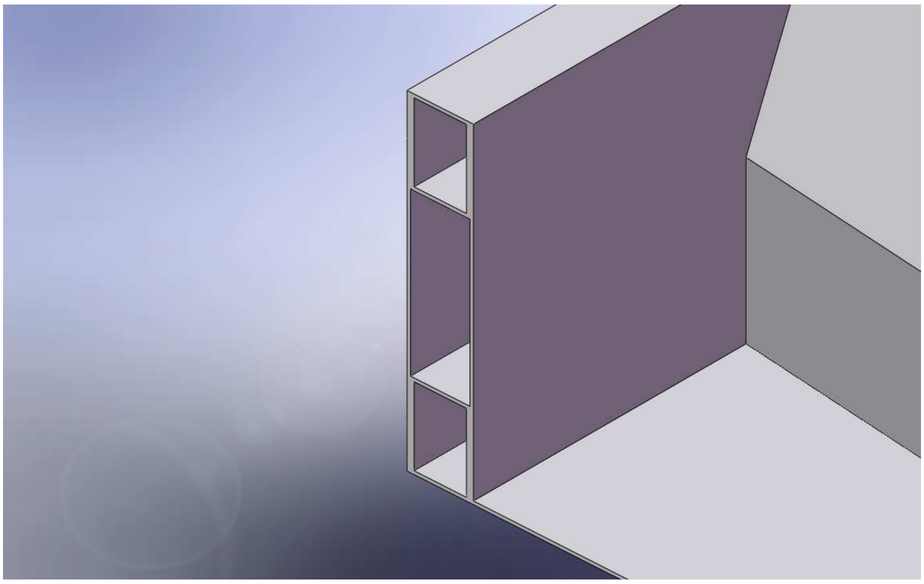

Figure 11.10: K1 Mark IV rear cross section detail

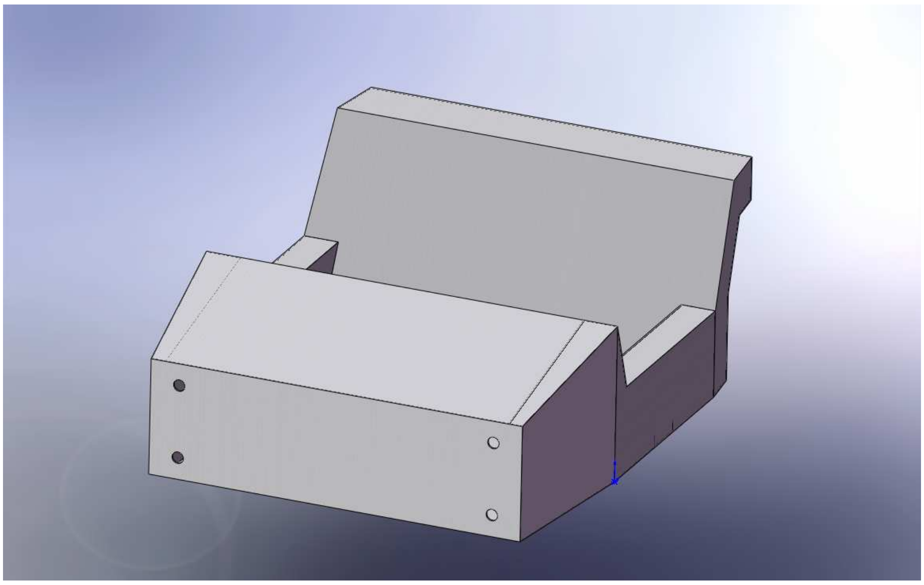

Figure 11.11: K1 Mark VI

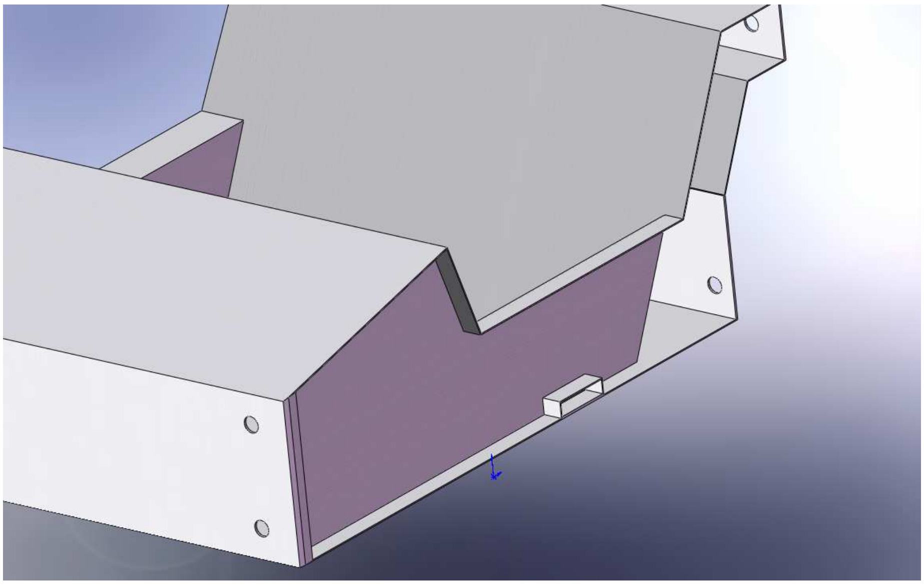

Figure 11.12: K1 Mark VI hollow interior and beam

The initial cross section was hollow with the exception of a beam accross the bottom with the idea of linking each side of the car together. This can be seen in figure 11.12. This would provide increased side protection by coupling both sides of the car so that in a side impact it would use the entire car as beam and push it rather than impacting into the side.

This left numerous problems of how to fill the gap. Figure 11.13 shows the centeral cross section. The rear section was especially difficult to deal with as it was not continously the same thickness which elimnated the idea of utilizing continous honeycomb material.

This lead to redesigning the structure so that the rear would be more continous in the Mark VII seen in figure 11.14. The rear was continously one thickness but left issues with trying to connect the sides of the chassis as well as a suitable reinforced frontal section could not be developed.

It was decided that Mark VI and Mark VII were again diviateing from the original idea and the project regained its original direction.

11.7 Mark VIII

The Mark VIII returned to the concept of the third idea presented and is shown in figure 11.15. The concept had been of creating longerons that tapered in at the front and the rear to better transistion forces that would be imposed from the suspension.

The idea that simple 90 degree panel holding extrustions exsisted made the

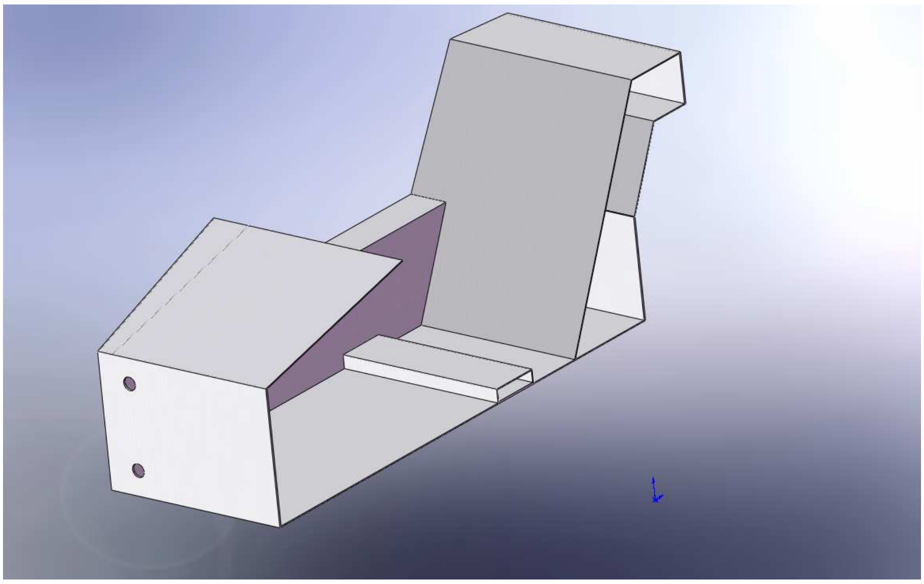

Figure 11.13: K1 Mark VI center cross section

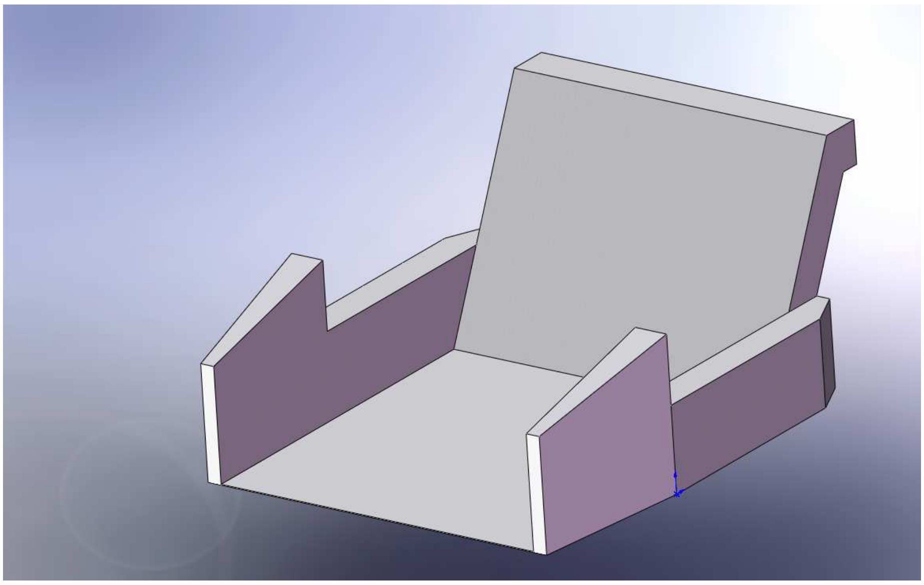

Figure 11.14: K1 Mark VII

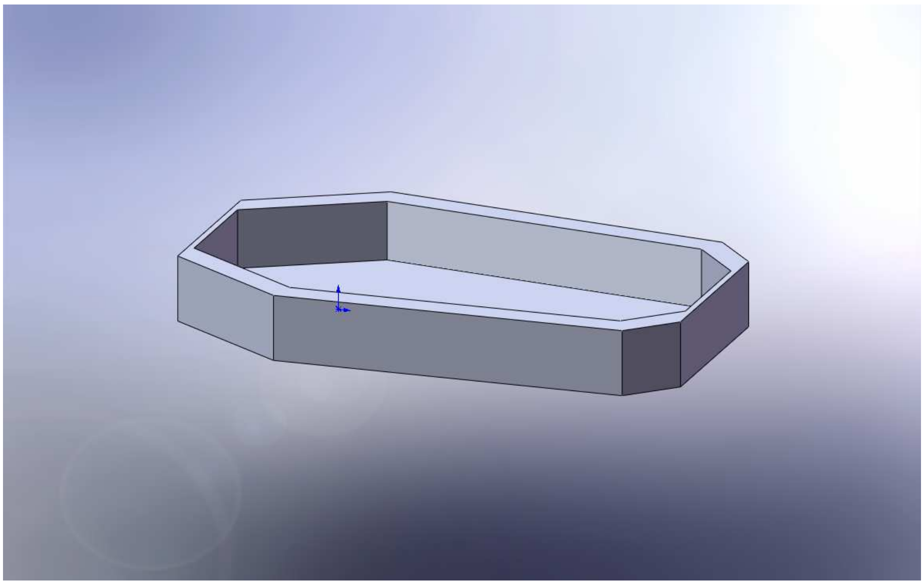

Figure 11.15: K1 Mark VIII

next step seem like a good one. Figure 11.16 shows two 90 degree panel holding extrustions. The idea was that simple honeycomb and aluminum sandwich panels could be created and cut to the proper fit. they could then be riveted into place. A better view of the underside of this structure is visible in figure 11.17.

The lower extrustions would connect the floor which is one large panel and the opening can be seen in figure 11.18.

11.8 Mark IX

While the idea for Mark VIII seemed sound the overall shape did not seem to be a correct fit for the desired design. The Mark IX would adjust this and continue design work. Starting with a newly defined cockpit floor layout shown in figure 11.19 the extrusion and panel layout restarted.

The initial edge layout was developed using the same extrustions as before and can bee seen in figure 11.20. The spacing was increased between outside and inside structure and a simple "T" extrustion was developed to join to the floor. All required extrusions and cuts were developed and shown in figure 11.21.

It was eventually realized that no off the shelf extrustions were available for this design and was therefore abandoned. However this did develop the use of honeycomb material combined with sheet metal and that multiple layers at the edge would improve performance of the chassis for torsional stiffness.

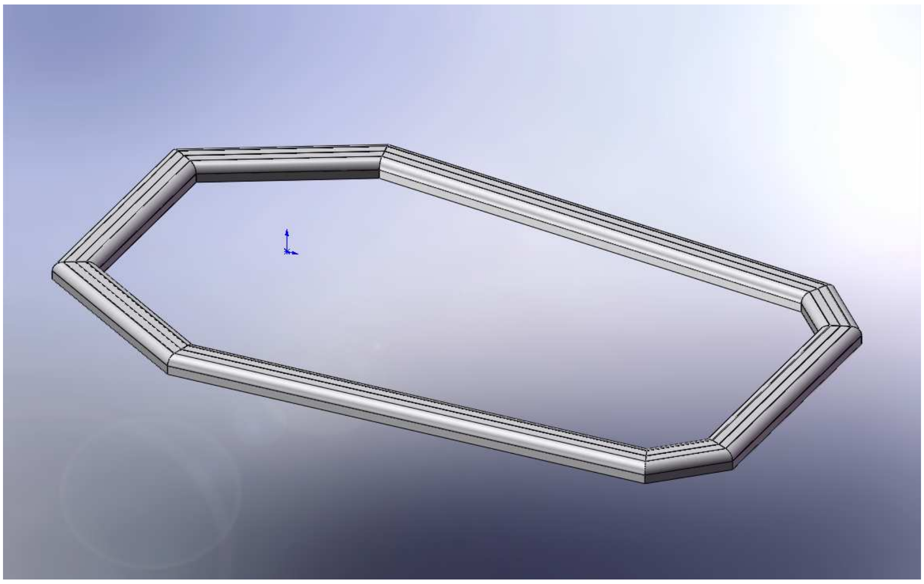

Figure 11.16: K1 Mark VIII 90 degree extrustions top

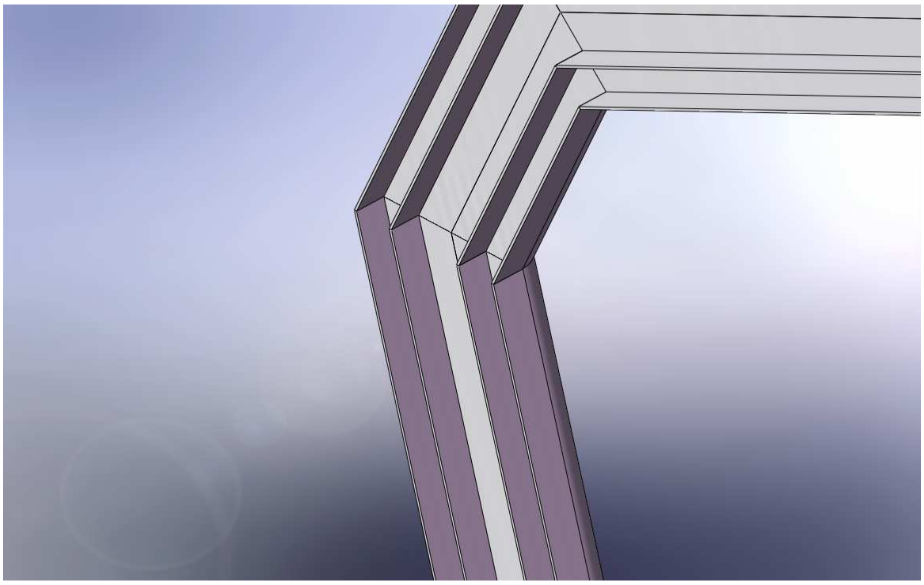

Figure 11.17: K1 Mark VIII 90 degree extrustions bottom view of top

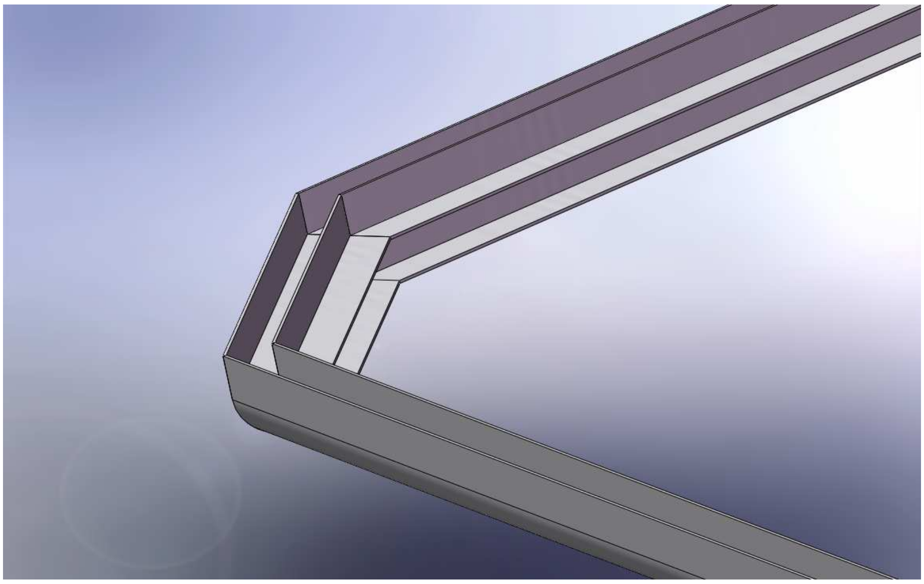

Figure 11.18: K1 Mark VIII 90 degree extrustions floor

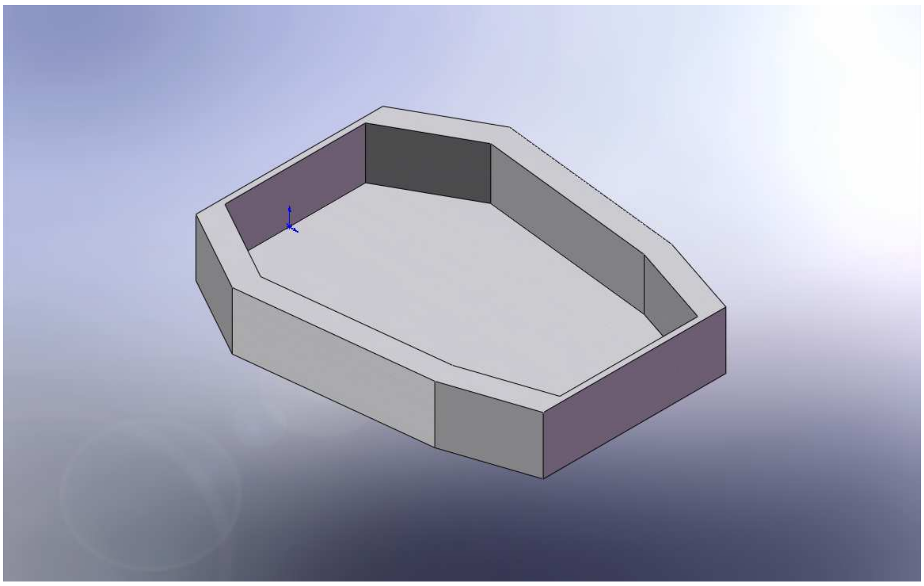

Figure 11.19: K1 Mark IX

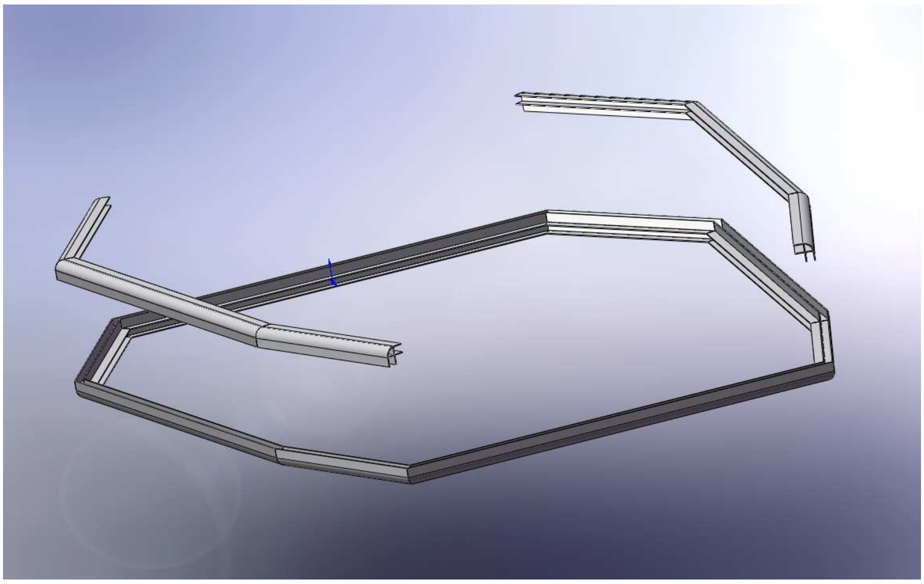

Figure 11.20: K1 Mark IX initial layout

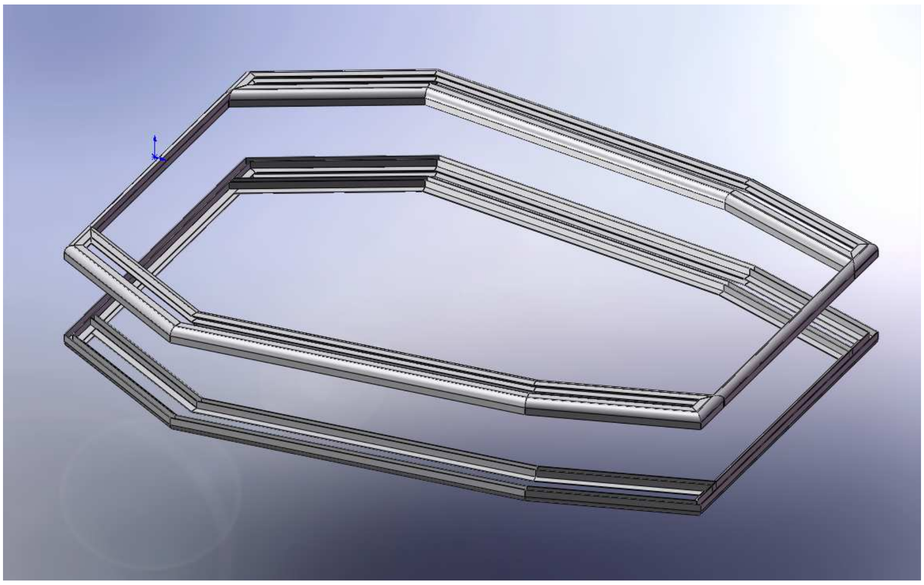

Figure 11.21: K1 Mark IX all extrusions

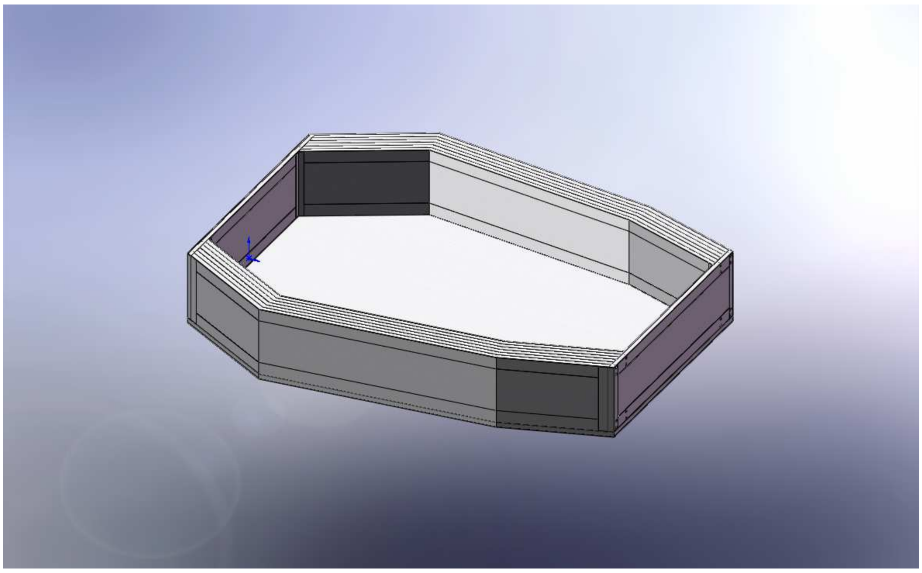

Figure 11.22: K1 Mark X

11.9 Mark X

The Mark IX had started to develop good chassis theory in relation to being a simple torsional member. This developed into a simple structure with many layers of aluminum sheet metal sandwiching a honeycomb material. These walls were made up of many layers of aluminum and additional pieces were added to keep all surfaces flush and add even more material. The Mark IX is shown in figure 11.22.

Unlike the Mark VIII, the Mark IX was intended to be made entirely of aluminum sheet metal with edges welded. The top plate is shown in figure 11.23. It is a simple cut out with flat edges. While this would be welded, the welds were not included in the design as seen in figure 11.24.

The lower plate shown in figure 11.25 is similar to the top except that it has edges that come downward so that the structure can wrap around the honeycomb based floor as well. The floor is a single aluminum honeycomb sandwich to support the loading of the people instead of the original design with a tubular member. This was done because of the area behind the occupants would be holding part of the weight of the battery system.

Figure 11.26 shows the internal wallstructure made of aluminum sheet metal. It also shows how the front structure with the mounting brackets are reinforced with standoffs. This was done to decrease the high stress caused by having bolts in these faces.

The design was considered very acceptable but there was difficulties in developing the front and rear suspension and drive structures. Part of the problem

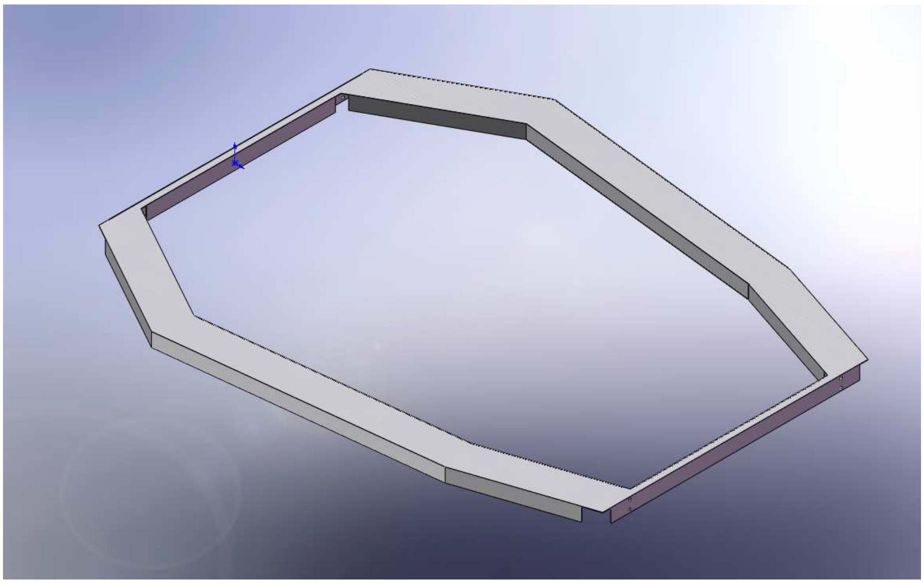

Figure 11.23: K1 Mark X top plate

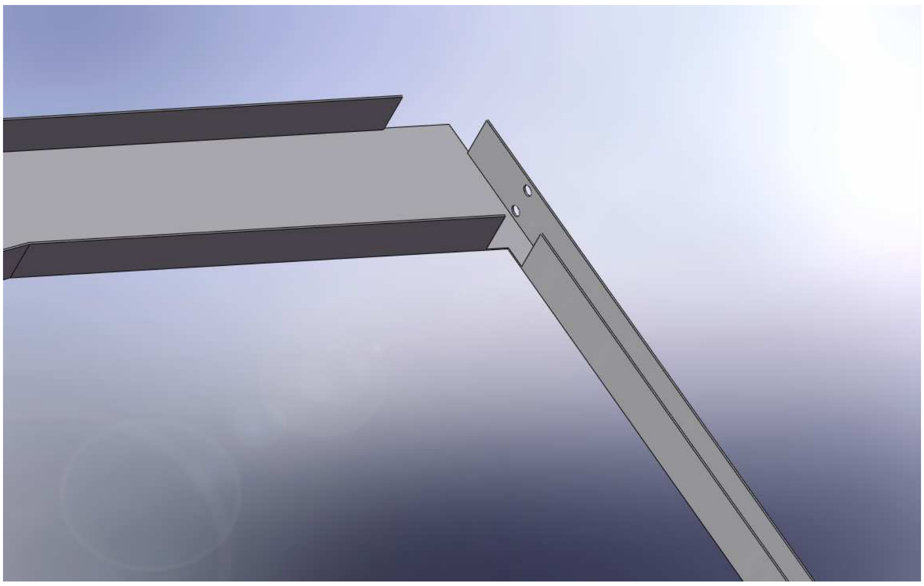

Figure 11.24: K1 Mark X simple design missing welds

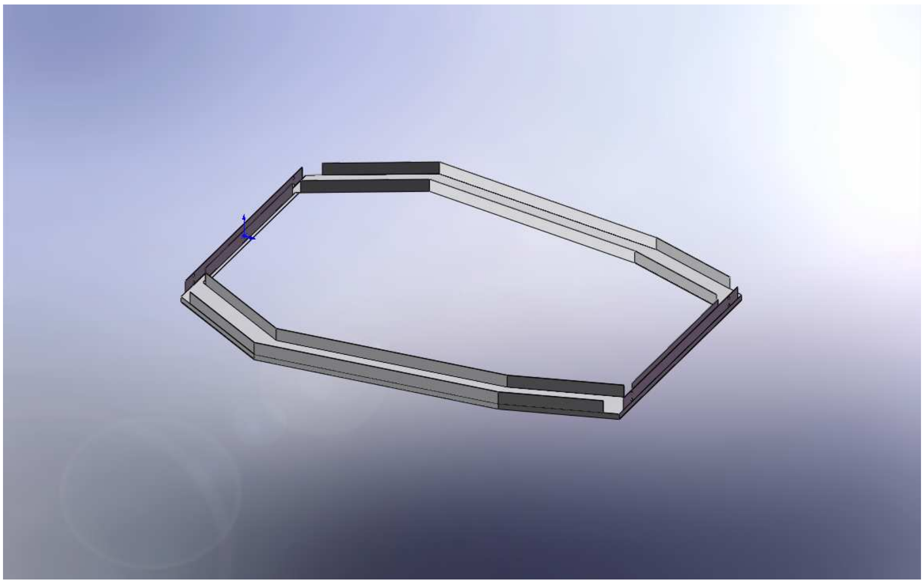

Figure 11.25: K1 Mark X floor structure

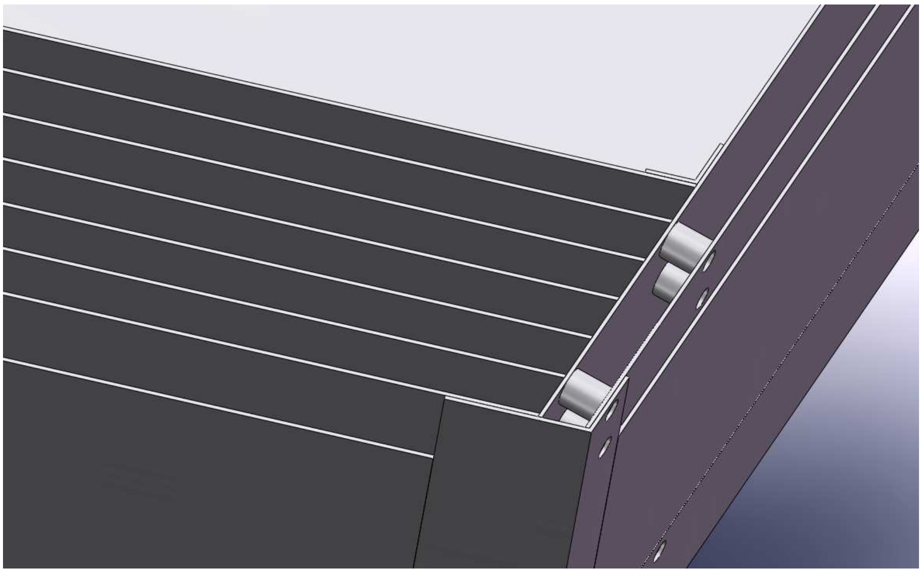

Figure 11.26: K1 Mark X wall structure

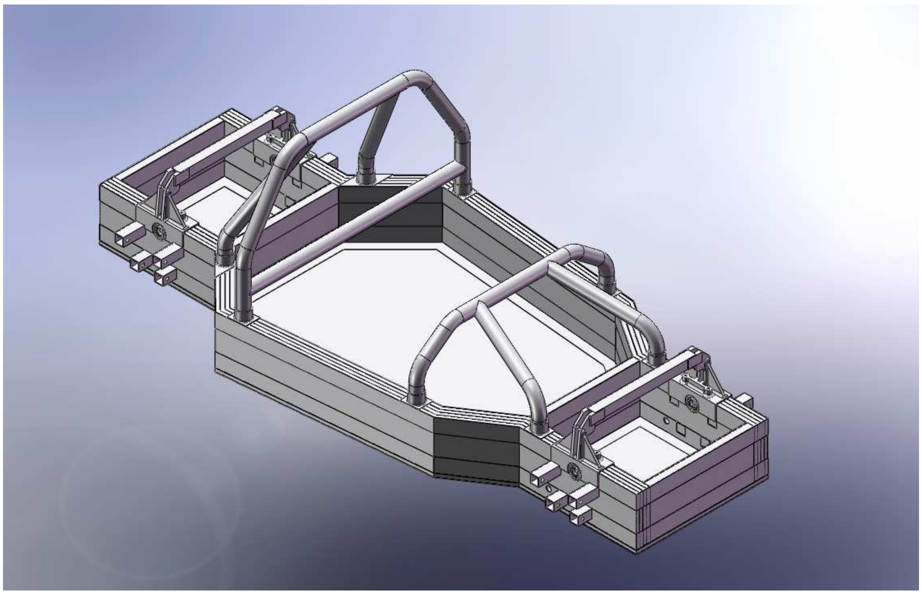

Figure 11.27: K1 Mark XI

was the discontinuities it created part was the difficulties in mounting. Several mounts were attempted but in the end it was decided to modify the chassis.

11.10 Mark XI - Final

The front and rear longerons were extended to create areas for the electric motors. Tubular members were added for roll over structure. Suspension mounting structure which incorporated brake mounts with a cross member were created as well. The final chassis is shown in figure 11.27. It is very similar to the original design with a simple sheet aluminum construction seen by the top plate in figure 11.28.

As in the Mark X, the Mark XI uses several parallel sheet metal sections that run the entire lenght of the chassis. This time they had been elongated for the front and rear suspension and motor structural areas. They can bee seen in figure 11.29.

Figure 11.30 shows a view of the motor enclosure area and suspension mounts. It can be see from the earlier figure 11.29 that the side panels contain 4 gaps for aluminum honey comb material. The bulkhead between the motor and cockpit only has one gap as this was considered sufficient for the structure.

The suspension points are constructed from square tubular members. The idea is that the initial layer would be laid out and the tubular members welded to it. Epoxy and honeycomb would be put on and then epoxy and aluminum.

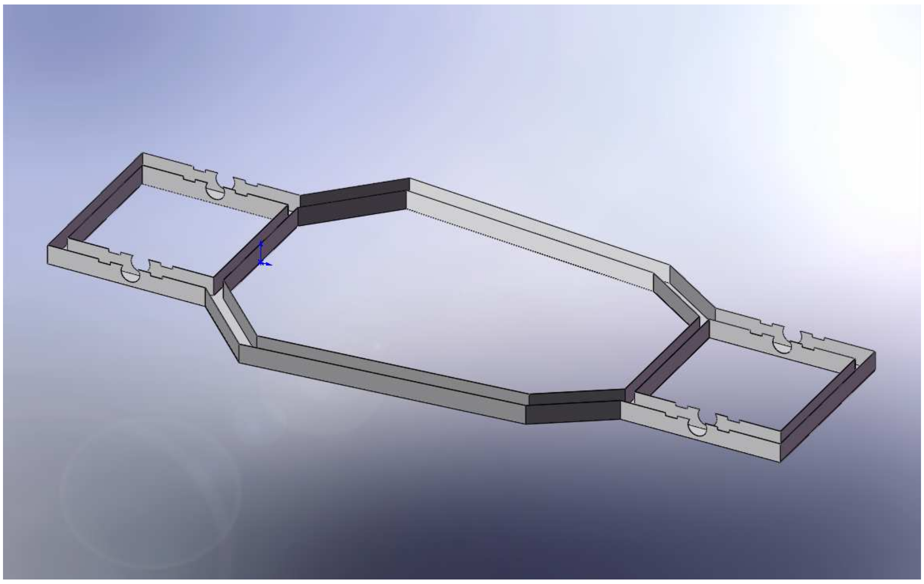

Figure 11.28: K1 Mark XI redesigned top plate

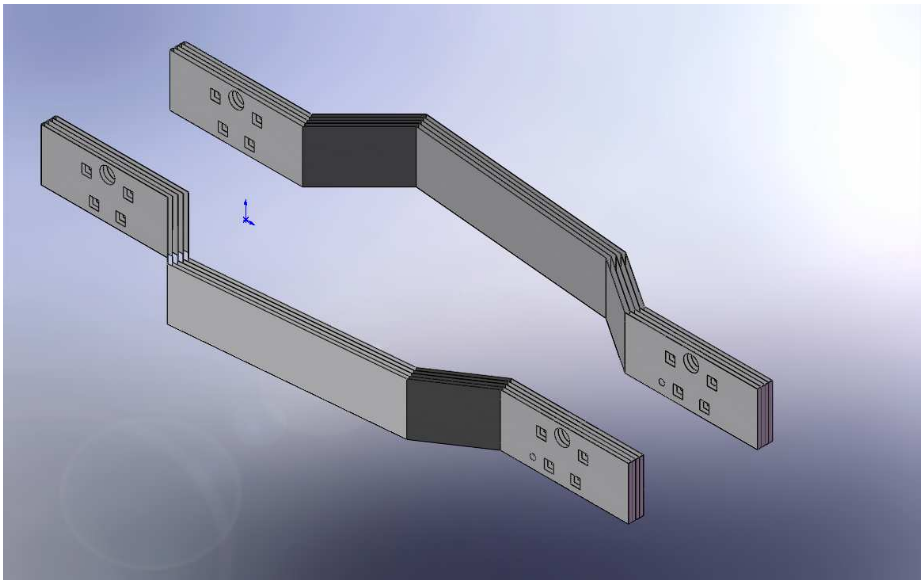

Figure 11.29: K1 Mark XI new longeron aluminum sections

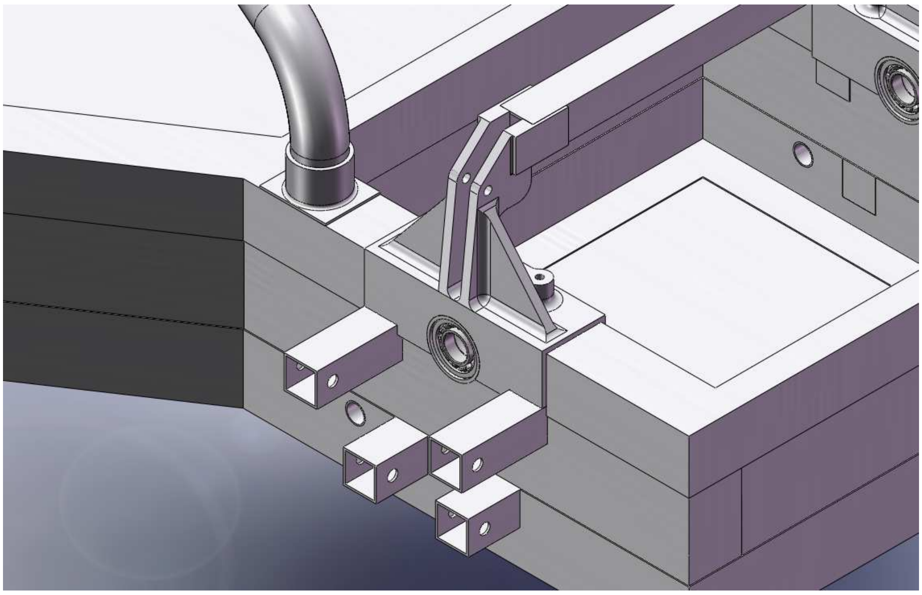

Figure 11.30: K1 Mark XI motor compartment

The next aluminum sheet layer would be put on top of the aluminum honey comb with the appropriate epoxy and the front and rear flats along with the tubular suspension members and bearing members would be welded at this time. Each successive layer would be finished with welding. This will allow the load to be distributed throughout a very strong beam for the forces that will exsist during cornering and steering.

The suspension needed a place to join as well as a place to mount the onboard brakes. While the direct drive motors can make use of regenerative braking the amount of backforce greatly depends on speed and how much current can be removed. Even at short circuit physical braking can provide much greater braking force.

The mount shown in figure 11.31 was designed to be made of thick aluminum so they would not create corrosion cell with the body. The fillets are to represent the welds that would be required. Since there will be a large load associated with this from the suspension it was determined that there would be a large bending force transfered at this point. To minimize this the structure was designed to have a bar placed between the two mounts. This would even out most forces and with the exception of heavy cornering should lead to only a vertical loading transfering to the chassis.

In retrospect this is a poor design and should be avoided. The point of application of suspension forces should be greatly reinforced.

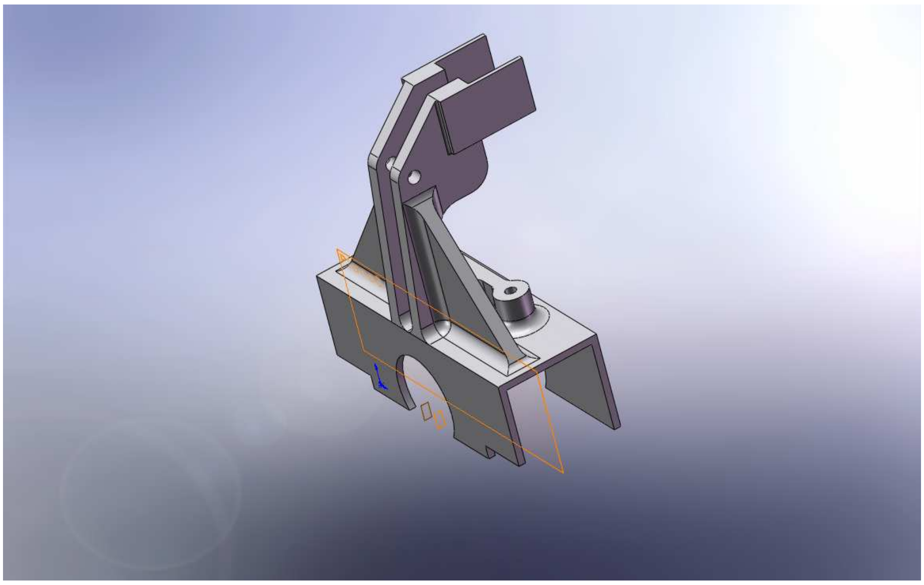

Figure 11.31: K1 Mark XI suspension and brake mount

11.11 K1

The final K1 design is shown in figure 11.32 with its wheels, motors, suspension, battery, braking system and roll bars.

The motors were mounted in the front and rear using plates that would transfer rotational back torque to the floor and bulkheads shown in figure 11.33. The bulkhead structures can take a significant bending load due to the sandwich construction while the plates evenly distribute the load amongst a large area. There are also front and rear overhangs that translate some of the force to vertical pulling or pushing.

The brake disc is inboard which will require duct work to bring air to the center of the disc. The brake caliper is located directly on top of the disc and mounted to the suspension mount visible in figure 11.34. While the idea of reducing unsprung weight seemed like a valid one it meant several difficulties in the design process. The tubular members for the suspension were originally intended to connect both the left and right side but due to the brake it was impossible to do this. The output shaft required the top most members to be fairly far away requiring large wheels to get the required turn radius.

The suspension was the double wishbone type visible in figure 11.35. It uses a ridgid link on the top suspension so that none of the force from the shock is lost laterally as it would be if the shock was mounted on an angle directly to the suspension. This arrangment keeps the shock acting as close to linear as possible. In a normal arrangement as the shock raises the angle becomes steeper resulting in more force pusing against the suspension latterally and not

Figure 11.32: K1

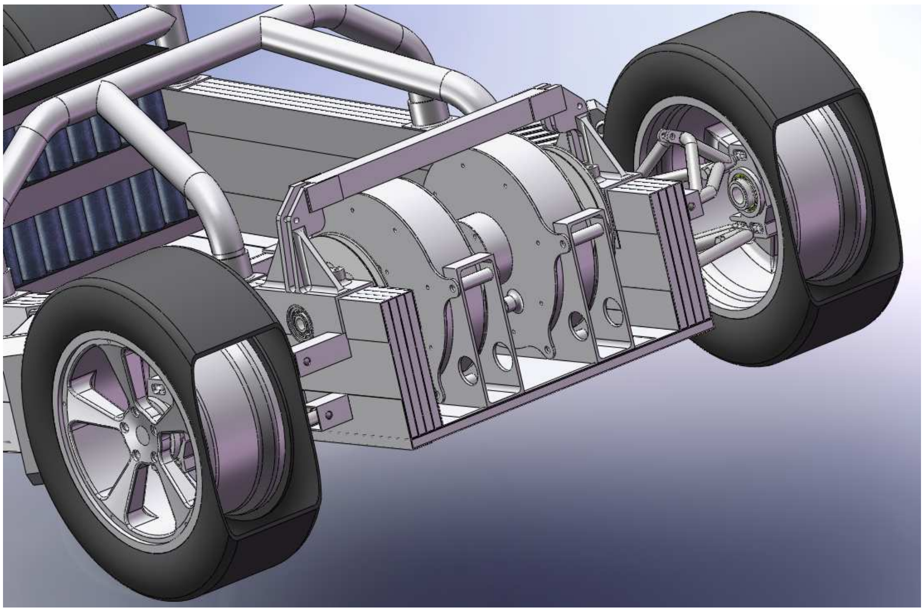

Figure 11.33: K1 motor mounts

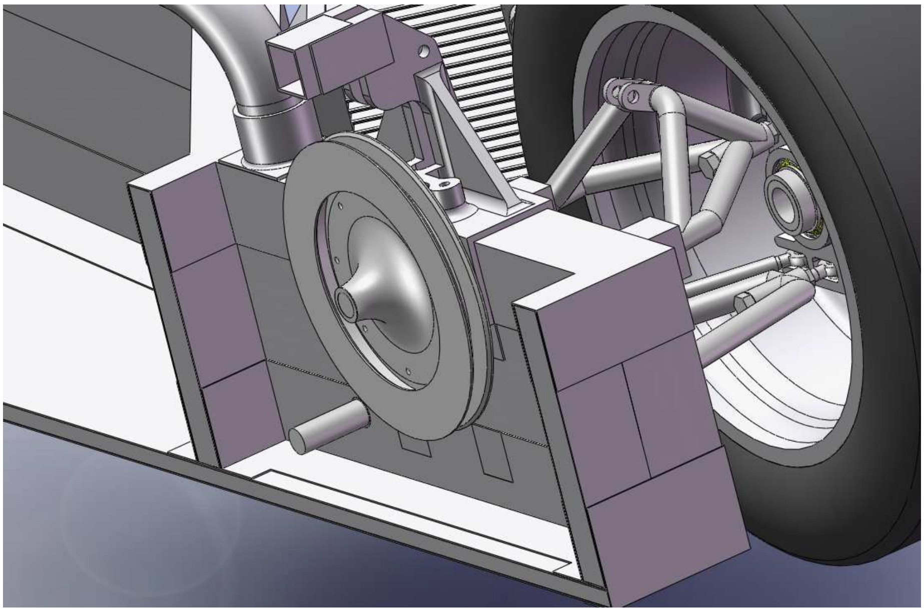

Figure 11.34: K1 inboard brake

vertically. This design means the the suspension does not travel more than it has to while achieving the same job.

Earlier in the book it was mentioned that aerodynamics would have influences on the shape of a chassis to some extent. In the case of the K1 shown in figure 11.36 individual radiators were chosen to be used for each motor. Normally air is ducted in through the opening around the suspension for brake cooling but in this design it isn't needed so the radiators were placed such that this air could be used for motor cooling.

Another aerodynamic related item was a flat bottom to the chassis shown in figure 11.37. Diffusers add downforce by expanding the air flowing under the body of the car. Adjustments to the shape will cause downforce to occur in certain areas and lift to occur in others. The flat bottom is a starting point for adding a diffuser to provide additional downforce for rear wheel traction useful in all wheel drive and rear wheel drive vehicles. The K1 being all wheel drive could make use of this. It also provides a good mounting surface to attach an surface designed to provide downforce underneath the chassis.

Roll bars are an important aspect of this chassis. The large tubular members used seen in figure 11.38 have several benefits. They were sized to be significantly large and so that they are not susceptible to bending moments. The rear also has a bar striaght across. This was a consideration for impact protection to translate impact force from one side of the chassis to the other so that the whole chassis is pushed rather than collasping one side duing impact. During an impact there is a significant amount of energy to be absorbed so the operation

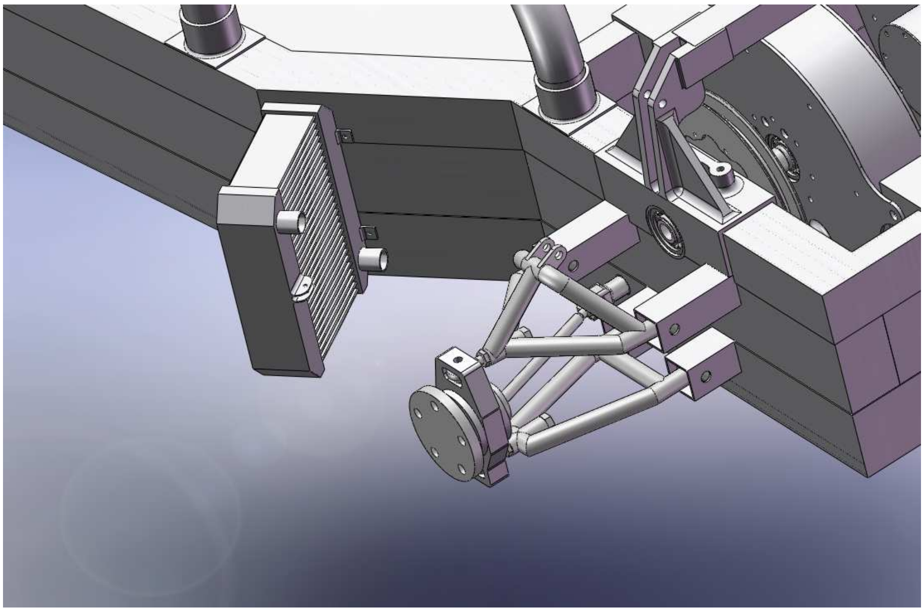

Figure 11.35: K1 suspension

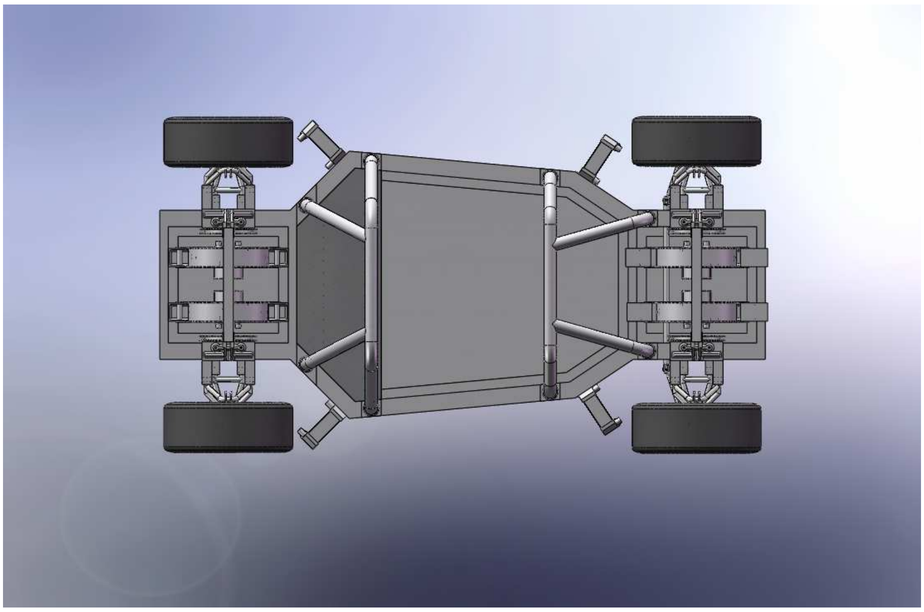

Figure 11.36: K1 radiator layout

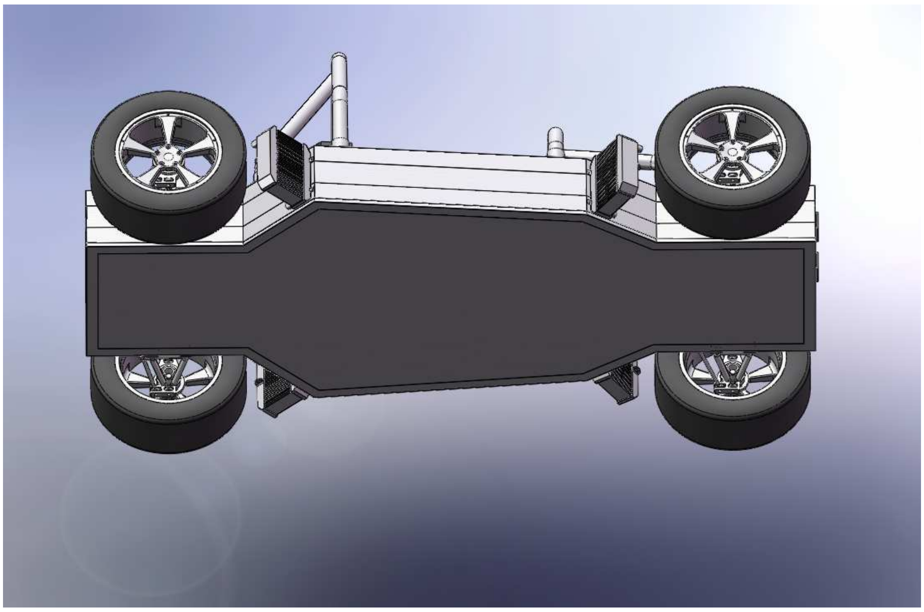

Figure 11.37: K1 flat bottom chassis

of this cannot be verified unless tested.

The steering components are a simple arrangement but placed very percisely. It runs parallel with the lower suspension member shown in figure 11.39 so that during any bump or rebound in the suspension the steering angle would not change. For instance if the wheel mount had been higher during a bump situation the wheel would toe out then toe in after passing the neutral point in rebound. This results in loss of traction and unpredictable steering during suspension movement. The design keeps things as predictable as possible.

11.12 Final Words

The K1 had been tested for torsion several times throughout the design process. The final design test was setup with the rear using cylinderic supports on all rear suspension mounts and one of the fronts. The forces on the suspension points on the free side were resolved mathematically and applied as direct forces resolving a 10000 N·M torque. The vertical deflection was measured at the suspension point and using trigonometry found the angle of deflection. Given the force and deflection torsional stiffness is calculated. In the case of K1 the target was that of the Lotus Elise 10 kN·M/degree. The calculation of the K1 gave a value of 15268 N·M/degree.

While it met the target value futher designs have proven to be significantly stiffer by raising the area around the chassis. It was K1 that founded the under-

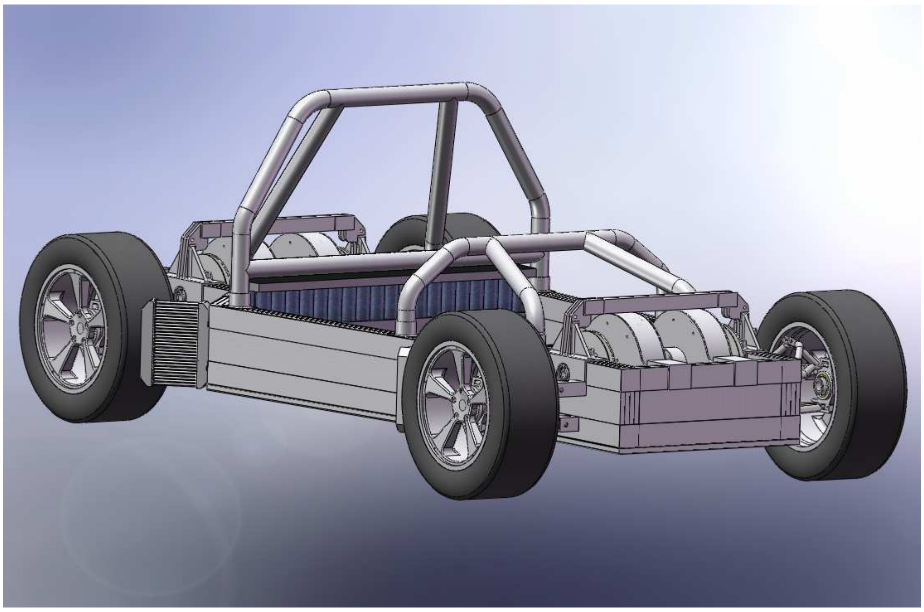

Figure 11.38: K1 roll bars

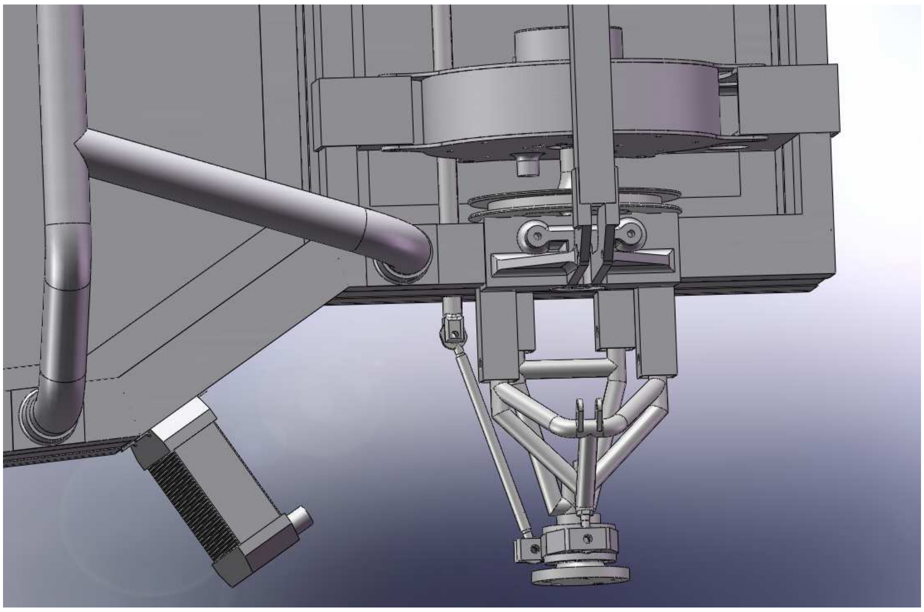

Figure 11.39: K1 parallel suspension arrangement

standing to use simple tubular member theory to improve chassis design. The construction of K1 is complicated due to the many layers of the longerons which turns out were unnecessary. One layer with thicker panels would provide similar stiffness and reduce the complexity of the chassis construction significantly.

Chapter 12

Lemans Style Angular Monocoque

12.1 Angular Monocoque Introduction: FM2

FM2 was the project which sparked the writing of this book. It is intended to be designed, simulated, built, lab tested, completed, and then road tested. The original idea was to have a small cockpit area that was made out of sheet aluminum and be similar in size and shape to the Caparo T1 Carbon fiber Chassis. Offset seating was abandoned and then revisited but decided to keep the symetric chassis that was a little larger.

The idea was that the rear section would be tubular so that drive trains could easily be unbolted and removed from the monocoque cockpit. This would require a very significantly ridgid structure that housed the driver and passenger to compensate for any weakness in the rear section. The idea was that it could be used as a test platform such that it could facilitate mid rear drive train testing and easy work on the engine.

12.2 Project Description

As in an earlier section FM2 was described in words.

> A roadgoing lemans style chassis midrear engined RWD 2 Seater, small luggaged, low aerodynamic drag, medium down forced car, similar in size to the lotus elise, low center of gravity, modifable rear bolt on end, small diameter tires and wheels for reduced weight and mass moment, minimalist interior, aluminum chassis monocoque, double A-arm suspension with anti-roll bars in both the front and rear, outboard suspension components such as shocks (if permissable), fiberglass body work, single vehicle road compliant, scca autoX compliant (unless to difficult)

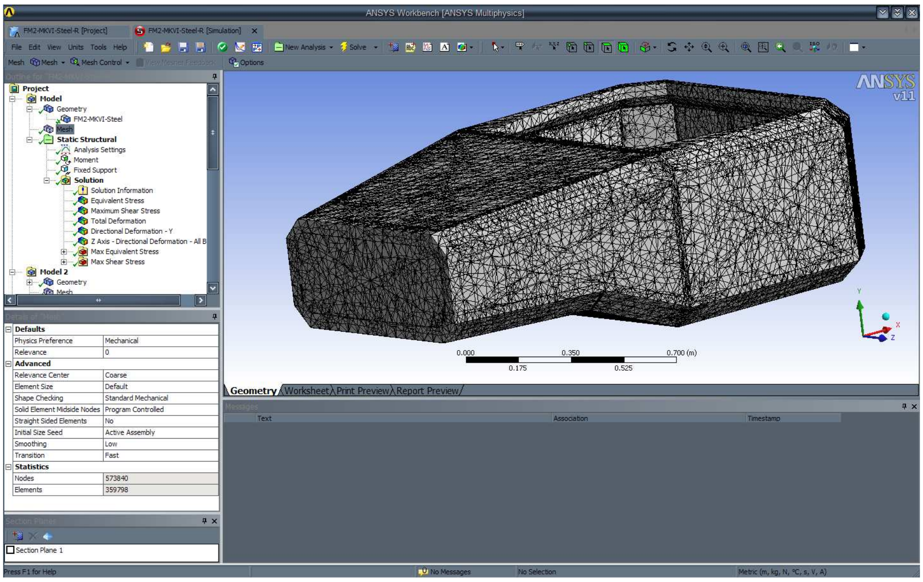

Figure 12.1: FM2-Ansys

A lot of information can be gathered from this. We know the approximate size and component layout. We also know that it's more fuction inside than art so it will likely be lacking in regards to interior comforts. The bodywork will be designed about the chassis so the chassis will need to incorporate the basic cars shape.

12.3 Testing Setup

As seen with the K1 project the FM2 utilizes the same method for testing torsional stiffness by applying a 10000 N·m/degree torque to one end while applying a fixed support at the other end.

The figure 12.1 shows a quick overview of the Ansys Workbench interface. The density of the mesh is misleading due to importing directly from Solidworks as a solid model. In regular Ansys the model could easily be developed as flat plates however that takes a relatively simple process and makes the setup more complicated. The idea is to streamline the test proceedure since computing power is vast and very low cost now. Like operating systems ease of setup is taking precidence over speed efficiency.

12.4 Mark I

The original Mark One chassis was more of a developmental idea. As shown in figure 12.2 it is a simple box like structure laid out for dimensioning. The

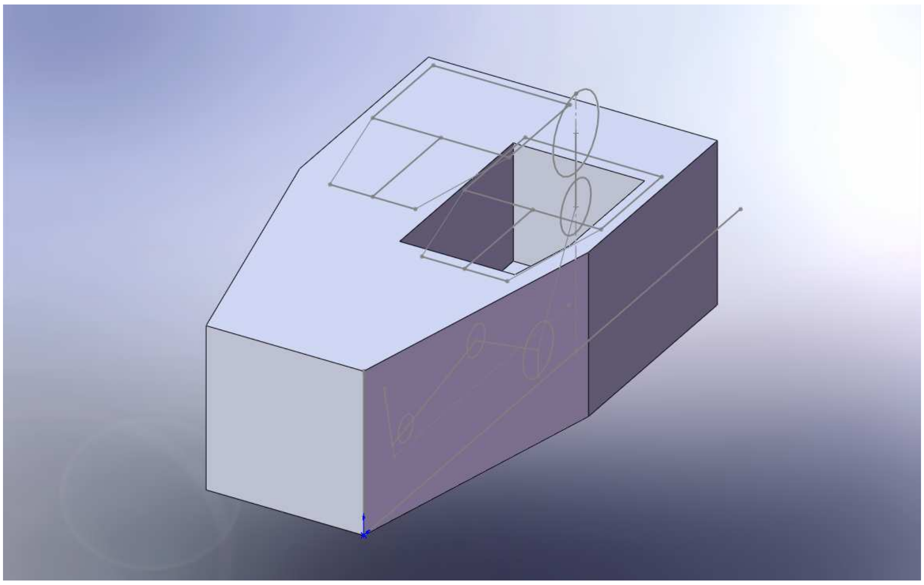

Figure 12.2: FM2-MKI

idea was to create as continous a structure as possible approximately 25mm to 40mm thick for an aluminum honeycomb structure.

It was quickly recognized that the taper was to much and the shape did not lend itself to the concept of the chassis. This idea was refined and edited into the Mark II which shows some similarities, but overall has large differences.

12.5 Mark II

The chassis builds on the Mark one's idea to taper the chassis and hollow out an interior section. The overall exterior is shown in figure 12.3 while the interior section is shown in figure 12.4. The chassis had a flat bottom and perpendicular walls around the perimeter. For torsional stiffness, the force being translated on the side walls is vertical and causes increased stresses around the edges. This is why the top leg canopy area is tapered to reduce this stress riser.

This theory is confirmed in figure 12.5 by utilizing the probe feature on the maximum shear stress visualization. In the middle the shear force is continous at approximately 2.6e6 pa. As the shear stress is tracked upwards it can bee seen that shear tapers off but at the change in surface angle it rises quickly again. The same occurs near the bottom of the chassis but to a much greater extent. The walls of this chassis are not stabalized with a honeycomb material. This causes increased stress in a very small area that translates this torsional shear to bending resisted by the floor.

Testing was conducted with and without the center channel in the chassis.

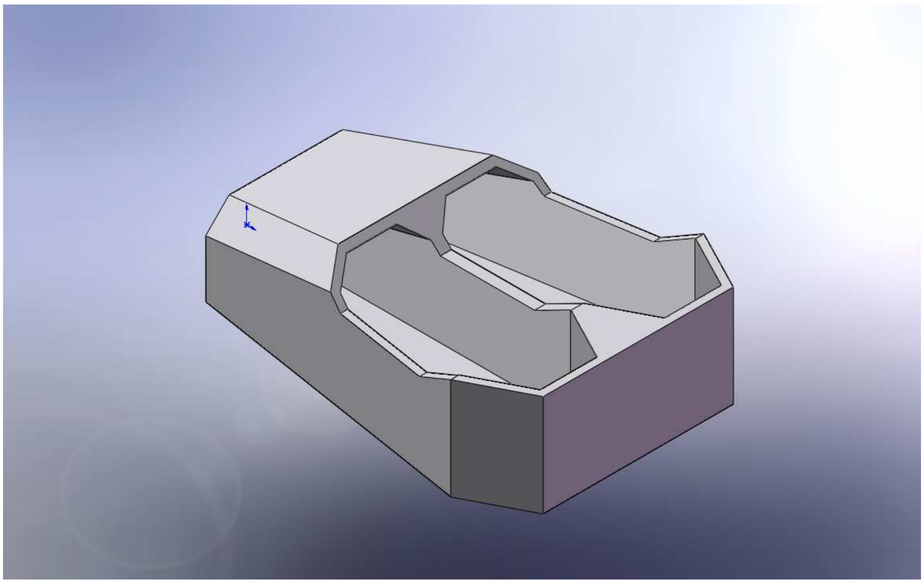

Figure 12.3: FM2-MKII

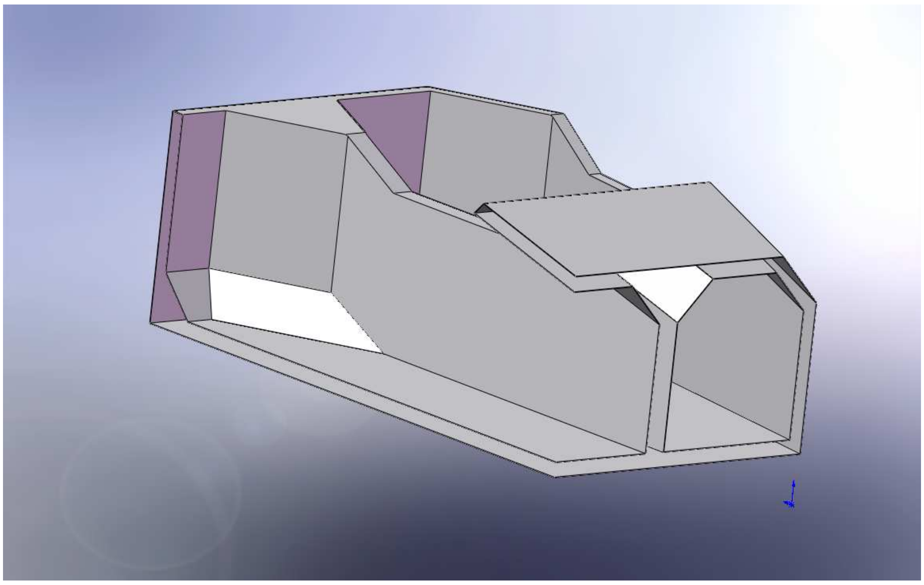

Figure 12.4: FM2-MKII interior cross section

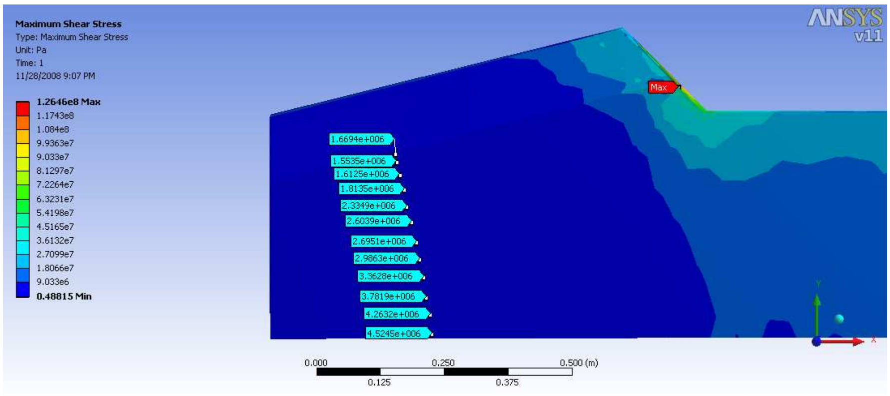

Figure 12.5: FM2-MKII maximum shear stress plot

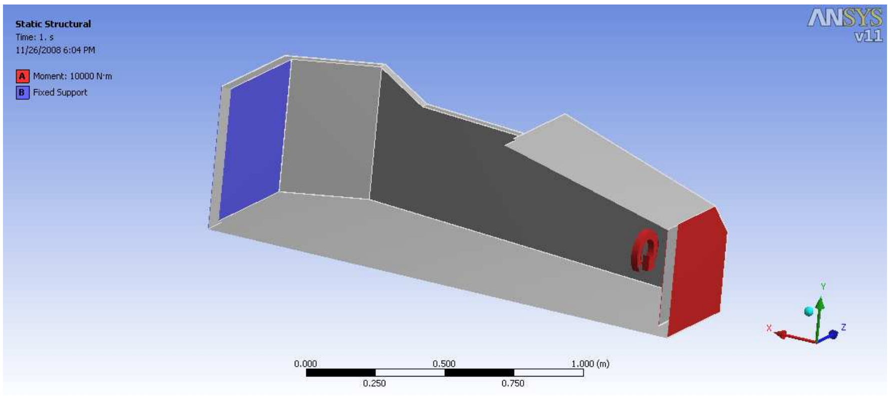

Figure 12.6: FM2-MKII Ansys force setup

As shown by the section in figure 12.6 there is no center channel but torque is applied to both the interior and exterior walls along with a fixed support. The deformation equivalence is given at 10969.7 N·M/kg at a weight of 47.71 kg. Adding the center channel raises this to 15420.7 at a total weight of 52.716kg. This gives the chassis without the divider a stiffness to weight ratio of 229.9 NM/kg while the one with a tunnel has a ratio of 292.51 N·M/kg. Deformation with the divider is still very similar in apperance in figure 12.8 compared to without figure 12.7.

This would appear to fall against the original theory presented in chapter 1 upon first inspection but it is illustrating a very important aspect of testing. Reliance on FEA simulations require quality input to get quality output. In examining figure 12.9 it can be seen that the vertical walls are being pushed latterally and holding against the rear structure. By adding another beam down

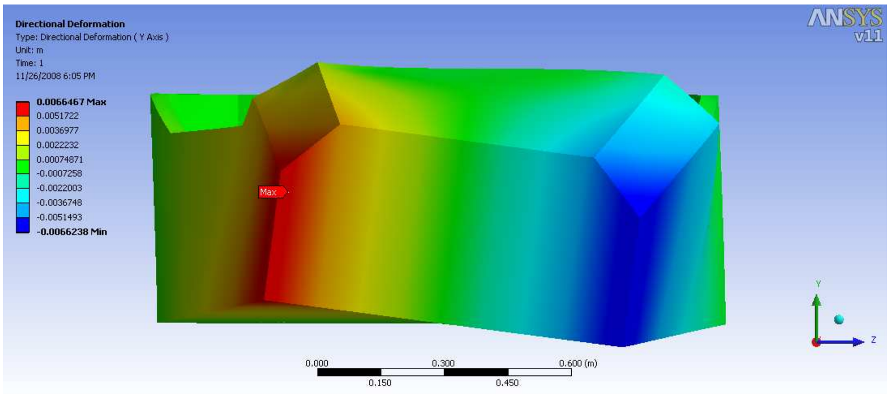

Figure 12.7: FM2-MKII torsion test without divider

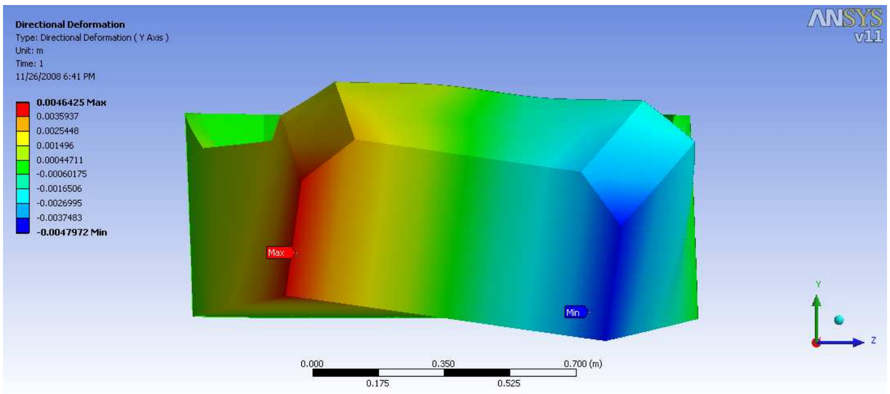

Figure 12.8: FM2-MKII torsion test with divider

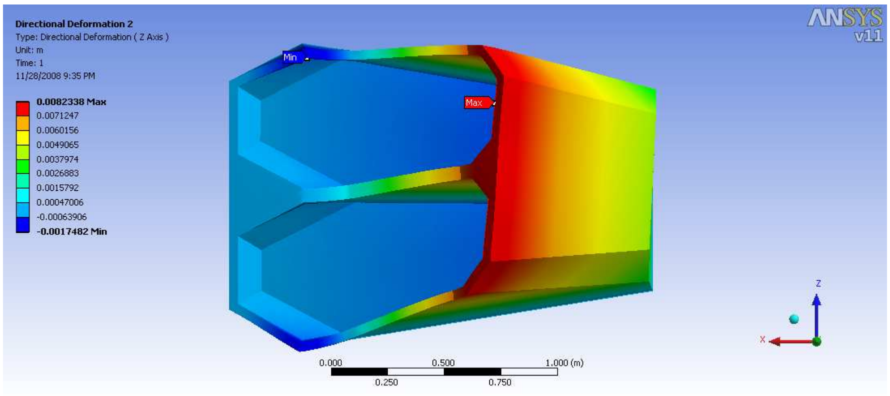

Figure 12.9: FM2-MKII Z axis deformation

the middle this latteral movement is constrained. It is interesting to note that this is a secondary mode of allowing twisting that is the result of having a very weak section for the cockpit opening.

Very weak is a subjective term by comparision to the original chassis. The original simulations lead to disapointment but had been conducted with hollow centers with the intention that later it would be simulated with the honeycomb core if it was on the right track. This would eventually lead to the Mark IV through Mark VI chassis because of its torsional weakness.

Upon revisiting and creating a solid internal structure and providing bonded contact regions in Ansys, an interesting result materialized. Keep in mind that this occured after Mark VI was developed and finalized. The Mark II chassis torsional rigidity became significantly higher than expected. With the divider the new stiffness was calculated at 92315.7 N·M/degree at 55.135kg and without the divider stiffness was 51789.8 N·M/degree at 49.477kg. It is interesting to note that the coupling of the interior to the exterior walls would give such a large increase in torsional stiffness.

12.6 Mark III

When Mark II seemed to be of lower strenght than expectedw, the Mark III was developed to raise the sides of the chassis. It is shown in figure 12.10 but design of the chassis was stopped because it was not progressing in the correct direction. The sills were raised in an attempt to avoid some of the deformations that were visible in Mark II but wasn't appearing that it would make the significant gains that was desired.

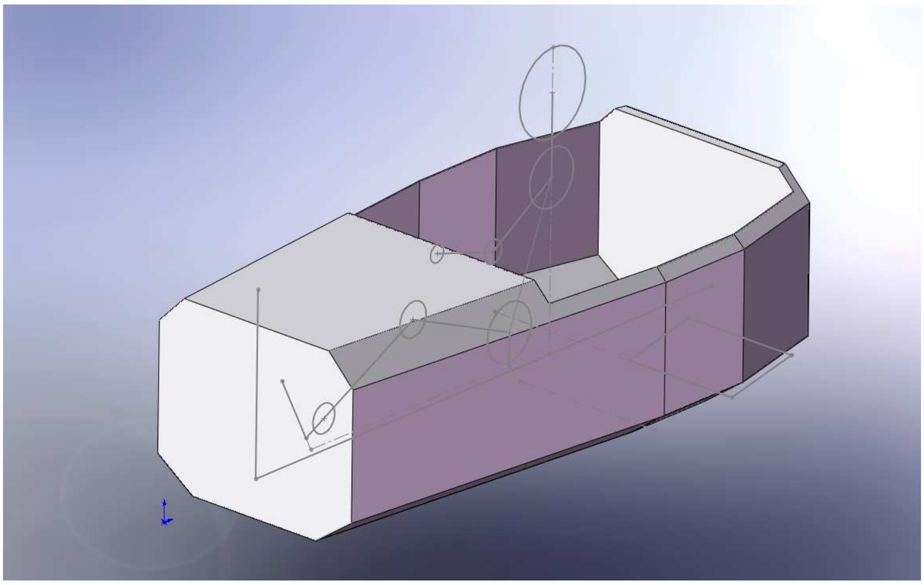

Figure 12.10: FM2-MKIII

12.7 Mark IV

The Mark IV put the FM2 project back on track by attempting to create a smaller and rounder chassis. Its shape was fashioned after the carbon fiber Formula one monocoque chassis. The original design is shown in figure 12.11 which developed the orignal shape.

The internal gap structure is shown in figure 12.12 which is 40mm with 1.65mm aluminum outer and inner structure. The idea was to create a small tubular structure with a small opening for entry and exit. 40mm thick aluminum honeycomb material was planned to fill this gap.

10000 N·M moment was applied to both of the front panels and a fixed support was applied to both the rear panels. The deformation is shown in figure 12.13 which highlights that only the edges near the front of the cockpit opening deforms irregularly.

The testing revealed something rather interesting when comparing steel to aluminum. 1.65mm thick aluminum was calculated at 42810 N·M/degree at 44.706kg while 1.65mm Steel calculated at 119212 N·M/deg at 126.69kg. This seems excessive for weight for the steel but if the stiffness to weight ratio is calculated the aluminum is 957.6 N·M/deg/Kg while the steel is 941.0 N·M/deg/Kg. The difference between the steel and the aluminum is minimal. Considering the tests were identical, with the exception of changing the material's youngs modulus and density, it shows an interesting artifact that aluminum in this chassis design in not significantly stronger than steel on a kg per kg basis.

Considering the idea for the aluminum structure was to have edges overlap

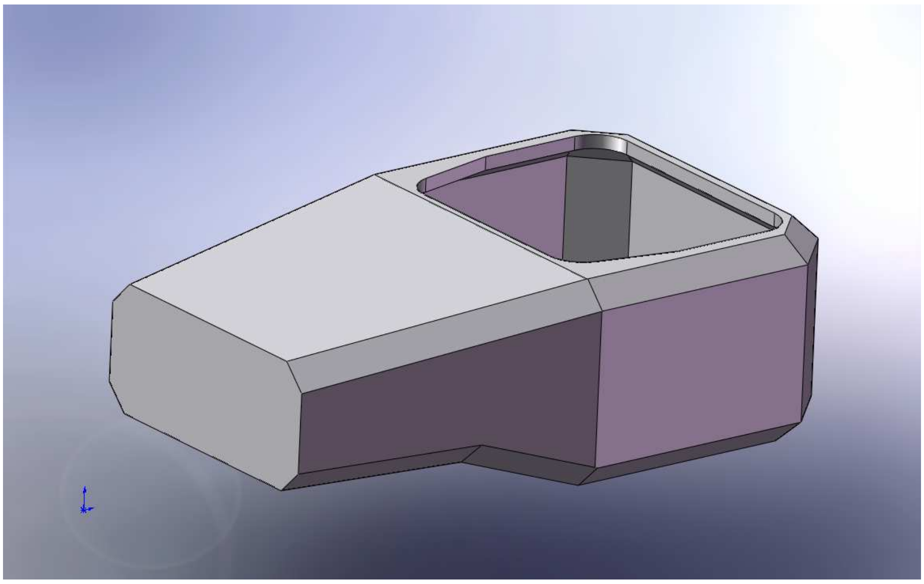

Figure 12.11: FM2-MKIV

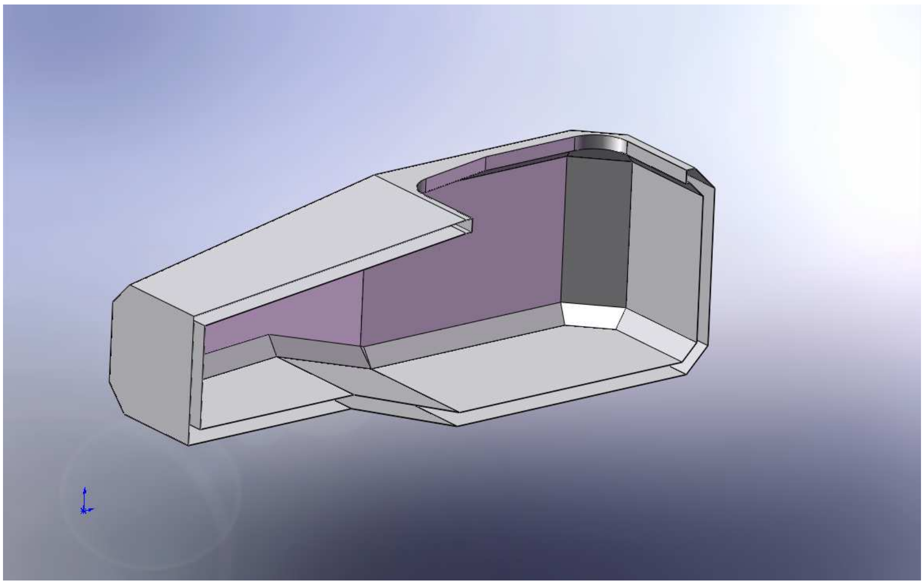

Figure 12.12: FM2-MKIV internatl gap

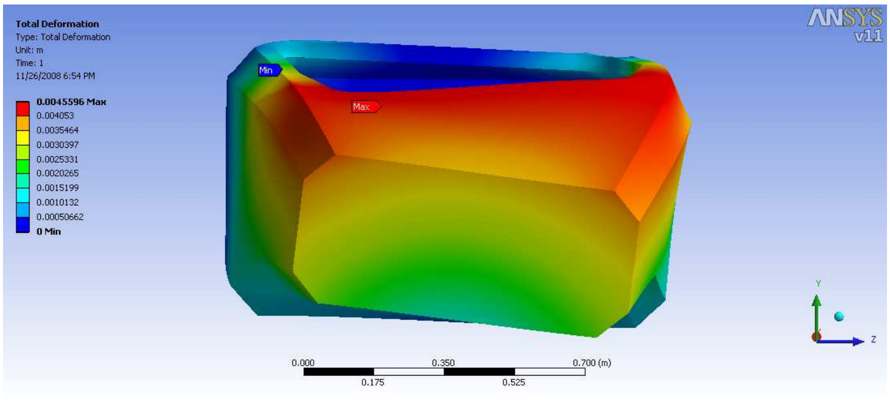

Figure 12.13: FM2-MKIV aluminum torsion test

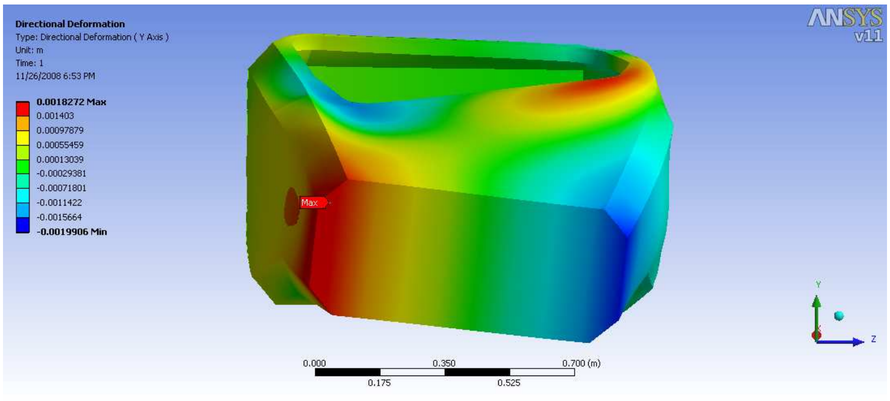

Figure 12.14: FM2-MKIV steel torsion test

and rivets which would create stress risers and add weight, steel now became a viable option. Aluminum for a monocoque deforms more than steel for given force. Structural failure is not part of this criteria but for performance through stiffness, steel appears to be very good optoin.

12.8 Mark V

Mark V was only a slight modifications to the shape, dimensions and openings. The rounded edges were removed from the opening to make construction simpler. The chassis was widened as well. The original Ansys torsional tests were run again and the results for both 1mm aluminum and 1mm steel are shown in figure 12.15 and figure 12.16 respectively.

The 1mm steel gave a result of 79177 N·M/degree at 80.775kg while the

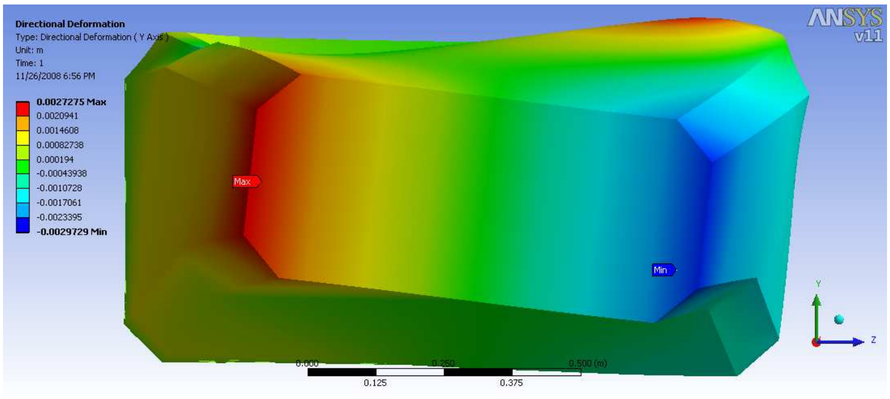

Figure 12.15: FM2-MKV aluminum torsion test

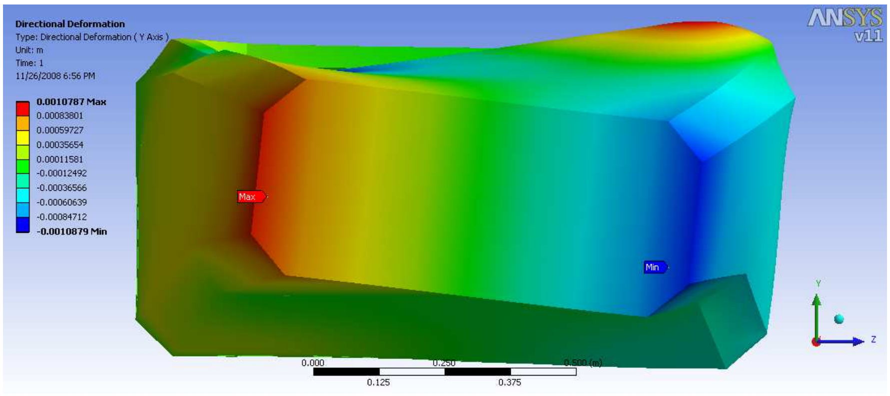

Figure 12.16: FM2-MKV steel torsion test

1mm aluminum yeilded 29659 N·M/degree at 28.503kg. Again comparing the stiffness per kg ratio, the steel yeilds a value of 980.2 N·M/deg/kg while the aluminum yeilds 1040.5 N·M/deg/kg. Again the difference is minimal once the stiffness for weight is compared.

12.9 Mark VI - Final

The first step in determining if the Mark V was viable was to determine the thickness of the metal skin and the structure that was to be placed inside. The target was raised to a high level of being at least double that of the K1. The same Ansys simulations were carried out for the Mark V with varying thickness's of metal and material. 0.5mm steel gave 37472.4 N·M/degree at 40.347kg, 1mm AL gave 28995.88 N·M/degree 28.465kg, 2mm AL 45640.6 N·M/degree 56.892kg. 1mm thick aluminum, or the closest gauge equivalent was chosen.

However, there was a problem with the interior material. All the price quotes for the honeycomb aluminum material was to expensives. In the order of several thousand dollar to do the entire car plus special epoxies. Many large sheets of aluminum was needed as well since access to good mig or tig welder for aluminum was limited so the chassis would be made of larger continous pieces of material bent and folded and riveted together. The aluminum sheets put the chassis in the several thousand dollar range for full construction at the time. The honeycomb material was abandoned and alternatives such as balsa and foam were looked at.

The low cost of steel eventually precluded switching the design material and building up a simple internal structure as shown in figure 12.17 to support and translate forces. A new simulation was setup for this and the torisional stiffness was calculated to be 82227.5 N·M/deg at 50.652 kg with 0.5mm steel. This also meant that a low cost mig welder could be used in construction along with having some of the individual panels cut out seperately to reduce wasted sheet steel.

Torsional testing carried out shows that stresses increase around the attachement points. This is likely to be expected as the shear forces are greatest here, trying to hold the outter to the inner skin which can be seen in figure 12.18.

12.10 Mark VI - Convergence

Convergence is a technique used to determine if a simulation is accurate. It requires refining the mesh smaller and smaller until the change in resultant value is small. Unfortunately this requires increasingly more time to solve and a limiting factor was struck upon. 32 bit Ansys in the Windows enviroment cannot handle much more than 600000 nodes. Eventually pushing it much beyond this will cause the program to not be able to find a solution due to memory limitations. The normal coarse element setting in Ansys with a relevance center at 0 was the starting point and had already created 574 thousand nodes. There

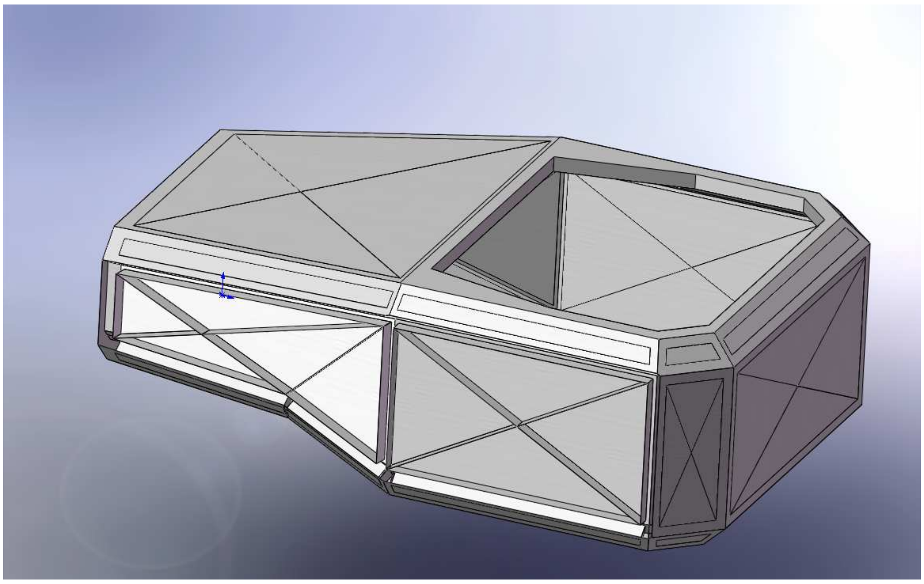

Figure 12.17: FM2-MKVI Steel interior support

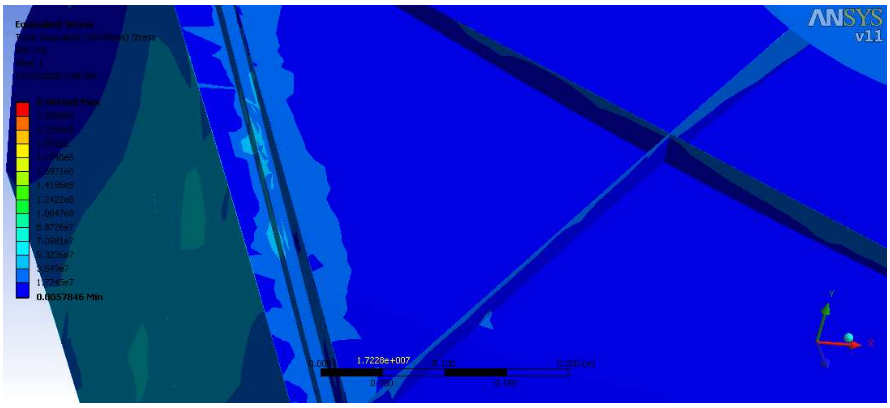

Figure 12.18: FM2-MKVI cross section of stresses during torsion test

wasn't much left in the system but convergence was attemped.

Relecance Center	Relevance	Nodes	Stiffness (N·m/deg)
Coarse	0	573840	82174.9
Medium	-80	585431	81157.9
Coarse	90	600693	80785.8

It is hard to determine from these results if the chassis is or is not convergent. Small variances in the meshing can cause differences. The first to the second losses approximately 1000, while to the next one is significantly less. A few more iterations could bring convergence and could be near the 80 kN·M/degree.

Afterword

This is a first revision. The hope is that this will eventually be expanded to include more information and detailed sections. All suggested static safety tests were carried out and converged for the FM2 chassis but there was not enough time to include these results. Please direct all comments to kwakeham@mun.ca or marked up versions. All criticsm is openly accepted and anticipated.