Design and Construction of a Space-frame Chassis

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Abstract

The purpose of this project is to design and build a space-frame chassis for a race car to compete in the FSAE-A competition as part of the UWA REV team. The FSAE competition is a competition for university students to design, build and race their own open wheeled race cars, there are also a number of static design events in the competition. The 2011 REV FSAE car will be powered by four electric motors with one mounted to each wheel's upright. This is a new configuration for a FSAE car and as such requires an entirely new chassis design that both supports the loads placed on it but also weighs as little as possible. The chassis design implements structural battery boxes which have the dual purpose of protecting the driver from the batteries and adding strength to the frame, this has not previously been used in any other FSAE car. Using these stressed battery boxes gives the chassis excellent torsional stiffness, yet the entire frame still weighs just over 40kg.

Acknowledgements

I would like to thank Adam Wittek for his advice throughout this project, the REV team and Swan Energy for funding the team for which the chassis has been designed, Ian Hooper for assisting with and providing the tools and facilities used for construction and Ed Farrar for aiding in and providing the press used for weld testing. Finally I would like to thank my family and partner for their support throughout the duration of my studies.

Contents

Introduction

The purpose of this project is to design and construct a chassis for an electric powered Formula SAE (FSAE) car to compete in the December 2011 FSAE-A competition. The competition is for students to design, build and race small open-wheeled race cars against the clock in a number of events. The competition also includes some static design events, where the cost and design of the car is judged by a panel. A unique chassis design is required as the car will be powered by four electric hub motors, as opposed to the more conventional internal combustion engine mounted within the frame. This is the first time that electric hub motors will be used in the Australian F-SAE competition and the first time four wheel-hub motors have been used in any FSAE competition around the world.

In 2010 the REV team converted a previously used petrol FSAE chassis to electric power in a similar configuration to the conventional combustion engine configuration. The chassis was made by UWA Motorsports and competed in the 2002 F-SAE competition. It was never intended for this petrol to electric converted car to compete in any FSAE event as it was only done as a prototyping exercise in an effort to investigate the potential of an electric F-SAE car. The chassis no longer meets the requirements for the FSAE competition as the rules for the competition have changed since 2002.

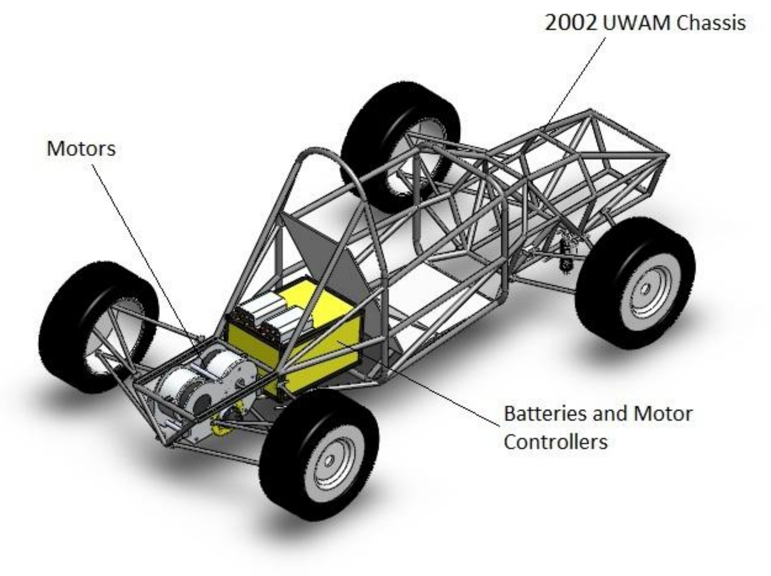

Figure 1 2001 UWAM Chassis converted to electric power using a conventional inboard engine layout

There is much confusion over the meaning of the word chassis as discussed by Aird in the book "The Race Car Chassis" (Aird,1997). In the early days of the automobile where coachbuilders were used, the term "chassis" was often used to describe the frame, engine and suspension as one complete unit. Essentially it described everything in a car other than the bodywork and cabin. In some other contexts "chassis" defines only the frame of the car with the drive-train and suspension being considered entirely separate items. This latter interpretation of the word is what is used throughout this project, where the terms "chassis" and "frame" mean the same thing are interchangeable.

When defined as above, a chassis is the component in a car that everything else attaches to. The most basic, common chassis design is referred to as the "Ladder Frame" due to its resemblance to a conventional lean-to ladder (Adams, 1992). A "Ladder Frame" consists of two long members that run the length of the automobile and are joined by a set of smaller members perpendicular to the two long members. The other components that make up the vehicle are then mounted to this chassis. In the case of the Ladder Frame; the body and engine are usually mounted to the top of the chassis with the suspension being mounted below. This type of chassis dates back to horse-drawn carriages, originally made of wood, but generally being made of steel in automobiles since the 1900's (Aird 1998). While being simple and easy to manufacture this type of chassis generally has a poor torsional stiffness which makes it undesirable for a race car.

In more recent times the chassis has evolved and in some cars it can be hard to distinguish between what makes up the body of a vehicle and what makes up the chassis. A monocoque chassis uses the body as the load carrying component and means that no separate chassis structure is needed. Entire panels carry the load rather than specific members, often these panels are the outermost parts of the body which means that a higher polar moment of Inertia (about the axis running from the front to the rear of the car) is achievable. A high polar moment of inertia about the longitudinal axis is a desirable property for a chassis as it is directly related to torsional stiffness (Aird, 1997). The drawback of a monocoque chassis is that they can be difficult to manufacture and are comparatively expensive in small production numbers, which is why a monocoque will not be used in this project.

A space-frame chassis lies somewhere between the ladder chassis and the monocoque, it is constructed from an arrangement of small, simple members which make up a larger frame. A space-frame is analogous to a truss style bridge which is made up of small (generally straight) members in a triangular pattern which are always in pure compression or tension. By having members in pure compression or tension (ie. they do not experience bending forces) they do not have to be oversized to support bending loads (Budynas,2011).

Light weight is a primary goal for all components in a race car as a lower weight requires less force to accelerate by the same amount. Newton's 2^{nd} law says;

$$Force = Mass \times Acceleration$$

So given the same force, a lighter car will accelerate quicker. This applies in all transient conditions including braking and cornering. If a car accelerates quicker, then it reaches a higher speed quicker and therefore it is faster, which is the purpose of a race car. So wherever possible everything in a race car should be as light as possible.

Stiffness is also a desirable property for a race car chassis to have. The suspension for the 2011 REV FSAE car has been designed by another student under the assumption that the chassis acts as a rigid body (Kiszko,2011) so if the chassis deforms too much under load then the suspension is unlikely to work as desired.

The chassis is being built for the UWA REV team who have previously converted two production cars to electric power, a Lotus Elise and a Hyundai Getz. The FSAE car being build in the REV team is being funded by a solar panel company Swan Energy. The sponsor is providing $25 000 to the team to construct the car and although the team have secured the money in advance of competing in the competition, the performance of the car at the competition will affect the sponsor's willingness to sign up for future sponsorship deals with the UWA REV team.

Literature Review

Before commencing any design work it is useful to see what is already being done by others in the same field. As mentioned in the introduction the 2011 REV FSAE car will be powered by a unique drive-train and as such requires a unique chassis, however the basic principles of chassis design still apply.

For a background into chassis design a relevant text was discovered and reviewed. The book published by Penguin Books is entitled “The Race Car Chassis” and is written by Forbes Aird. The book discusses different types of chassis’ and the history of chassis evolution. It focuses primarily on space-frames and stressed skin type chassis’ which is highly relevant to this project due to the low cost, readily available materials used and relatively simple manufacturing processes. “The Race Car Chassis” is somewhat of a review of different chassis designs used by different race cars, discussing chassis’ from all manner of classes such as drag, circle track and even passenger cars. The book also covers the different materials commonly used to construct chassis’ and lists each material’s advantages and disadvantages. Aird includes information regarding suspension and other loads on the chassis and how these should be supported. Significantly the book covers the design process for space-frame chassis’ including material selection, tube sizing and member arrangement. “The Race Car Chassis” was originally written in 1997 which means it is not up to date with the latest and most advanced technology however space-frames have not changed significantly in recent years so the book is still highly relevant. The main advancements that have been made in chassis technology since 1997 are in composite monocoque frames which are not relevant to this project due to their relatively high cost and the REV team’s limited budget. Overall this is a very useful book for the project covering much relevant information without any significant bias.

Another text that was analysed for this project was “Chassis Engineering” written by Herb Adams and published by Penguin Books. The book was first published in 1992 making it slightly older than “The Race Car Chassis” described above. Contrary to Aird and this project, Adams considers the chassis to include suspension and bodywork components so the book contains a large amount of information about suspension setup and tuning as well as tyre characteristics which is not relevant for this project as the suspension for the car has already been designed by another student. Much of the frame design information covered in this book is the same as found in “The Race Car Chassis” which serves to validate and confirm the information already found rather than actually providing any new information. This does not make the book useless though as it is useful to have a second source back up the information already gathered. “Chassis Engineering” does include some useful pictures of various chassis design models being tested in torsion which serve to give a good idea of what designs work well and which ones don’t. This information is not quantitative and cannont be directly applied in the design process, but it is likely to be useful in that the design will have a better starting point.

The University of Western Australia has a history of competing at the FSAE event successfully. UWA Motorsport (UWAM) has been competing at the event since 2001, winning the Australian competition in 2005 and 2007 and even winning the international competition in 2008. UWAM has been using carbon fibre monocoque chassis’ since 2003, as discussed earlier the 2011 UWA REV team would not be using a carbon monocoque due to the cost associated.

Design Process

Design Requirements

The design of the chassis must work around a number of parameters and constraints in order for it to perform well and for it to be eligible to compete in the competition. These requirements can be broken into several categories which will be discussed below. If any of these requirements are not met, the consequences range from sub-optimal performance to not being eligible to compete in the competition or even chassis failure. So it is clear that all requirements must be carefully considered and even re-visited when designing and building the chassis.

Rules

The first thing that must be considered when designing the chassis is the 2011 FSAE-A rules, there is no point in designing a chassis if it will not be allowed to compete in the competition for which it is designed. The FSAE rules require a front and rear roll hoop, a side impact structure, a front bulkhead and supports for the aforementioned components be integrated into the chassis. By representing graphically these requirements one may create a "minimum chassis' Figure 2 which shows the simplest possible configuration of members that include the required components mentioned above. Figure 2 is a side view diagram of what this "minimum chassis" looks like, it does not consider driver ergonomics, cockpit entry or suspension points etc, and is merely a pictorial representation of some of the required members.

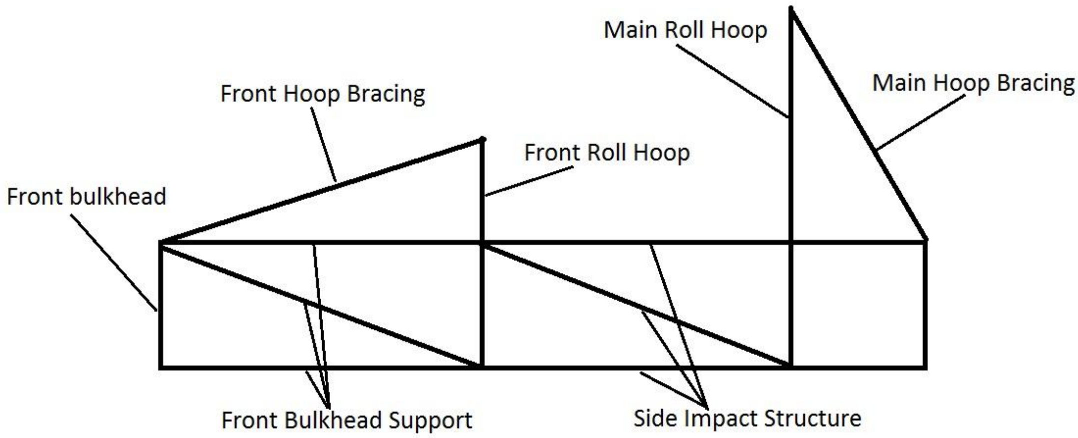

Figure 2. Pictorial representation of the members required by the FSAE rules.

The FSAE rules define a minimum size for all the chassis members shown in Figure 2 and for some other members not shown. To avoid adding un-necessary weight, the chassis design should make best use of the required members so that as few possible additional members are needed. This is where much of the design work needs to be done for the project because as the rules limit many of the members, little design work can be done in optimizing the size of the chassis members.

ITEM or APPLICATION	OUTSIDE *DIMENSION* X WALL THICKNESS
Main & Front Hoops, Shoulder Harness Mounting Bar	Round 1.0 inch (25.4 mm) x 0.095 inch (2.4 mm) or Round 25.0 mm x 2.50 mm metric
Side Impact Structure, Front Bulkhead, Roll Hoop Bracing, Driver's Restraint Harness Attachment (except as noted above)	Round 1.0 inch (25.4 mm) x 0.065 inch (1.65 mm) or Round 25.0 mm x 1.75 mm metric or Round 25.4 mm x 1.60 mm metric or Square 1.00 inch x 1.00 inch x 0.049 inch or Square 25.0 mm x 25.0 mm x 1.25 mm metric or Square 26.0 mm x 26.0 mm x 1.2 mm metric
Front Bulkhead Support, Main Hoop Bracing Supports	Round 1.0 inch (25.4 mm) x 0.049 inch (1.25 mm) or Round 25.0 mm x 1.5 mm metric or Round 26.0 mm x 1.2 mm metric

Figure 3 2011 Formula SAE Rules for Member size. Adapted from 2011 Formula Student rules (SAE, 2010)

The FSAE rules also require a firewall barrier to isolate the batteries from the driver, it must cover the vertical and horizontal portions of the battery box that face the driver. 2.6mm aluminium sheet is suggested for this firewall but 1mm steel has been approved as an alternative by the FSAE-A rules committee. The chassis must also provide sufficient space for cockpit entry, where the driver enters the cockpit. FSAE rules require a template shown in Figure 4 be able to pass vertically through the cockpit opening until it reaches the height of the top bar in the side impact structure.

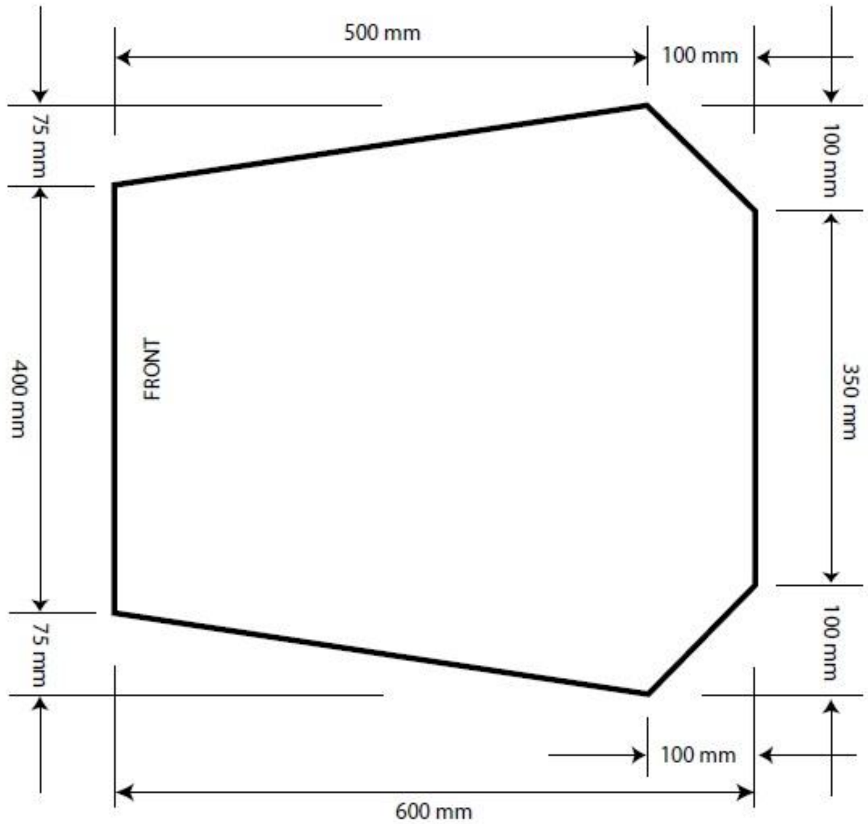

Figure 4 Cockpit entry template

A sufficiently large foot-well area must also be present in the chassis for the driver's legs and feet. The foot-well is the area where the accelerator and brake pedals are located and is where the driver's legs lie when driving. The foot-well area lies between the front suspension pivots so the design will have to work around this area carefully so that the suspension loads are adequately supported, to avoid damaging the chassis and potentially injuring the driver. Figure 5 shows the template that must be able to pass horizontally through the foot-well according to the FSAE rules.

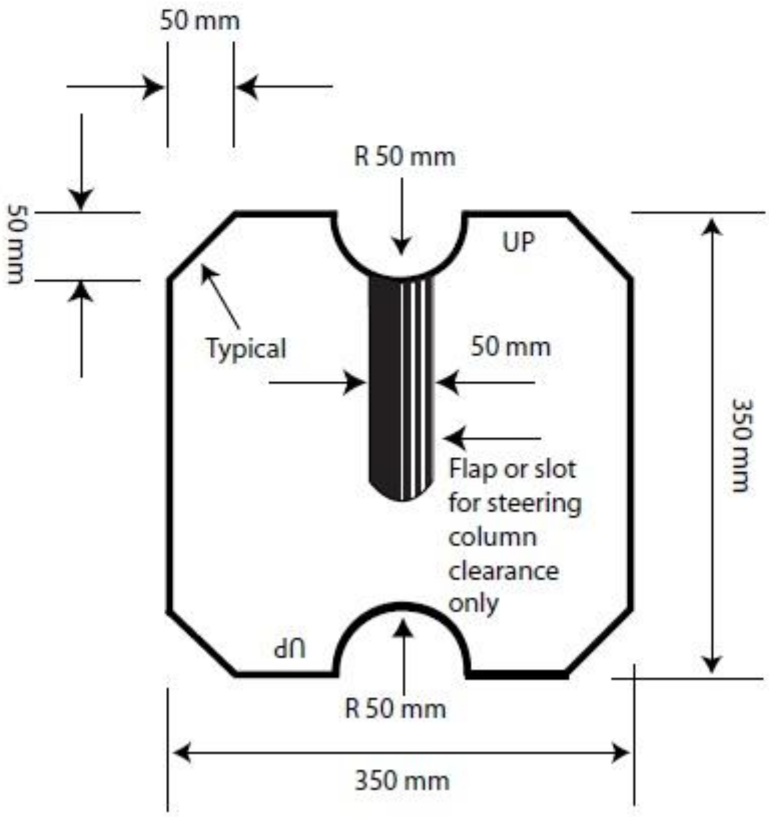

Figure 5 Foot-well clearance template

FSAE rules require that a 95th percentile male can drive the car with clearance to the two roll hoops. A template of a 95th percentile male as shown in Figure 6 must be able to fit in the seat with a minimum of 2 inches (50.8mm) clearance to a tangential line running from the top of the front roll hoop to the top of the main roll hoop. As none of the drivers in the REV team are as tall as a 95th percentile male then if the design fits the template it will be known to fit any drivers from the team. The roll hoops must therefore be sized to fit this 95th percentile male template.

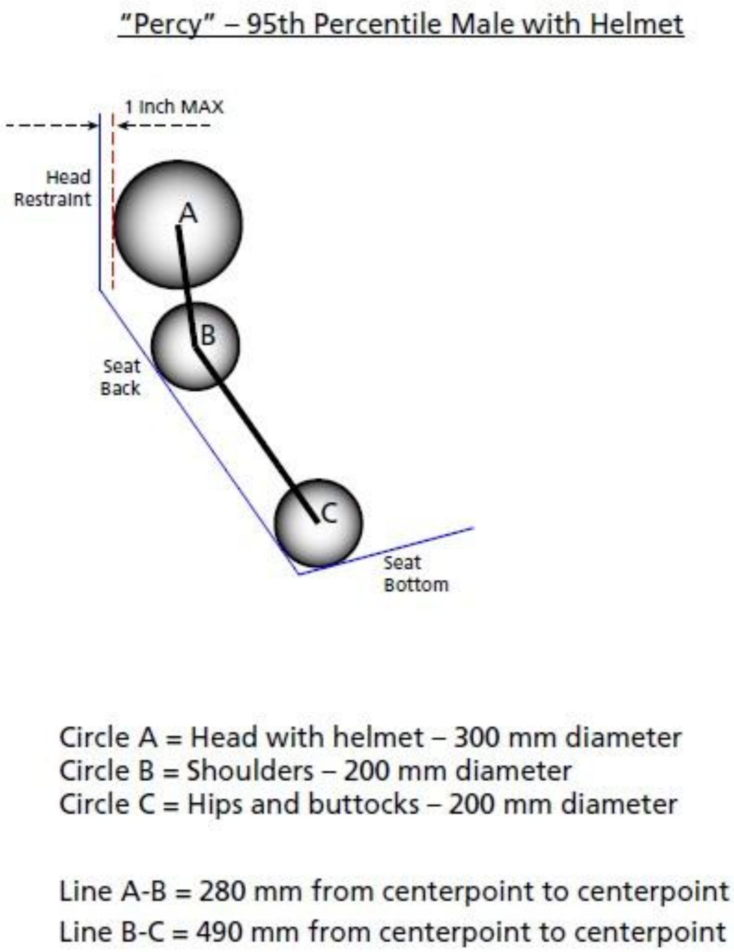

Figure 6 95th Percentile Male Template

Suspension Design and Forces

In addition to ensuring the design meets the FSAE competition rules there are pre-defined suspension points which the chassis must provide support and attachment for. The suspension system for the 2011 REV FSAE car has been designed in another student's thesis (Kiszko, 2011) and in order to maintain the designed suspension geometry, the suspension points should not be moved from their designed locations.

To produce a space-frame chassis with sufficient stiffness and to ensure the chassis is safe, the design must be constructed so that bending moments are not introduced into any of the chassis members. Figure 7 shows a basic layout of the ends of the chassis that are required to hold the suspension pivots in their correct locations.

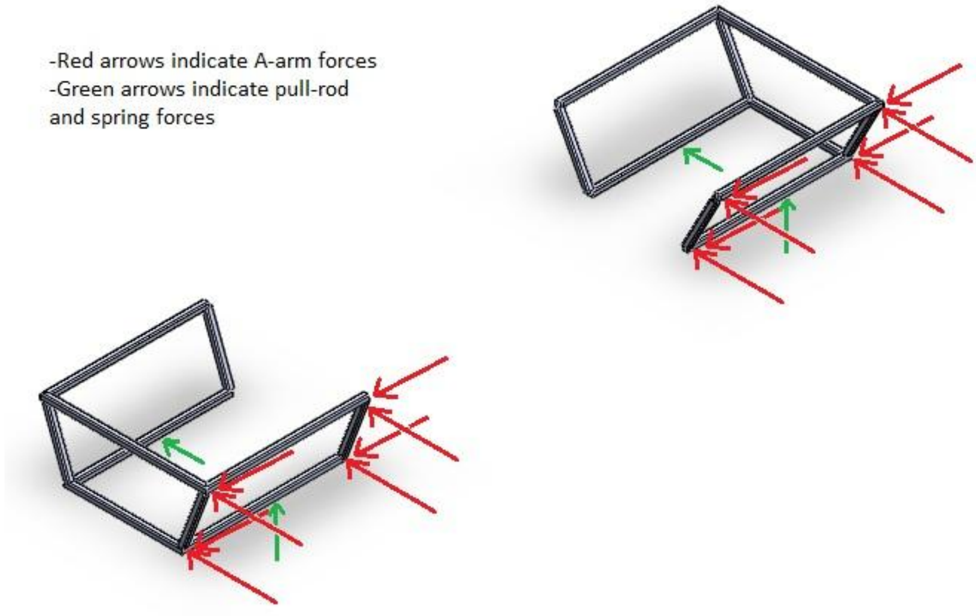

Figure 7 Basic ends of the chassis that hold the suspension arms in place.

(Forces are mirrored on the opposite side of the chassis)

The suspension design uses unequal length double A-arm suspension with inboard mounted springs connected to the wheels via pull-rods and bell-crank rockers. The A-arms are mounted to the chassis via spherical bearings which transfer loads into the chassis in a plane parallel to the ground (shown as the red arrows in Figure 7). Forces from the A-arms occur when the car is accelerating which includes; forward acceleration, braking and cornering. Ideally the A-arm forces should act as near as possible to a node in the chassis so the reaction forces consist of pure compressive and tensile forces in chassis members. Nodes (joints) in the chassis also have the least amount compliance in the chassis, which improves suspension performance as the wheels will be better located and deflect less under loads. The pull-rod and spring forces act in a plane parallel to the front bulkhead (the forces are shown by the green arrows in Figure 7). Forces from the suspension springs and rockers are present even when the car is stationary, resting on its wheels. However these forces increase under suspension movement which occurs as a wheel runs over a bump and/or when the chassis pitches, dives or rolls while driving. Additional diagonal members must be added to the basic frame shown in Figure 7 to prevent the spring and rocker forces (currently acting on the middle of the member) from creating bending moments in the horizontal transpose members.

Packaging

In conjunction with meeting all the rules and providing attachments for the suspension components, the chassis must also fit the driver and all the required components into the frame. The most significant of these components being:

- Seat and driver harnesses
- Batteries
- Electronic control components (motor controllers, BMS, Sensors etc.)
- Driver controls (steering wheel, pedals, switches etc)

The driver must be considered first as he/she will be bigger than any other component in the car and must fit comfortably. Driver ergonomics must be considered to ensure the driver is able to complete each driving event comfortably. Points are also awarded in the static phase of the competition for driver ergonomics so it is beneficial to pay close attention to this area while designing. As mentioned in the rules section, the 95th percentile male must be able to fit in the chassis with clearance to the front and rear roll hoops so

Fortunately most of the other required components can be made to fit into the small remaining spaces as their shape is quite flexible. The batteries will be made from 600 small cylindrical cells meaning their required volume is significant but their shape can be made to suit the chassis design. However a relatively simple shape is desirable in order to prevent un-necessary complexity in connecting the cells. A motor controller is required to control each of the 4 motors and should be mounted as close to each motor as practically possible. The motor controllers must be mounted as close to the motor that they are controlling as possible so the front motor controllers can be mounted to the back of the front bulkhead, in front of the driver's feet. The remaining rear motor controllers and other electronic control units are able to be located in the rear section of the chassis behind the driver, space which is otherwise unused as the 2011 REV FSAE car does not have an inboard mounted engine.

Material

It was decided that the frame would be constructed from steel due to its availability and relatively low cost. There are many different grades of steel available however many of the FSAE teams around the world from universities such as UWA (for the rear space-frame section), Curtin, RMIT, Missouri S&T use 4130 SAE grade steel (which contains

Chromium and Molybdenum alloying elements) due to its higher yield strength. In the first part of the design phase when the chassis material was chosen, the team had a limited budget which resulted in the decision to use mild steel instead of 4130.

Lightweight and stiffness are the most important properties of a chassis and the stiffness of the completed chassis will be affected by the stiffness of the material from which it is built. Material stiffness is known as Young's Modulus and the controlling mechanism for stiffness in a material is the inter-molecular forces. So stiffness or Young's Modulus is a material constant which cannot be significantly changed by any mechanical or chemical processes. Alloying elements also have little effect on stiffness meaning that more expensive grades of steel have the same stiffness as mild steel (Callister, 2007). This justifies the decision to use mild steel for chassis construction as more expensive steels are unlikely to improve the chassis' stiffness.

Aside from cost there are other advantages to using mild steel over more expensive alloy steel, it is easy to machine and weld, also it does not become brittle in the heat affected zone when welding. (Black,2008) The FSAE rules also state that using stronger steels does not allow the use of smaller chassis members so there would be no weight advantage in using the more expensive SAE grade 4130 steel for these members. The downside to using mild steel comes with its lower yield strength, in the event of a collision or some other impact the chassis may become damaged at a lower stress than if it were built from 4130. This disadvantage is also present when there are small impacts on the chassis, an example of this would be small stones being picked up off the road by the tyres and hitting the chassis. The chassis may dent and its structural integrity may be compromised easier than an equivalent alloy steel chassis. In order to prevent this from endangering the driver, routine checks of the chassis for dents and damage must be made prior to anyone driving the car.

Manufacture

In order to improve manufacturability, square tubing may be used for many of the horizontal frame members. This makes cutting planar joints easier and simplifies suspension mounting points. Due to availability 25.4mm x 25.4mm x 1.4mm square tubing was used, which is larger than the minimum size required by the FSAE rules in Figure 3.

On many chassis designs a significant amount of construction time is taken up by making jigs to hold the fame in place during welding. Making a jig is very labour intensive and it can even use as much material as the chassis itself. To improve the manufacturability of the chassis it should be designed so that it is “self jigging”, which means that it can be constructed in separate parts which are then joined together. This significantly reduces the time and material required to make the chassis which greatly reduces the cost. It should be noted that this approach is suitable for a one off process which is the case for the construction of this chassis. However if a number of the same chassis are needed to be made then it the cost of making a jig is justified as it decreases the amount of time required to build each individual chassis (Black,2008).

Square vs Round

To assess the potential advantage or disadvantage using square instead of round tubing some simple calculations should be made from the pipes’ cross sections. Figure 8 shows the closest pipes sizes to the minimum required by the FSAE Rules that were available. The round tube used is the same size as the minimum size required by the FSAE rules however the square tube has thicker walls than the minimum required.

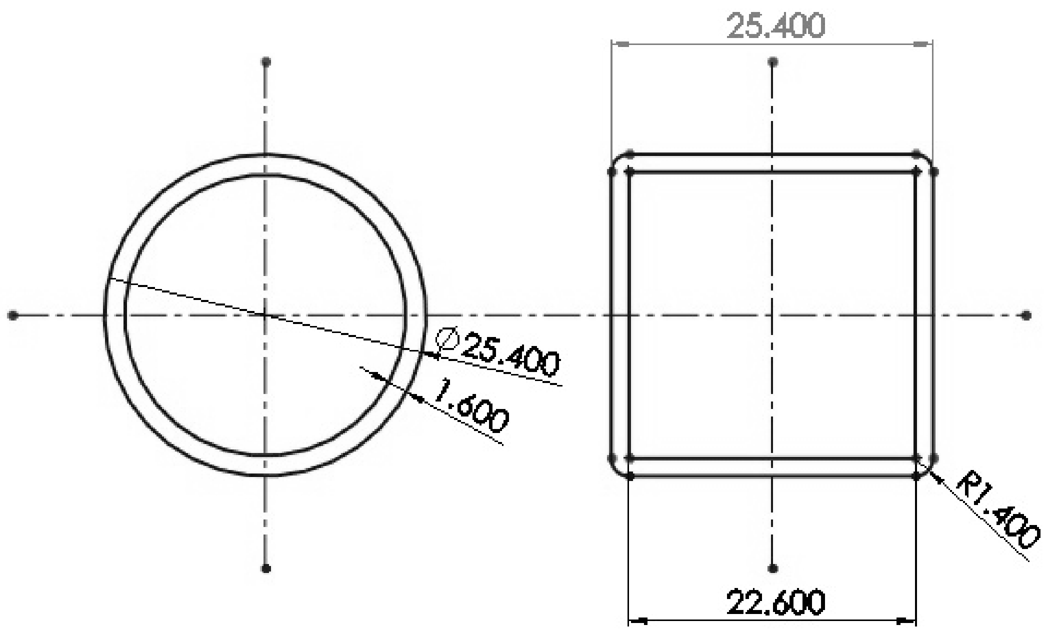

Figure 8 Dimensions of the square and round tubing used

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

Figure 9 Data calculated for the available square and round pipes

*Lowest Ixx for square tube, calculated about central axis parallel to face.

**For mode 1 buckling where both ends are free to pivot.

Figure 9 shows the weight compromise for using the square tubing, the compressive stiffness of each tube is proportional to its area so it is not shown. From the table it can be seen that with just an 11% increase in weight a 50% increase in yield strength is obtained if buckling is the failure mode. Using one or more square pipes as part of the side impact structure will make the chassis stronger than an equivalent structure using only round members which is what the 2002 UWAM petrol-electric converted chassis uses.

By using square tubing for the horizontal sections, the joints between members in the chassis can easily be cut with a mitre saw and the members can be simply clamped to a flat surface while welding. The suspension brackets can also be bolted directly onto the square members with no additional brackets required to produce a flat mounting surface.

Triangulation and Stressed Skins

Triangulation involves adding a diagonal member to an arrangement of four members to break the section into two three member sections. The resulting triangles are able to carry all forces in pure tension or compression without introducing bending stresses into the joints. To represent the effect of triangulation, a model of an un-triangulated square frame similar to what would be found in the chassis, is stressed with and without triangulation. The model is tested in SolidWorks with its inbuilt finite element analysis software under the same load and boundary conditions for each trail. The test model is a 500mm square arrangement of pipe sections constructed from the square 25.4x25.4x1.4mm tubing used in the chassis. The upper face of the top member is fixed in all degrees of freedom and the lower section has a force of 1kN applied uniformly to its lower face in the X direction. The same loading was applied to three different iterations of the same basic structure and the maximum displacement and maximum Von-Mises stress was recorded.

Test 1 applies the load to the square frame by itself with no other support. The resulting maximum displacement in this sample frame section is 2.65mm and the peak stress introduced into the frame section is 188MPa, Figure 11 shows that the largest stresses occur in the corners of the frame where there is a large amount of bending. The mass of this un-triangulated frame is 1.99kg.

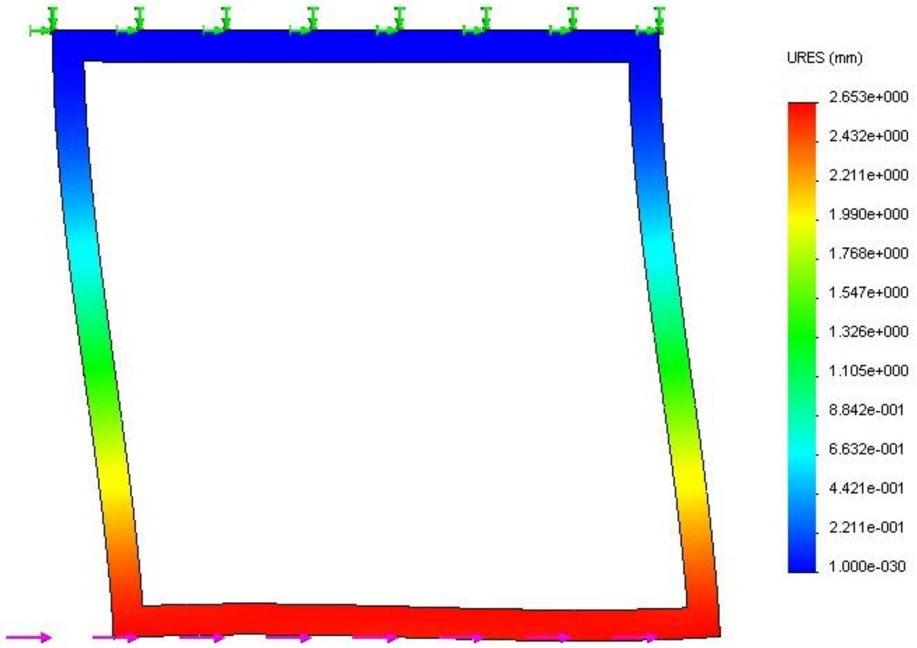

Figure 10 Displacement contour for SolidWorks model of an un-triangulated square frame

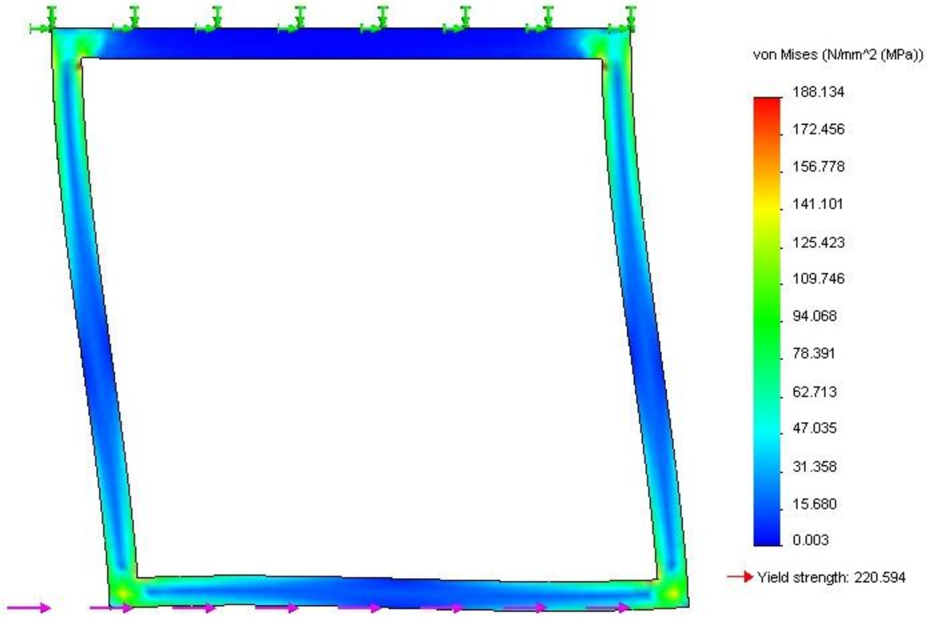

Figure 11 Von-Mises stress contour for SolidWorks model of an un-triangulated square frame

Test 2 applies the same force to a frame which now has a diagonal member included. The diagonal member is constructed from the same size tubing as used for the four outer sections. The addition of a diagonal member decreases the maximum displacement to 0.0727mm and peak stress is reduced to 18.94MPa under the same loading conditions as Test 1. The change in displacement is not visible from the shape of the figure as SolidWorks scales the deformation to look the same after loading. With the diagonal member added the weight has increased to 2.62kg. The stress contour Figure 13 shows how the stress concentration in the corners has decreased dramatically.

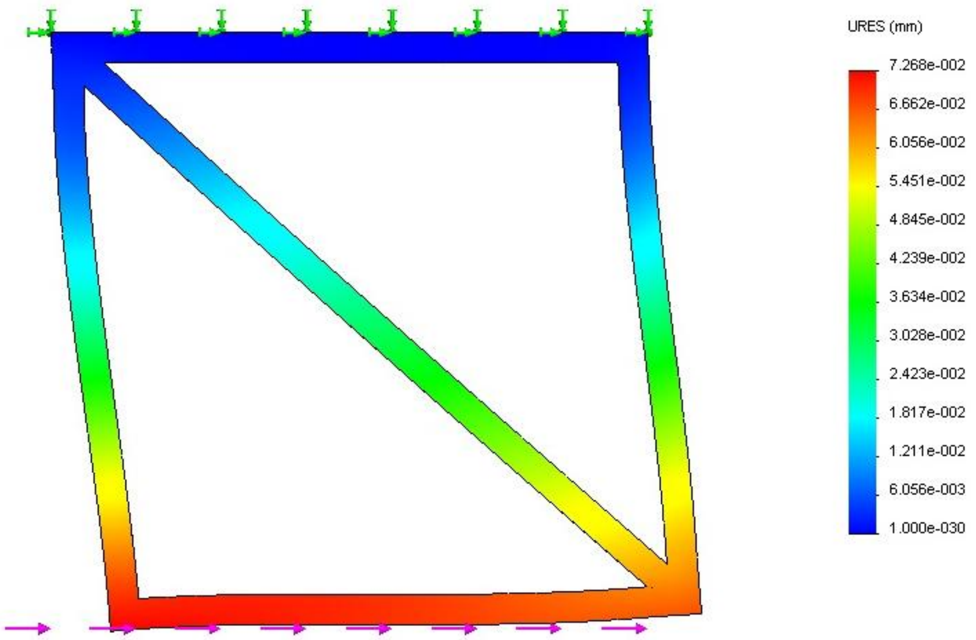

Figure 12 Displacement contour for SolidWorks model of a triangulated square frame

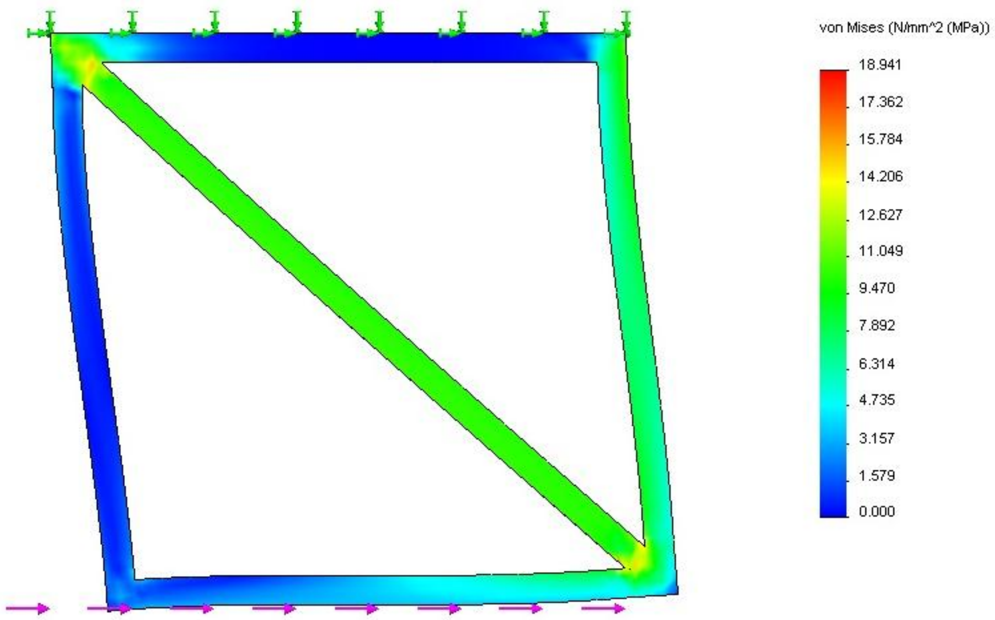

Figure 13 Von-Mises Stress contour for SolidWorks model of a triangulated square frame

Test 3 replaces the diagonal member with an entire sheet of steel, in order to maintain symmetry in the model for a 2 dimensional analysis 0.5mm thick sheet steel is added on both sides of the frame. This weighs the same as the 1mm thick steel which would be used on just one side of the frame in practice. This method of reinforcing the frame results in a maximum displacement to just 0.0220mm and a maximum stress of just 7.75MPa, but the total weight is increased to 3.56kg.

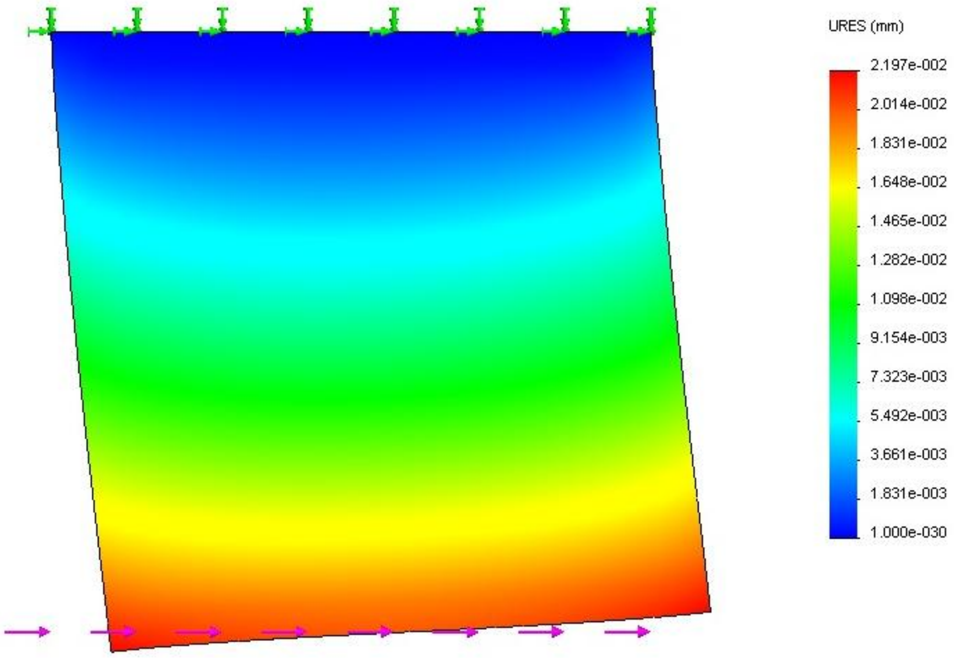

Figure 14 Displacement contour for SolidWorks model of a square frame with stressed skin reinforcement

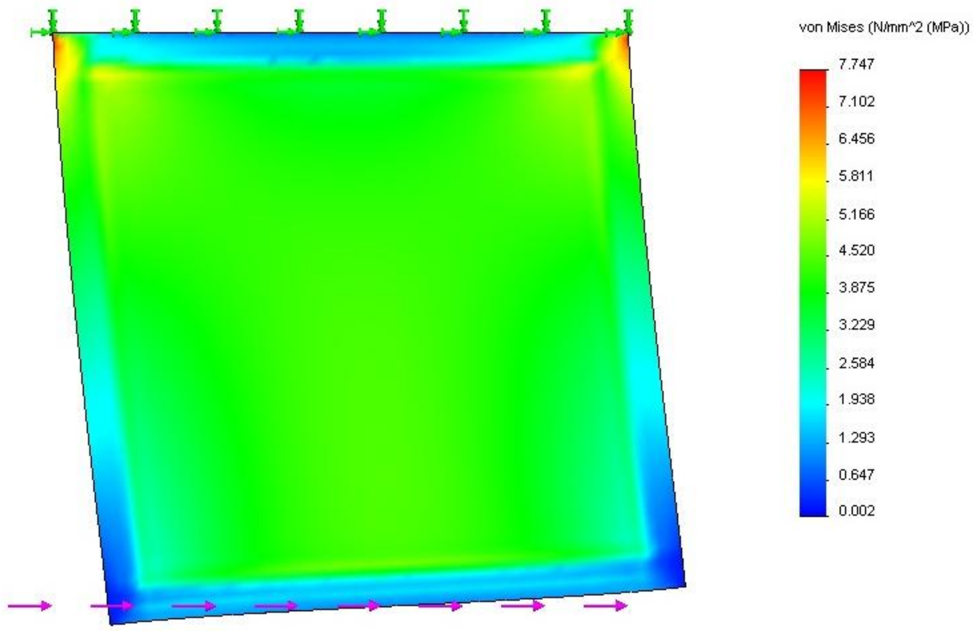

Figure 15 Von-Mises Stress contour for SolidWorks model of a square frame with stressed skin reinforcement

	Weight [kg]	Displacement [mm]	Von-Mises Stress [MPa]
Square Frame	1.99	2.65	188
Diagonal Member	2.62	0.0727	18.94
Stressed skin	3.56	0.022	7.75

Figure 16 Comparison of results from the three trials

Figure 16 clearly shows that adding some sort of reinforcement to any square sections of frame can greatly reduce stress and deformation in the welded joints under load. Simply adding a diagonal member to a rectangular section can reduce the deformation by at least an order of magnitude which greatly reduces stress in the welds, making the chassis much stiffer and safer. Adding an entire sheet steel panel to a rectangular section provides only a minor improvement in stiffness when compared to adding a diagonal member however in this case it adds a significant amount of weight. The result of this is that wherever open rectangular sections are present in the chassis, a diagonal member should be added to "triangulate" and stiffen the section. FSAE rules require that the floor of the chassis is closed to prevent debris entering the cockpit and potentially hitting and injuring the diver. The front bulkhead is also required to have a 1.5mm steel anti-intrusion plate welded to the front members. In these sections where sheet metal is already required, the sheet metal should be welded to the frame to provide reinforcement which means these sections will not require diagonal members to be added for triangulation.

Stressed Battery Boxes

For the quickest possible transient response, race cars aim to have the lowest possible moment of inertia about the vertical axis. To achieve this with the 2011 REV FSAE-A car it is desirable to have the heavy batteries located as close to the chassis' centre of gravity as possible. It is also desirable to have the batteries as low as possible to keep the chassis' centre of gravity as low as possible which can improve the weight transfer of the car and improve the handling characteristics (Puhn, 1981). To achieve this, the batteries shall be placed on either side of the driver's hips within the cockpit section of the chassis. To further lower the centre of gravity this centre chassis section should be made lower than the front and rear sections which support the suspension components. In order to fit the batteries and driver within the frame the middle section must be wider than would otherwise be required which is actually beneficial from an ergonomics point of view as it makes ingress and egress easier because the cockpit opening will be wider.

Having a wider chassis also means the chassis easily meets the requirements for the cockpit opening Figure 4.

The batteries must be isolated from the driver by a flame-proof barrier (firewall) which covers the top and inside sections of the batteries. This firewall will be constructed from 1mm sheet steel with an electrically insulating coating covering the inner faces. By closing these box sections and integrating them into the frame they have the potential to improve the chassis' stiffness across the open cockpit section of the chassis. As shown earlier, triangulation or some other sort of reinforcement that supports the shear loads and reduces bending stress is extremely important in maintaining stiffness. The cockpit opening cannot be triangulated with a diagonal bar or a stressed skin panel so this section of the chassis is much less stiff than the front and rear sections of the chassis.

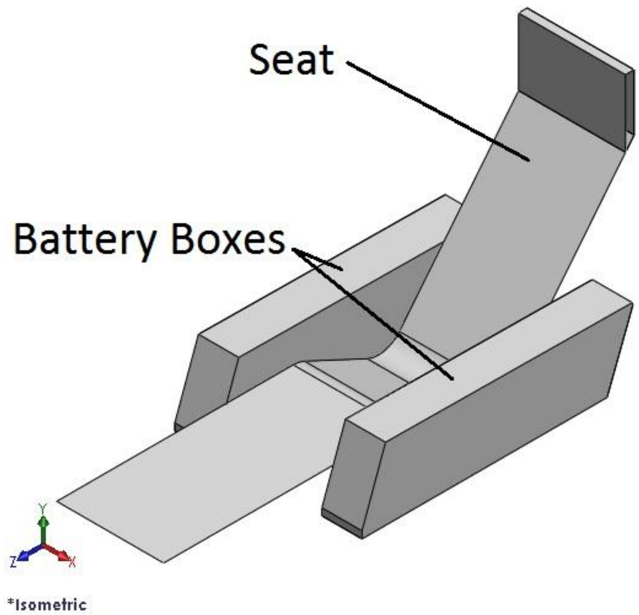

Figure 17 Stressed battery boxes and seat used to stiffen cockpit section of chassis

To assess the potential of stiffening the cockpit section by using the battery boxes as structural components, a SolidWorks model was made of a closed box which representing the ones required to house the batteries. The model is used as an approximation of box's performance, however in the chassis one of the box walls would be replaced with the side impact structure which is constructed from tube members. The box model was tested in both torsion and in bending to assess its potential performance benefit.

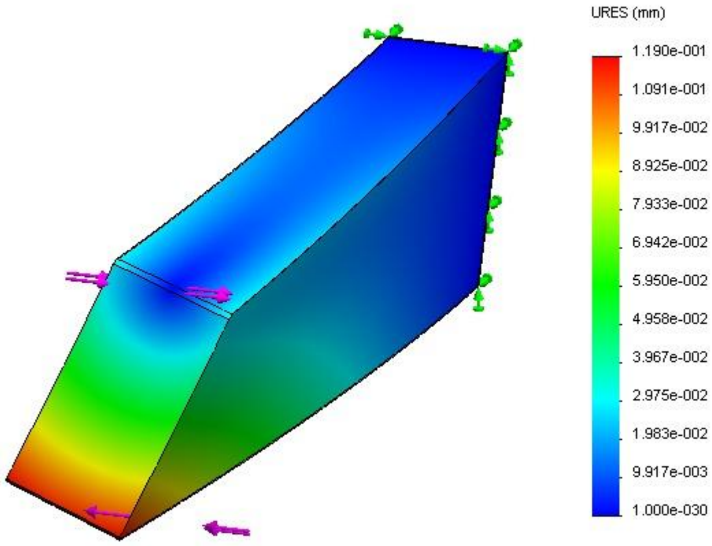

Figure 18 SolidWorks model of a single battery box in torsion

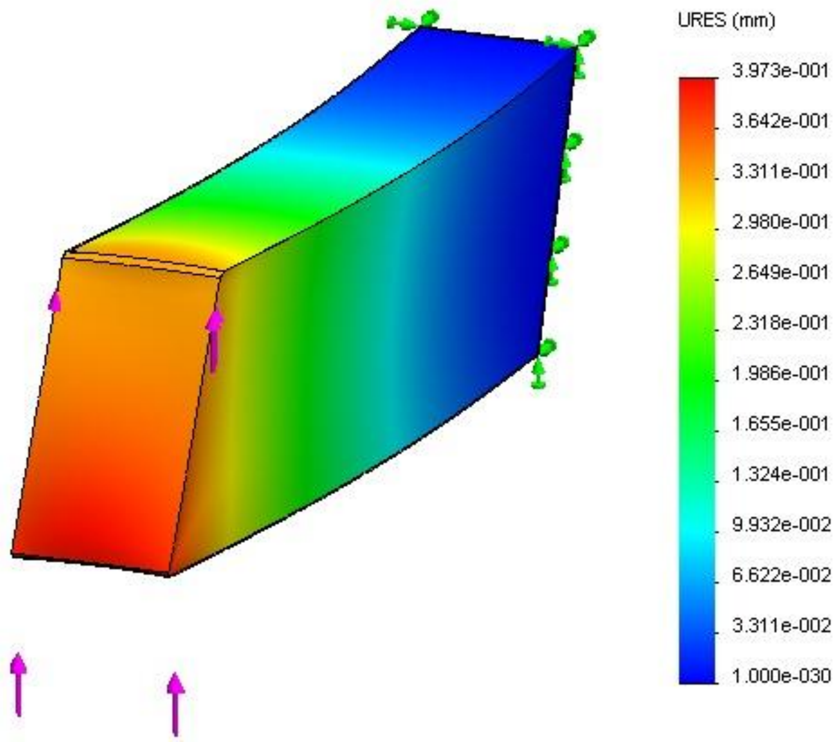

Figure 19 SolidWorks model of a single battery box in bending

The SolidWorks model of a single battery box showed that each box had a torsional stiffness of roughly 10000Nm/degree. However the bending simulation is more likely to give a better representation of how the battery boxes are likely to improve the chassis performance. The vertical applied force is multiplied by the distance to the vehicle centreline to get a torque and the vertical displacement divided by the distance gives the tangent of the twist angle, thus a torsional stiffness of 6600Nm/degree is obtained for the two battery boxes as they would be mounted in the chassis. This stiffness would significantly increase the stiffness of the open cockpit section so it is worthwhile investing the extra time to integrate the boxes into the frame as a structural component. As the firewall(s) are constructed form steel they can be welded straight to the chassis members rather than using fixing screws/bolts, which can work loose over time.

The FSAE rules also require a side impact structure be present on the outside of the battery boxes so by placing them within the cockpit section where a side impact structure is already present, there is no need to add a second side impact structure elsewhere just for the batteries which would add otherwise un-necessary weight.

To further improve the effect of using the battery boxes as structural components to stiffen the cockpit section, the seat should be welded to these battery boxes to increase the stiffness of the assembly. This would also add support to the large side faces of the boxes to prevent them from buckling.

Final Design

Front and rear sections

The first thing to consider in the design is location of the nodes for the suspension mounts as these cannot be moved, all other components must then work around these points. Figure 20 and Figure 21 list the locations for all the required suspension pivots in XYZ coordinates where X is the horizontal axis that runs across the width of the car, Y is the vertical axis, and Z is the horizontal axis that runs down the length of the car. Figure 22 shows these node coordinates in isometric view, joined by lines to make the points easier to see.

Node Number	x	y	z
1	250	320	0
2	175	120	0
3	250	320	-500
4	175	120	-500

Figure 20 Front suspension point coordinates (in mm, mirrored about YZ Plane)

Node Number	x	y	z
5	250	320	-1600
6	150	120	-1600
7	250	320	-2100
8	150	120	-2100

Figure 21 Rear Suspension point coordinates (in mm, mirrored about YZ Plane)

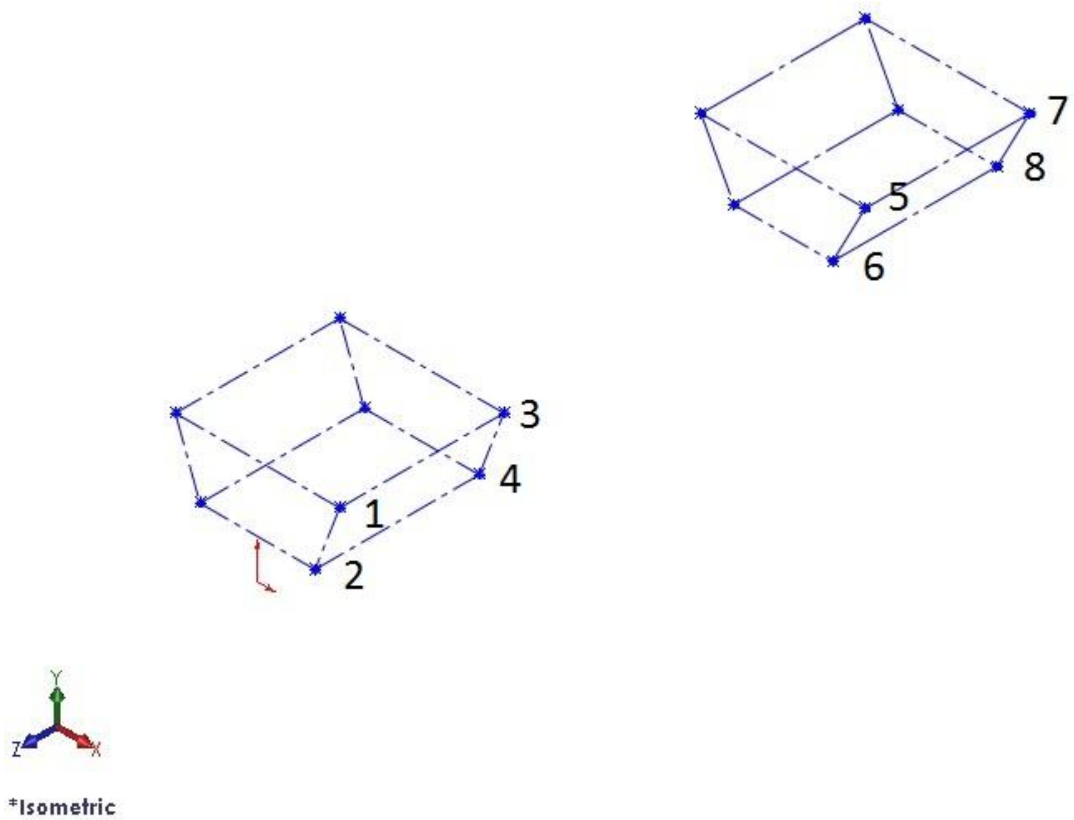

Figure 22 Nodes required for the chassis, lines connect the nodes to make it easier to visualise the node locations in 3D

To allow room for fixings, the A-arms do not mount directly to the nodes but are is mounted as close as is practical so that minimal bending is introduced into the chassis. The nodes required for the suspension also define the minimum length required for the chassis, and by making the chassis no longer than this, no un-necessary material is used which would increase weight. The front and rear bulkheads will be constructed at the location of the front-most and rear-most nodes in Figure 22 to provide maximum strength to support the suspension loads. Bulkheads are very stiff points on the chassis and include horizontal transverse members which directly connect nodes 1, 2, 7 and 8 with their mirrored counterparts. This means there is minimal deformation at these points under loads induced by breaking, cornering and acceleration. Minimizing potential deflection is essential for each suspension mounting as this ensures the wheel does not move and change its geometry under load. If the wheel's geometry were to change under load the suspension may become difficult to tune and optimize as the wheel would move away from the position which provides the best grip for the tyre.

To comply with the FSAE rules, it is not practical to include the member that runs between node 3 and its mirrored counterpart in Figure 22 as this would obstruct the foot-well area of the chassis. This means that other members will have to be placed around this node to support the forces which generated by the suspension that connects to the node.

With the A-arm pivot locations defined, the remaining components for the suspension must then be mounted to the frame. The suspension design uses a pull-rod and rocker arrangement to connect the wheel's motion to the inboard mounted spring. This introduces significant loads into the chassis even when the car is stationary so the arrangement of the members around it must ensure no bending forces result.

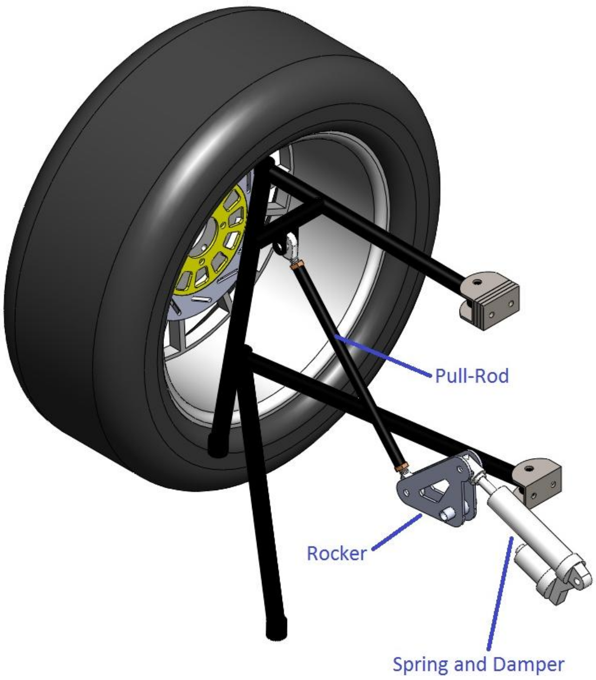

Figure 23 Front-Right suspension assembly as designed by Marcin Kiszko (Kiszko, 2011)

The rocker is mounted to the lower chassis member (The member connecting nodes 2 and 4 in Figure 22) via a pivot, the forces from the spring and rocker act in a plane parallel to the front bulkhead and thus have X and Y components but no Z or moment (torque) components.

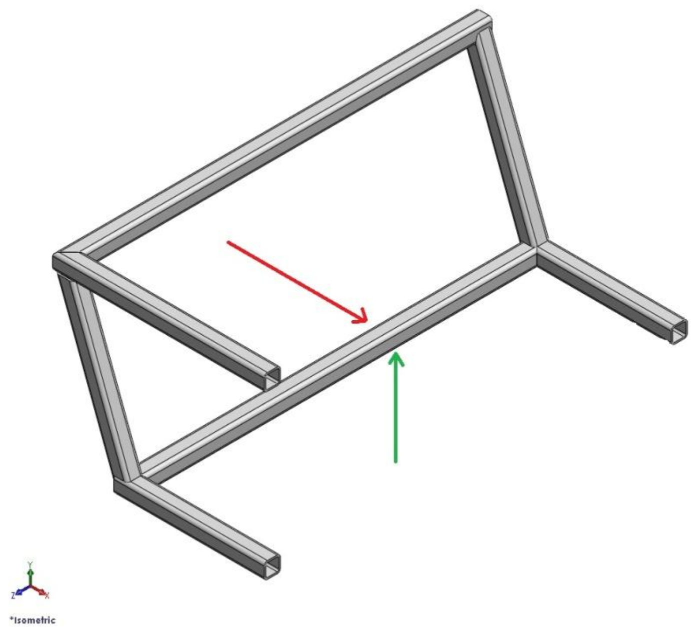

Figure 24 X and Y forces introduced into the frame by the suspension rocker

Figure 24 shows the force components introduced into the frame by the suspension rocker. The Y component of these forces (green vector) can be supported by adding diagonal members between the rocker mount and suspension nodes 1 and 3. The added members are also required by the rules as part of the "Front Bulkhead Support" and thus they must meet the minimum size requirement detailed in Figure 3.

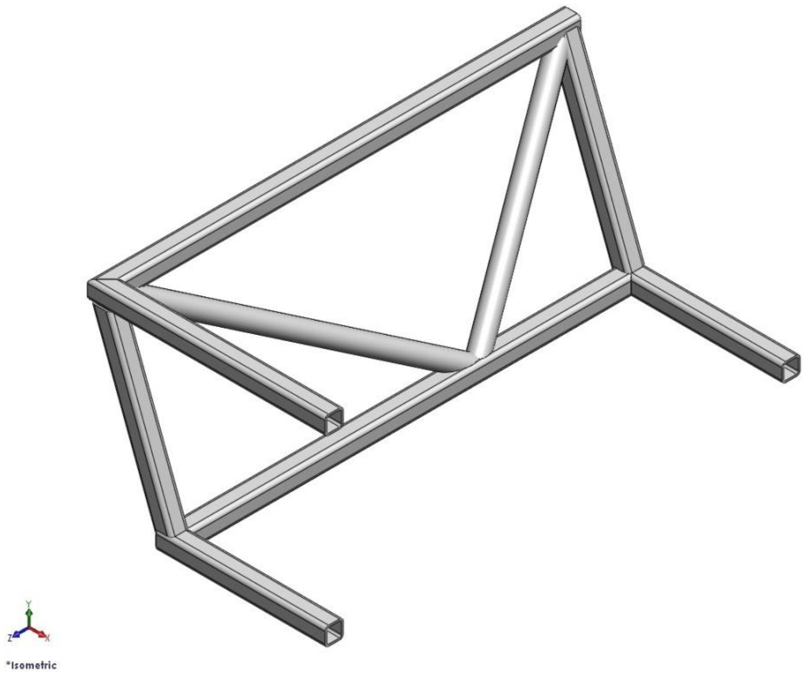

Figure 25 Front-Right chassis section with Triangulation used to support Y component of suspension force

The X component of the force shown in Figure 24 (red arrow) could be supported by adding a similar arrangement of members in the horizontal plane however the spring also acts in this plane so it is useful to mount the spring to the same structure. To support this X component of force from the rocker ant to hold the spring two 3mm steel plates are laser cut to run between the left and right hand side frame members. To triangulate the bottom of the section 1mm sheet steel is welded to the frame members and the 3mm plate spring holders. As well as triangulating the bottom section of the frame this sheet steel increases the 3mm plates' buckling strength which is otherwise quite low due to its thin cross section.

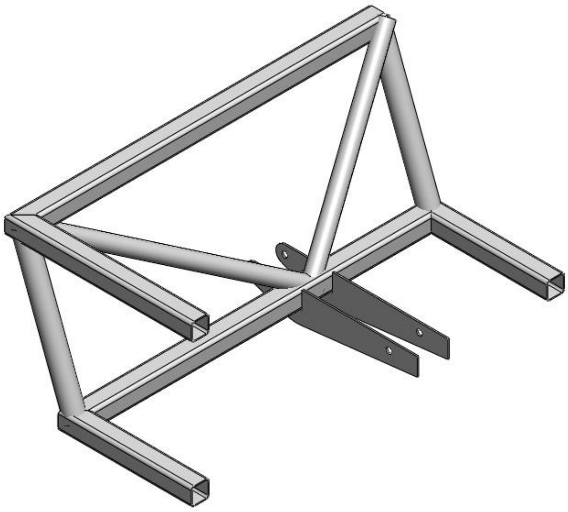

Figure 26 3mm Laser cut plate steel sections to mount spring and rocker

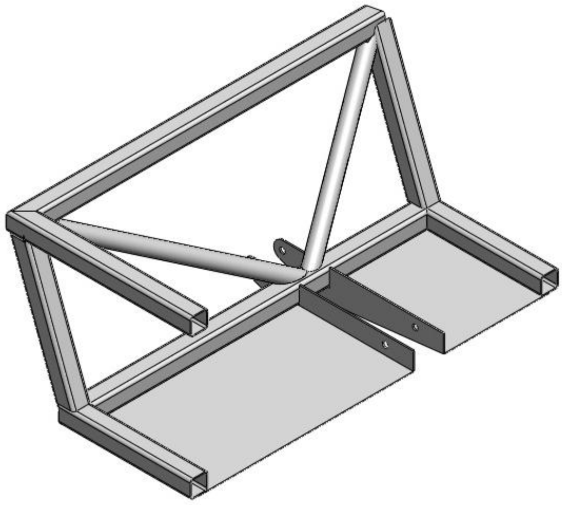

Figure 27 Stressed skin floor added to triangulate section and support the spring mount against buckling

The same design can be applied to the rear of the frame which gives us the foundation of the chassis, to which all other members must be added. The rear section can be completely triangulated as there is no foot-well or other requirements restricting the members in it.

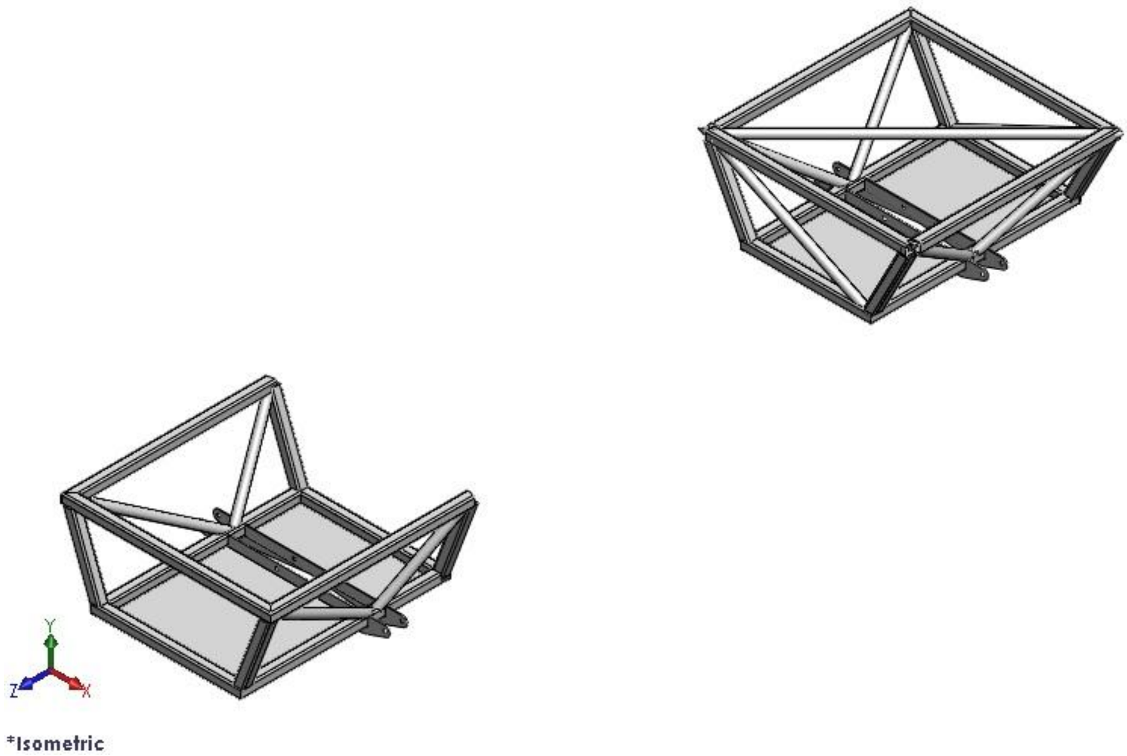

Figure 28 Front and rear chassis sections defined by suspension design

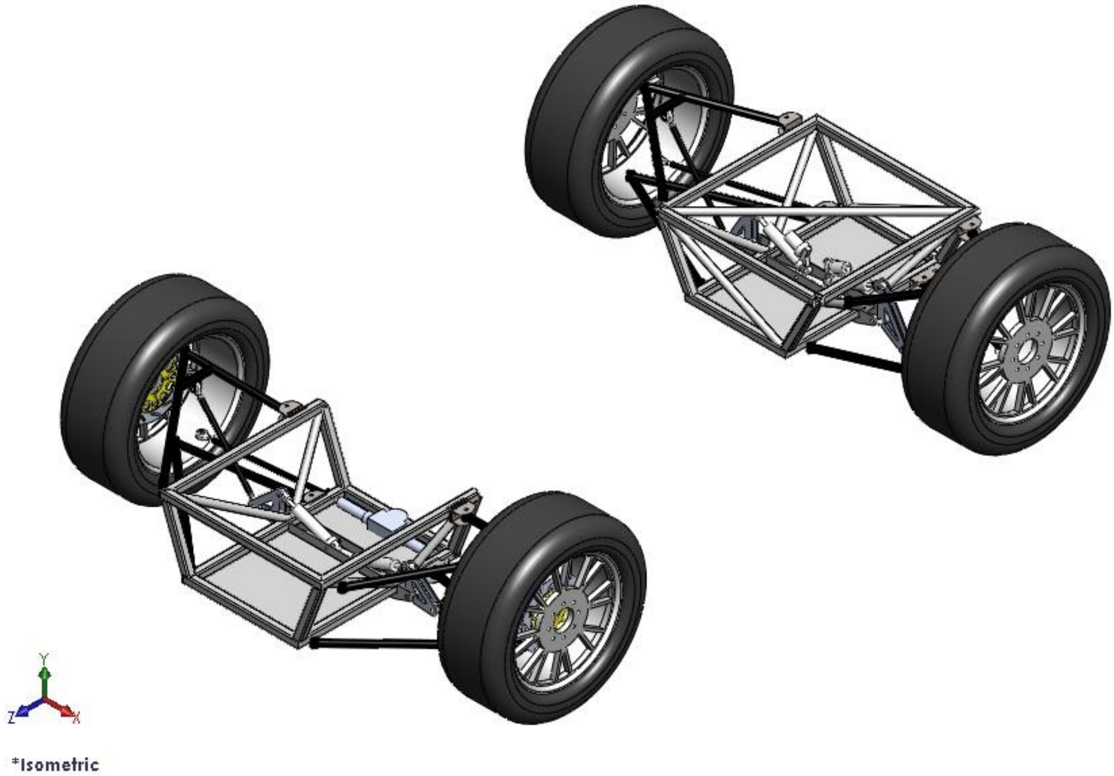

Figure 29 Front and rear chassis sections with suspension shown

Roll hoops

With the suspension pivot and spring locations now defining many of the front and rear members as well as the location of the front and rear bulkheads, the design must now incorporate the roll hoops. As discussed earlier the chassis is required to fit a 95th percentile male with clearance to the roll hoops, the template for this is shown in Figure 6. This template must have 2 inches of clearance to a tangential line from the front to the rear roll hoop and to a line from the rear roll hoop to the rear bulkhead.

To avoid adding additional un-necessary members it was decided to locate the main roll hoop in the same Z plane as suspension node 5 in Figure 22. The bracing for the main roll hoop must be mounted as near to the top as possible and must be inclined by at least 30° from the main roll hoop in side view. Since the roll hoop will be mounted in the same Z plane as suspension node 5 in Figure 22 and the roll hoop supports must mount to node 7 (and its mirrored counterpart), the angle between the roll hoop and the roll hoop bracing is what limits the height of the main roll hoop. The maximum possible height of the roll hoop can easily be calculated using trigonometry. In side view the distance between the rearmost section of the frame and the roll hoop is the same as the distance between nodes 5 and 7 in Figure 22 which is 500mm. The minimum allowable angle between the roll hoop and the supports is 30° therefore:

$$Max\ Roll\ Hoop\ Height\ above\ top\ suspension\ nodes = \frac{500}{\tan 30}$$

This gives a maximum height of 866mm above the upper rear suspension nodes if the bracing is attached to the very top of the roll hoop. The rules permit the bracing to be mounted up to 160mm below the top of the roll hoop, however for safety and manufacturability reasons it was decided that the bracing should be attached to the top-most part of the hoop.

The batteries will be placed on either side of the driver's hips with the supporting boxes making up the sides of the seat. This requires the centre section of the chassis to be wider than the front and rear sections so both the batteries and driver can fit. A mock up seat was constructed from wood to test comfortable seat widths for each of the drivers and it was determined that 400mm is the smallest comfortable width for all drivers in the team. The boxes either side of the diver must be 150mm wide to fit the batteries and the required insulating layers, which means the distance between the insides of the chassis members in the centre section must be 700mm. As the roll hoops will attach to these side members, this means the width of the roll hoop must be 700mm between inside edges at the base.

In a race car it is desirable to have the centre of gravity as low as possible (Puhn, 1981) so the heavy batteries should be mounted as low in the frame as possible. To do this the floor of the centre chassis section was lowered to 50mm from the ground, which is 70mm lower than the floor of the front and rear chassis sections. Additional members are added to triangulate the roll hoop back to the rear section of the chassis as the FSAE rules require a fully triangulated structure from the roll hoop bracing back to the four points where the main roll hoop attaches to the side impact structure.

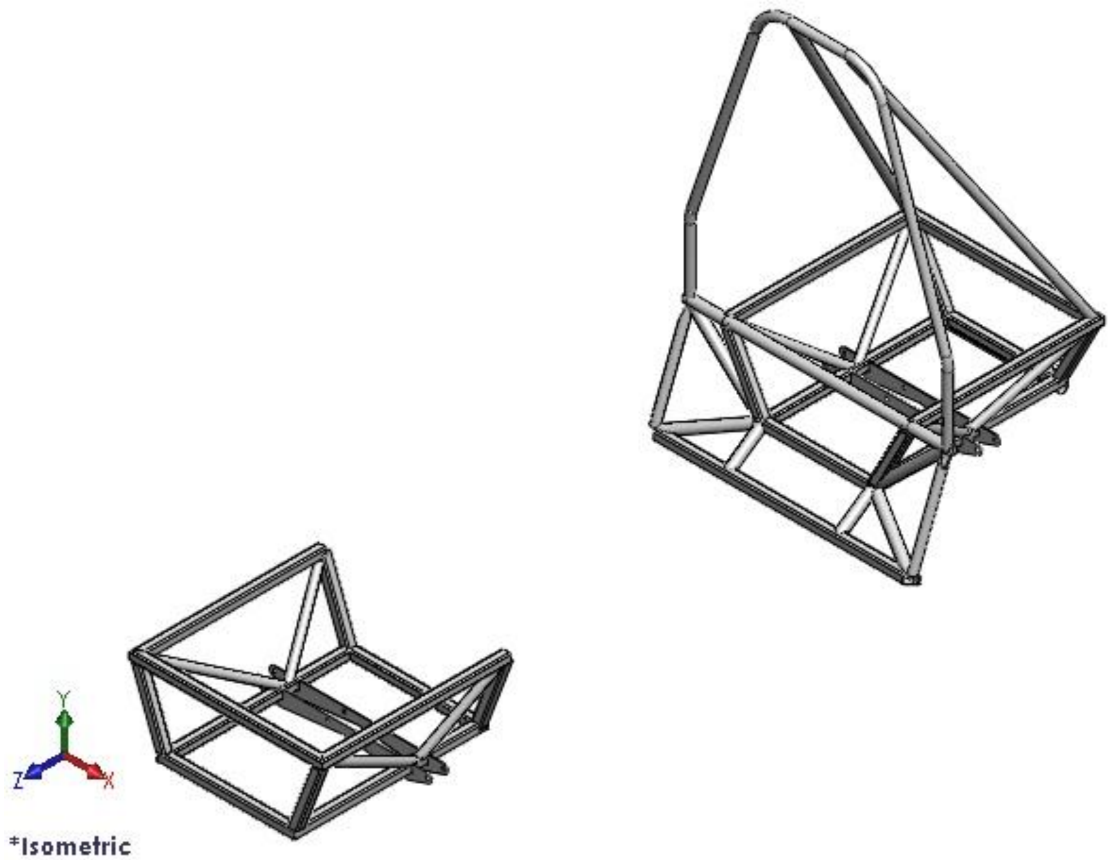

Figure 30 Front and Rear sections with main roll hoop and roll hoop supports added

As listed in Figure 3 the main roll hoop is required by FSAE rules to be made of at least 25.4x2.4mm round bar, however larger tubing was used as it was the closest size to the minimum that was available. The pipe used is 26.9mmx2.6mm round which has a 14% larger cross sectional area and a 28% larger Second Moment of Area than the minimum size required. Due to its length to diameter ratio, buckling is the most likely failure mode for the roll hoop so it is able to withstand roughly a 28% larger force than if it were built using the minimum allowable pipe size. To further test the safety of the roll hoop SolidWorks' in-built Finite element simulation software was used to analyse the strength of the roll hoop. The roll hoop was tested in isolation without including the bracing as the simpler the model is, the more likely it is to be accurate. The expected weight of the completed car is about 200kg. To test the roll hoop the entire weight of the car was applied as a force to one top corner of the roll hoop, which simulates where the roll hoop would likely contact the ground in the event of a roll over. The bottom faces of the roll hoop are restricted in all degrees of freedom to represent its attachment to the rest of the frame.

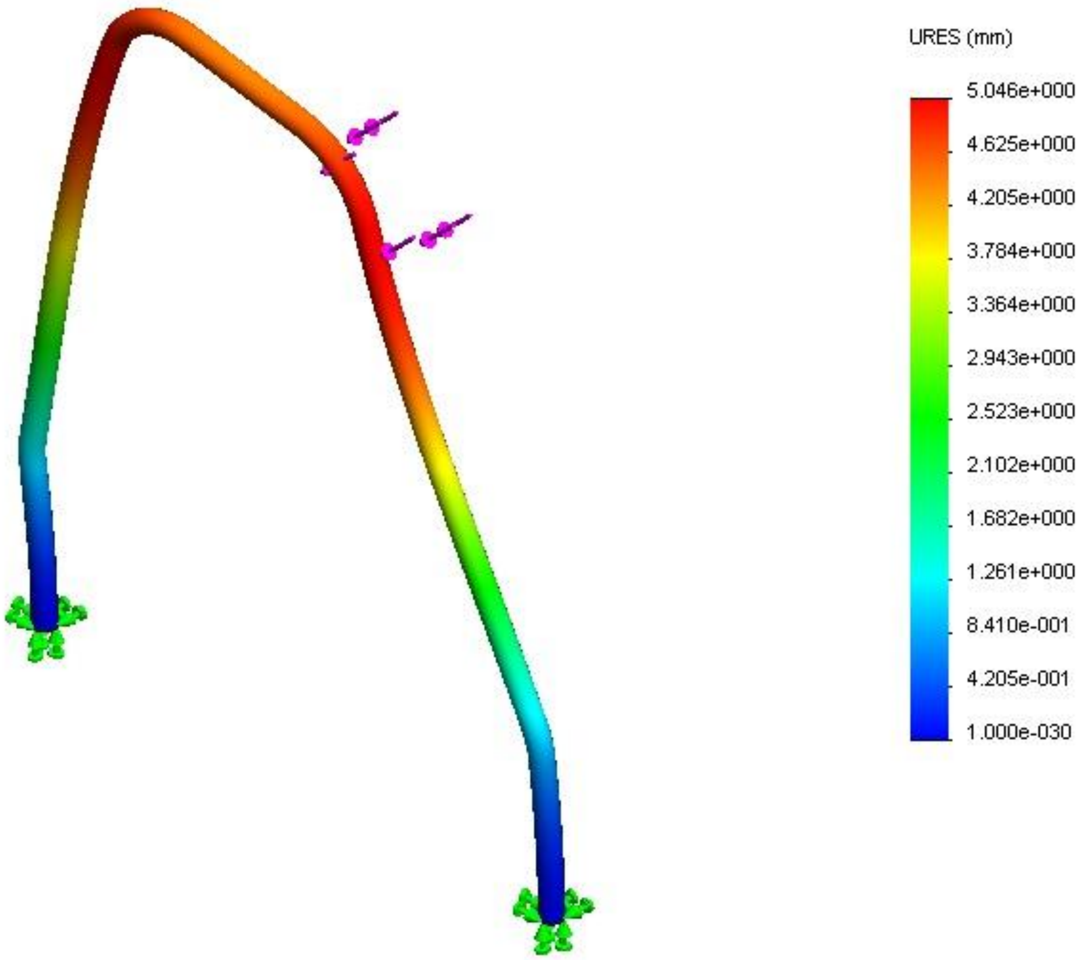

Figure 31 SolidWorks simulation of roll hoop in roll over situation

In practice it is not likely that the entire weight of the car would be concentrated just on one part of the roll hoop, the front roll hoop would also support a significant amount of the load. Under this loading configuration, the roll hoop alone was able to support the applied load without any yielding, the maximum displacement of the roll hoop is just 5mm which means the driver's head is not likely to be impacted by the roll hoop deforming, however the drivers head may swing and contact the roll hoop which is why the FSAE rules require the roll hoop to be padded. This simulation does not include the roll hoop supports which would significantly increase the strength of the roll hoop structure, which suggests the designed roll hoop will be sufficiently strong to protect the driver in the event of a roll over.

As mentioned the batteries will be located either side of the driver's hips, between the front and rear roll hoops. It is desirable for this volume to be as large as possible to allow the batteries to be moved forwards and backwards to adjust the finished car's centre of gravity. This can be used to alter the car's handling characteristics which has the potential to make the car faster (Puhn,1981). To keep the volume for the batteries between the roll hoops as large as possible, the front roll hoop is angled rearwards from vertical. Doing so maximises the distance between the bases of the roll hoops but keeps the top of the front roll hoop in the desired position. The location of the front roll hoop's upper horizontal section governs the position of the steering wheel. According to the FSAE rules the steering wheel must be no greater than 250mm from the front roll hoop. The front roll hoop must therefore be leant rearwards so that the driver can comfortably reach the steering wheel while in the seat.

Leaning the roll hoop in the rearward direction as such requires additional bracing be added to the rear of the front roll hoop according to FSAE rules. Having additional bracing on either side of the driver has the potential to hinder the driver while getting in and out of the cockpit. This is more than just an inconvenience for the driver as the FSAE rules requires the driver be able to exit the cockpit in less than 5 seconds. If it is difficult for the driver to exit the cockpit then this could also be a safety concern, in the event of a fire, possibly caused by a failed battery for example, the driver could be injured if he/she is not able to exit the car easily and quickly enough. In order to make it as easy as possible for the driver to get over these required roll hoop supports they are connected to the rear roll hoop where it meets the side impact structure. This makes it easy for the driver to swing his/her legs over the lower rear part of this support while holding their weight with their arms on the higher front part of the roll hoop support.

Side impact structure

The FSAE rules require a side impact structure to be present in the frame to protect the driver in the event of a side-on collision. It consists of two horizontal members and one diagonal member, the side impact structure connects the front and rear roll hoops. With the car at its normal ride height with a 77kg driver seated in the driving position the upper member must be 300mm to 350mm from the ground. This height corresponds to the height of the upper chassis members in the front and rear sections so the upper side impact member can simply connect these sections. There is no requirement for the height of the lower side impact member so it can be placed at the desired height of 50mm above the ground. The diagonal side impact member simply runs between the intersection of the front hoop and upper side impact member, and the intersection of the rear hoop and the lower side impact member. This diagonal also provides additional support for the front roll hoop and triangulates the sides of the frame.

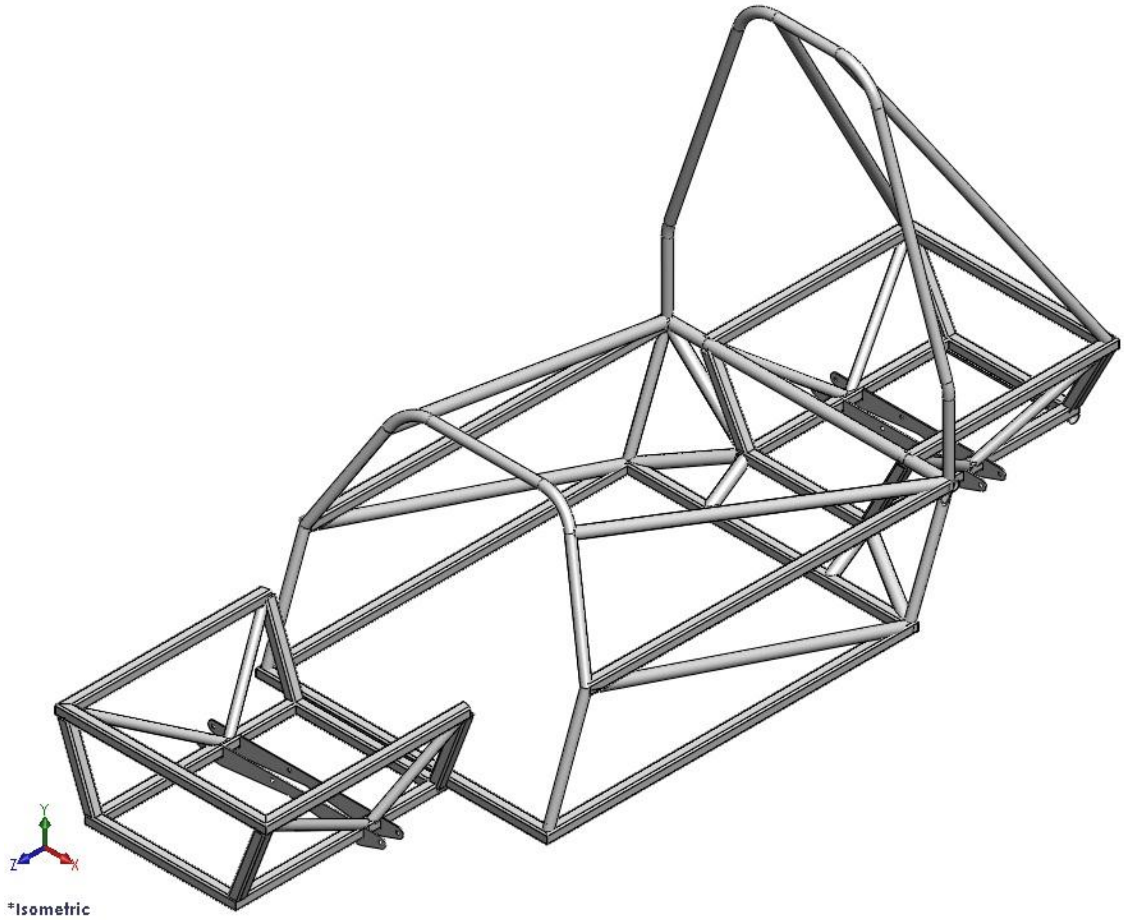

Figure 32 Front roll hoop, roll hoop supports and side impact structure now shown

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Front Bulkhead and Foot-well

The FSAE Rules require supports that extend from the front roll hoop to the structure in front of the drivers feet. In this chassis design that requires the forward hoop supports connect to the front bulkhead. The foot-well will have a raised floor to clear the internally mounted front springs so the front bulkhead must be high enough so the braces clear the foot-well template in Figure 5. The springs necessitate a floor that is 50mm above the height of the upper surface of the lower frame members in the front section.

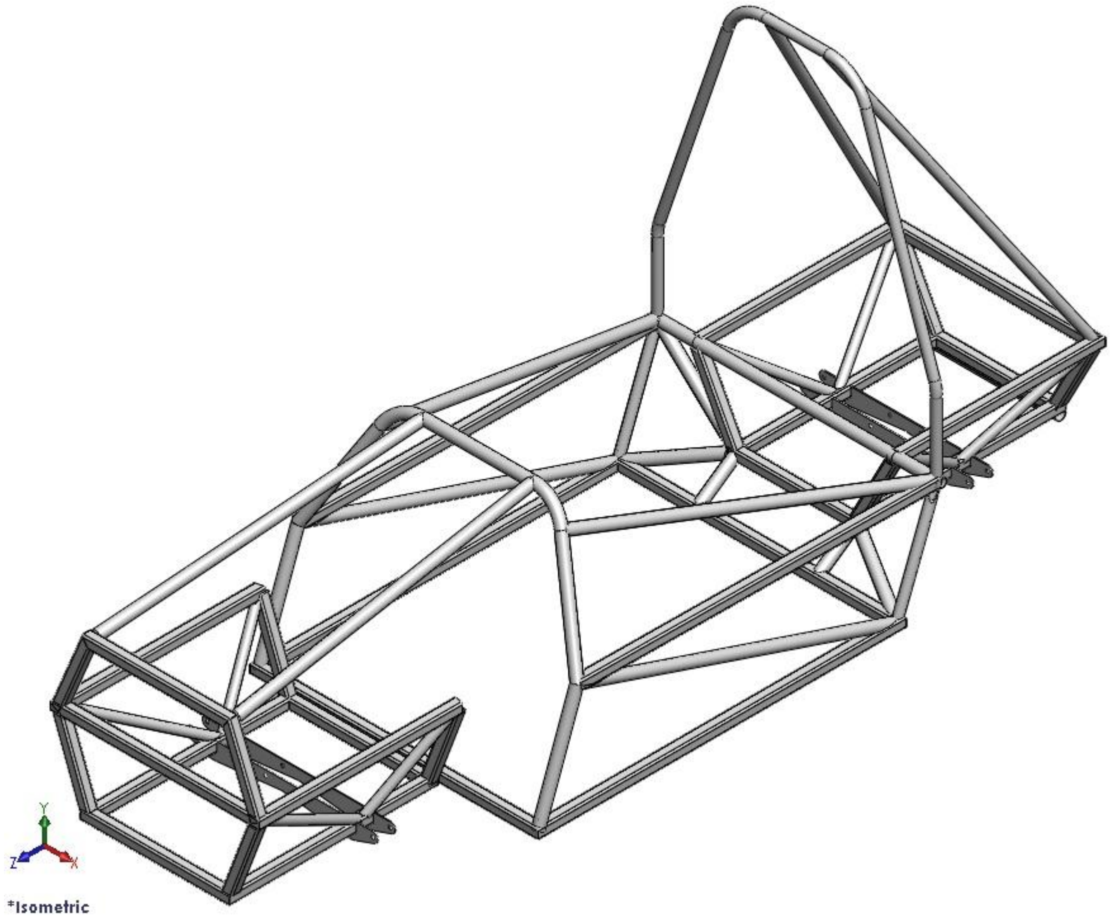


Figure 33 Front Bulkhead and forward front roll hoop supports

Completing the Space-Frame

To finish off the basic space-frame some additional members are required to connect the nodes which are not yet fully supported and to ensure all the FSAE rules are met. As discussed at the start of this section, the top-rear node in the front section of the chassis cannot be supported by a transverse member as it would block the foot-well. To support this node four members are added which extend out to different parts of the chassis. These members also act as part of the front bulkhead support required by the FSAE rules, as well as triangulating parts of the structure. A cross is also added to the forward facing front roll hoop supports to triangulate them, these members are not required by the rules and as such can be made from the same 20mm pipe that the suspension A-arms are constructed from. A cross is used because the relatively large length of the members makes them susceptible to buckling, in the cross configuration they help to support one another when under load. The shoulder restraint bar and its supports are also added to the main roll hoop supports.

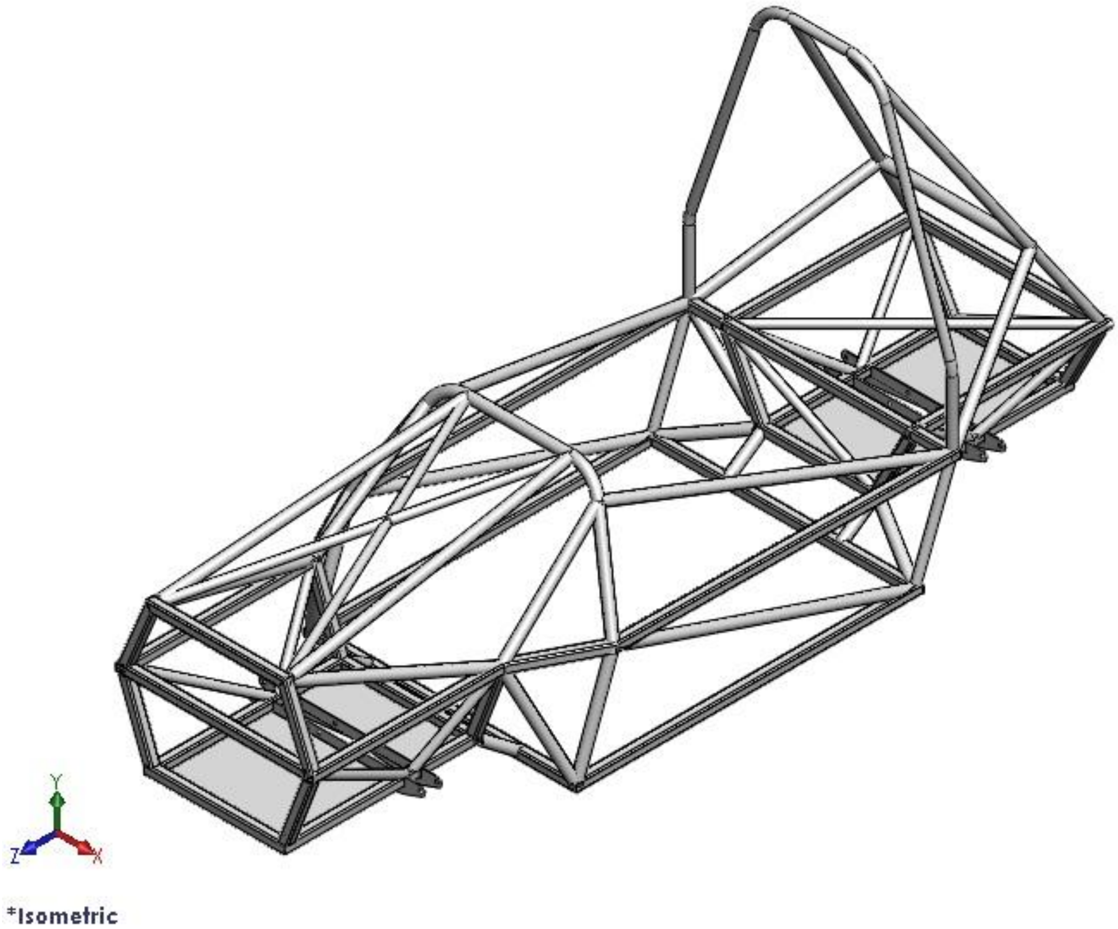


Figure 34 Completed space-frame

Battery boxes

The design as it stands is completely triangulated in both the front and rear sections, however the centre section, with the cockpit opening is lacking some bracing. To remedy this, the battery boxes are used as structural components located on either side of the driver. They are constructed from 1mm sheet steel folded into the required box shape which is then spot welded to the frame in various locations. The red regions in Figure 35 show where these battery boxes are welded to the frame.

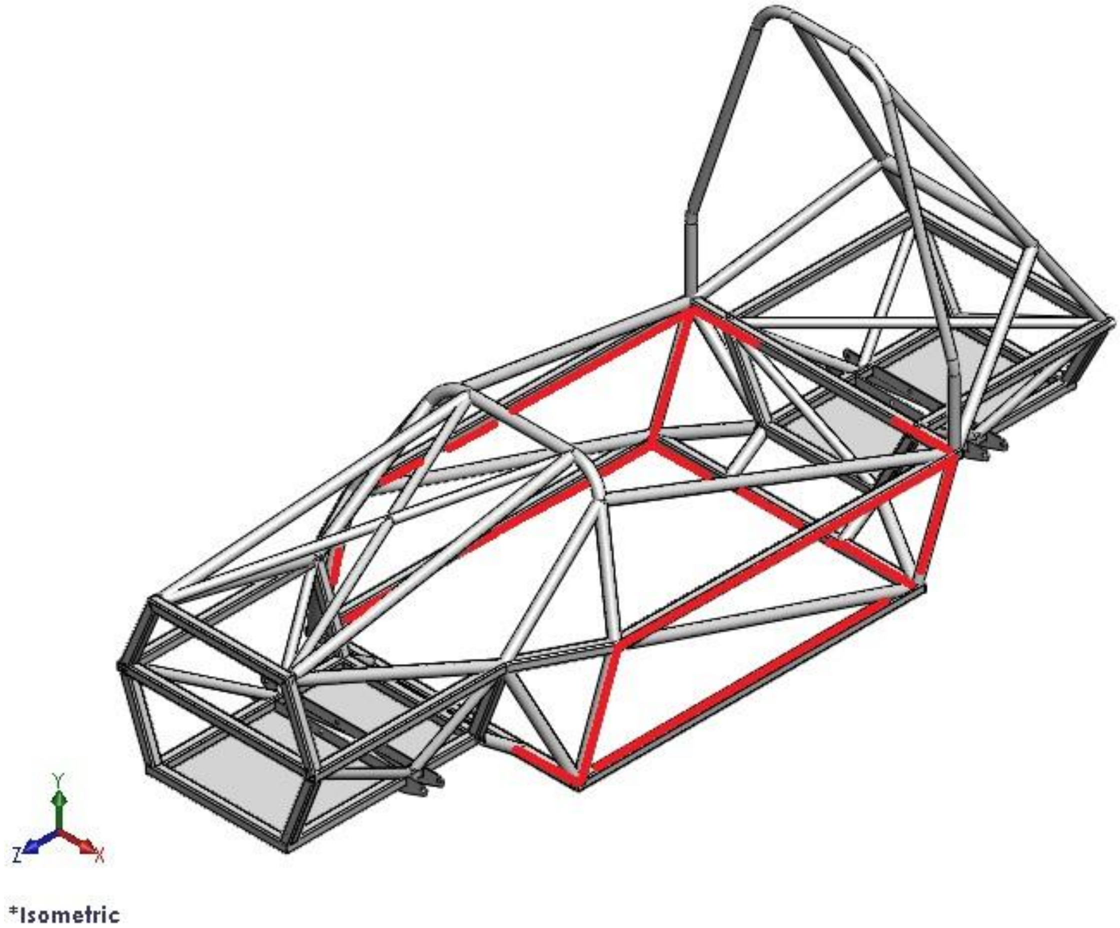


Figure 35 Battery box to frame weld attachment

Final Design Summary

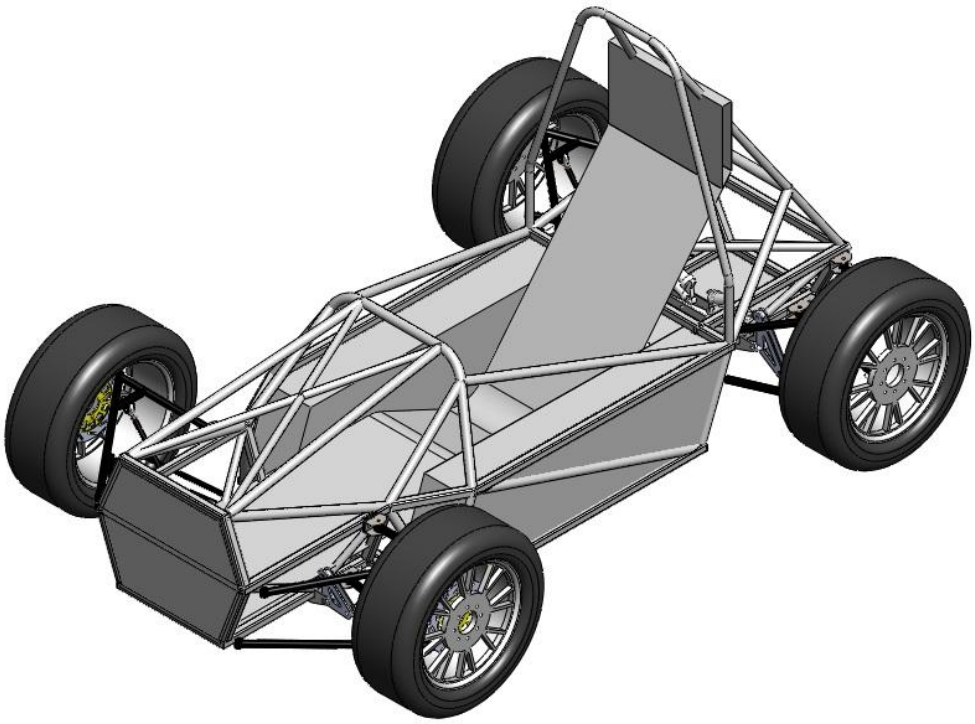


Figure 36 Complete chassis with suspension

The final chassis design meets all the requirements placed on it by the rules and suspension design. It makes the most of the members required by the rules, requiring few additional members to support loads and add triangulation. The design utilises the required battery firewalls as a structural component to make the most of the weight that they add to the chassis.

The weight of the complete space-frame is 35kg which is only half the weight of the batteries that it has to support. When the stressed battery boxes and seat are included the total weight comes to 42kg which is on target to achieve a total car weight of 200kg.

The design includes good driver ergonomics and it is easy for the driver to climb in and out of the car due to the low roll mounted hoop supports.

The chassis is 2125mm long, 725mm wide, rides 50mm from the ground and the roll hoop is 1113mm tall.

Construction

Welding

The space-frame part of the chassis will be constructed by cutting straight lengths of tube at precise angles and welding them together. There is a large number of welds in the space-frame so it is important to ensure they are strong enough to withstand the loads placed on the chassis and that they do not warp the chassis during construction.

The suggested welding process for constructing the chassis would be MIG (Metal Inert Gas) welding as it is one of the quickest manual welding processes (Black, 2008). Due to availability reasons the process used was TIG (Tungsten Inert Gas) welding which is slower than MIG welding. TIG welding consists of a Tungsten electrode an inert gas (Argon) shield and a filler metal rod. TIG welding produces neat welds which are similar to MIG welds with no slag that needs to be removed after welding, however TIG welding does have the advantage of having more control of the weld current and feed rate of the filler.

Metal in the weld region heats up to and above its melting temperature during welding, it then cools after welding and the material shrinks. Often this heating and shrinking will not occur evenly over a join and thus the weld can cause warping. To avoid or minimize this effect the welding process must be performed in a particular order. One method of reducing the warping due to weld shrinkage is to tack joints in place before making a complete weld. The order of welding also plays a part in how the structure reacts to weld shrinkage. Welds that will cause shrinkage and warping in opposite directions should be done consecutively so the residual stresses balance one another. When welding to square tubing pieces together this means that the joint should be tacked first, then one face welded, followed by the opposing face, then the remaining faces can be welded.

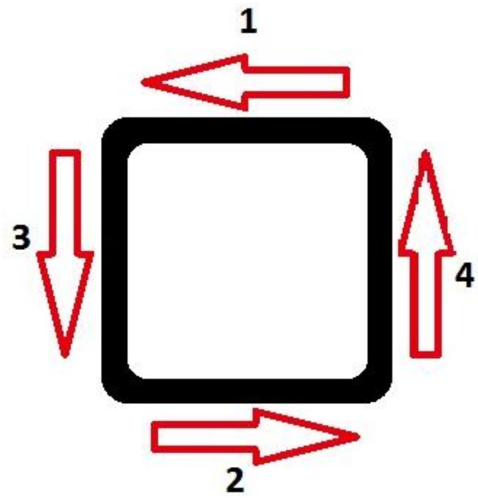


Figure 37 Order and direction welds should be made around a square tube joint

For welding of the tubes in the frame a weld current of 50 amps DC is used with a fixe polarity current. The Electrode is machined to a point like a pencil and 2mm steel filler rod is used. As the tubes in the chassis have relatively thin walls no gusseting is required in the joint to achieve complete weld penetration.

Construction Process

With a complete design the construction stage of the project can begin. The construction process must be carefully considered to avoid problems such as warping of the frame due to weld stress. The FSAE Rules require the roll main roll hoop be made of one uncut piece of steel pipe so the construction process needs to work around this. The design is self jigging where the frame can be constructed in parts which are then connected together. If the chassis was not self jigging then additional time and material would be used up making jigs to hold different members in place for welding. This method is not viable for one off builds due to the time and materials that needs to be invested into a jig, however if a number of the same chassis are being built then this process can make construction faster after the jig is constructed. (Black, 2008)

The design of the space-frame includes four horizontal sections made from square tube that can be constructed on a flat surface where they can be clamped down. As each of these sections is in a single plane the cuts that make up the angled joints can be made accurately with a mitre saw, meaning that the weld does not have to bridge a gap in the joint due to poor cutting tolerances. With the members clamped to a flat surface they can be welded together to form each rectangular section as well as the more complicated top section.

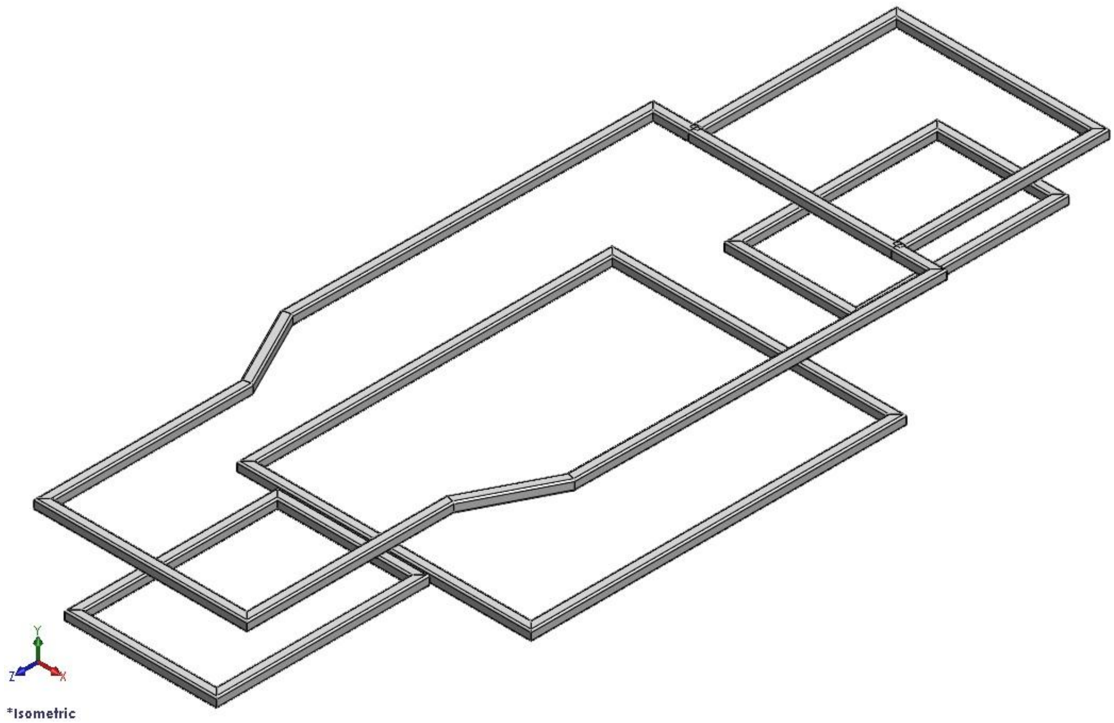


Figure 38 Horizontal Planar sections are welded first

Once the flat horizontal sections are complete then they need to be joined together with the vertical plane members. By using square tube for the horizontal sections these upright members can also be cut simply with a mitre saw rather than requiring a “fish mouth” joint which would be needed if round pipe was used for the horizontal sections.

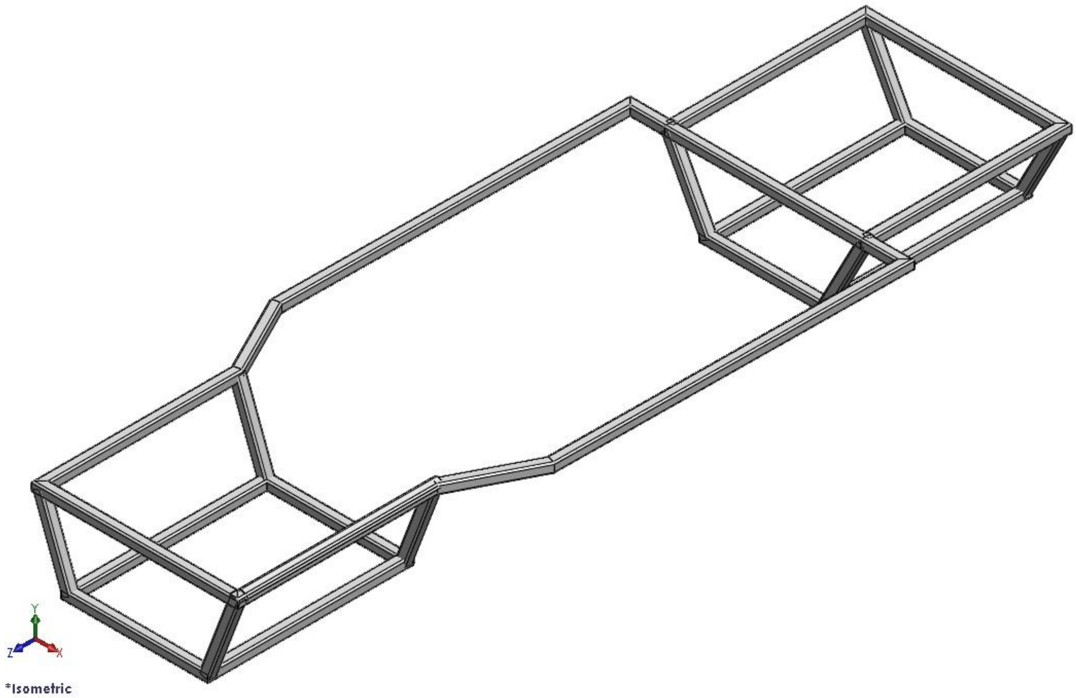
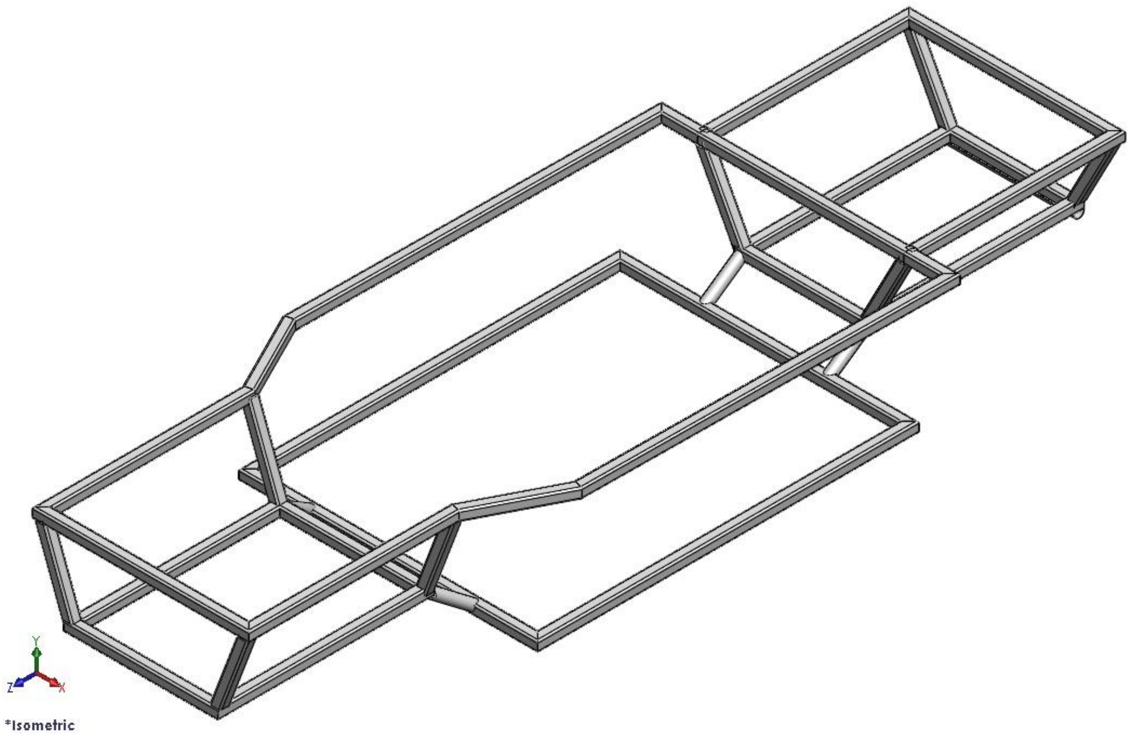


Figure 39 Front and rear lower sections attached to main horizontal section

The front and rear sections then need to be spaced up from the ground by 70mm. This allows the lower centre section to be added while clamped to the ground, the small connecting members can then be welded into place. These appear to not line up with a node in the chassis, however they will connect to vertices of the battery boxes.



With the horizontal sections in place the roll hoops need to be added, which as mentioned earlier must be constructed from a single uncut piece of pipe. The material for the roll hoops is supplied in straight lengths so it must be cut to size and bent into shape. Bending hollow tube is difficult as the tube must maintain its structural integrity in the bends and not have any kinks or creases in the tube walls. This is an FSAE rule requirement and also a safety concern. If there is any damage to the pipe during bending it could significantly weaken the roll hoop which may cause it to not sufficiently protect the driver in the event of a roll over or accident. Initially a three point press bend was tried but this was not very effective and it caused the pipe to kink instead of forming a smooth bend. To make the bends without kinking the roll hoop pipe a rotary draw bender was used. A rotary draw bender consists of a round die that matches the pipe diameter and has a set bend radius. A second die is drawn around the round die bending the pipe with it.

To include the roll hoops into the frame the top horizontal section is notched at the rear for the rear roll hoop and at the middle inside for the front roll hoop. Notching involves making a semi-circular cut in the frame member for the round roll hoop to fit into. The front bulkhead extension can also be completed at this stage.

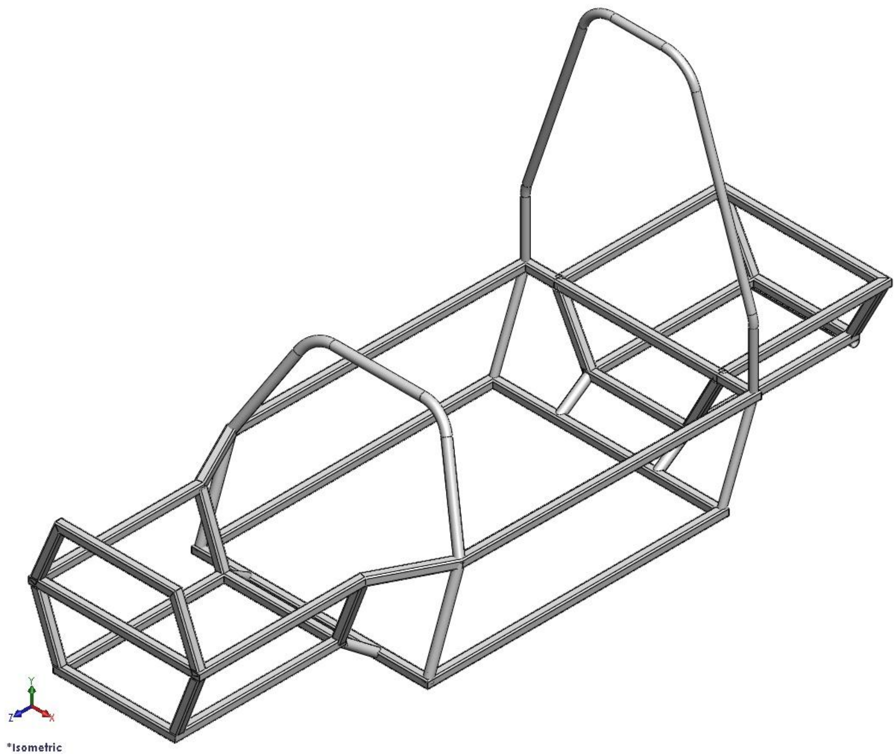


Figure 40 Roll hoops then bent into shape and added to the rest of the frame with the top section of the bulkhead

With the roll hoops in place the bracing for the roll hoops and the side impact diagonal members can also be added.

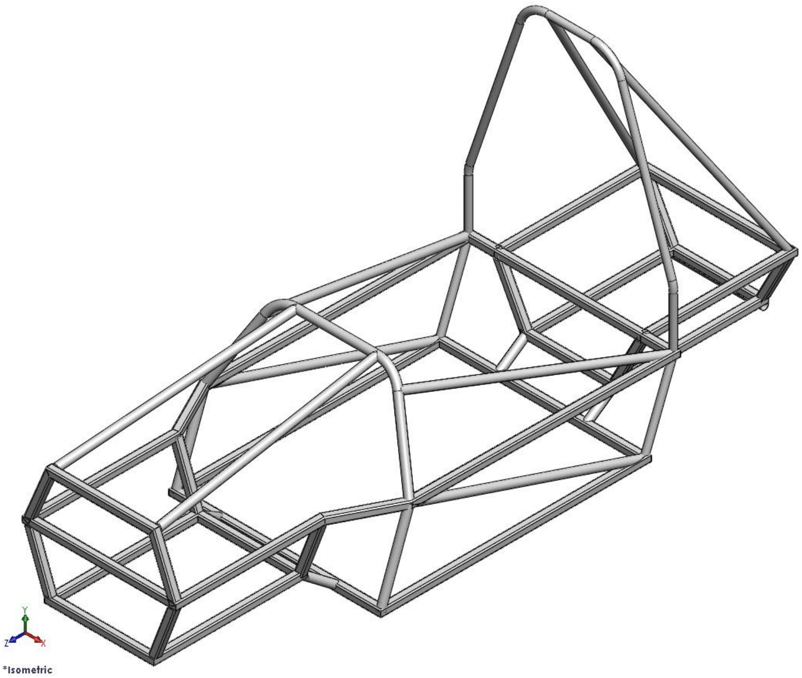


Figure 41 Roll hoop supports added along with side impact diagonal members

This completes the basic layout of the space-frame, the remaining diagonal members and triangulation can then all be cut to shape and added to the frame. The shoulder harness supports and suspension spring and rocker mounting can also be welded into place.

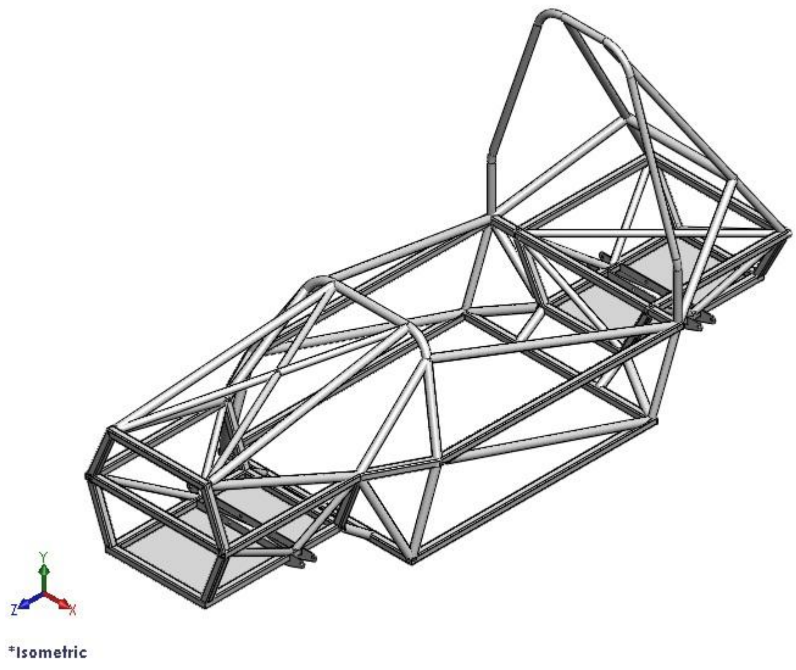


Figure 42 Completed Space-frame

With the space-frame complete, the sheet metal battery firewalls can be bent into shape then spot welded into the frame. Spot welding is used because it is much quicker and easier than the arc welding (Black, 2008). The seat can also be bent by hand over a round form and stitch welded to the sides of the battery boxes. Finally the 1.5mm sheet steel anti-intrusion plate can also be welded to the front of the front bulkhead. This should be done last as it will restrict access for welding the front portion of the seat in place.

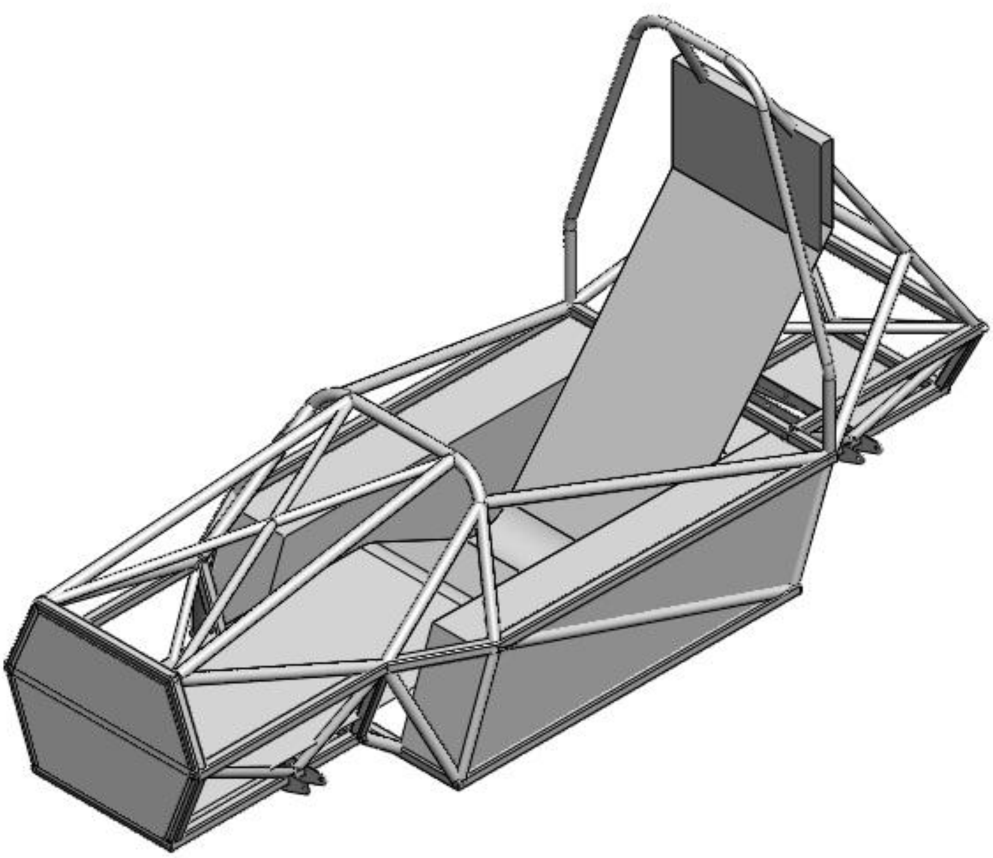


Figure 43 Complete Chassis

Work completed

At the time of writing a significant amount of construction work has been completed on the chassis. The Space-frame part of the frame is nearing completion with the basic layout complete.

During the construction phase of the project, very few changes had to be made to the design which indicates that the design was practical. Potential manufacturing issues were dealt with in the design stage of the project and as such the construction was not slowed by having to think of solutions to unforseen problems. Some minor changes have been made to the design, but most of these involve slightly moving the attachment point of a member so it connects right next to a node rather than directly on it. Doing so reduced machining and welding time but did not significantly weaken the joint.

Slight warping occurred at times during construction but on the whole, by following the process outlined in the welding section of this document no significant warping has occurred.

Figure 44 Image of the part-completed frame on display at the Royal Show for sponsor Swan Energy

Safety

Construction

The safety of the workers who construct the chassis design is an important issue for the designer to consider, to make the construction process as safe as possible a set of guidelines for construction should be implemented.

The key processes involved in the construction of the chassis are:

- Cutting
- Welding
- Bending

The construction of the chassis will take place in a workshop environment so closed shoes should be worn by all people in the workshop at all times. Any person using tools in the workshop should ensure that they do not have any loose clothing or jewellery which may become tangled in machinery leading to serious injury or death.

As mentioned in previous sections much of the cutting can be done on a mitre saw due to the use of square tubing. When cutting with an automated mitre band-saw several safety precautions should be taken. The pipe should be securely clamped into the saw's holding clamps for cutting to ensure the piece does not get thrown out of the tool if the blade catches on the work-piece. Safety glasses should be worn by anyone near the saw while it is cutting to protect them from flying chips that may be thrown off the work-piece. Before starting the saw, the operator should ensure that their own and others' hands and all other body parts are well clear of the saw to avoid being severely cut by the blade. Where tubing is being cut to attach to a round member it needs to be cut with a notching tool. This tool is like a hole saw but it is held in its own jig that also clamps the work-piece in place. The same precautions as using the mitre band-saw should be taken when using the notching tool.

Welding the joints in the chassis is potentially very hazardous work. Welding emits very bright light including ultra-violet light, if care is not taken than people near the welder may experience flash-burns to their retinas or even sunburn on their skin. To prevent this welding should be done away from other workers and the welder must wear clothing that covers all exposed skin. A welding mask must be worn when doing any welding. Welding also makes the work-piece very hot (the weld region reaches the metal's melting temperature of ~1500°C (Callister, 2007)) so gloves made for welding must be worn when handling any work-pieces that have been welded. Due to the mass and cooling rate of the steel, a welded work-piece will stay hot for several minutes so to ensure no person is burnt by handling a recently welded work-piece, hot parts should be cooled in a designated area. If the hot work-piece cannot be isolated from all people in the workshop then they should be informed that a particular part is hot and should not be touched.

Bending the roll hoops is not as dangerous as cutting or welding but the process still involves risk. The pipe bender applies significant amount of force to the work piece so there is a hazard of crushing fingers in the bender, to avoid this, a check should be made before bending to ensure that the operator's fingers are safely located on the bender's handle. The bender causes the work-piece to undergo significant strain and if there is any coating (such as paint or rust) on the piece then this may chip and fly off, this could potentially injure someone's eyes so safety glasses should be worn when operating the pipe bender.

Operation of the completed chassis

Once the construction of the chassis is complete then there is a risk of the chassis failing in use which may injure the driver or bystanders. Failure of the chassis may involve a weld breaking under normal operation which could lead to a part or complete loss of control of the vehicle. In an effort to ensure this does not happen, the completed chassis should be tested in a controlled environment before being used. The testing should stress the chassis in a similar way to how it is stressed in use and as such it should be tested in torsion. Doing so will give a quantitative indication of how the chassis performs by giving a measured value for the torsional stiffness in N/m. The testing procedure will stress the frame and all the welded joints to a higher amount than they would be in normal operation, if the chassis does not fail or yield in any way then the chassis can be considered safe.

The chassis may also be involved in an accident, colliding with a barrier or rolling over, it should be sufficiently strong to withstand the loads induced by the accident. The FSAE rules for the minimum sizes of some chassis members are chosen such that the chassis should be strong enough to survive these types of collisions. The chassis designed in this project uses larger and stronger members than required by the FSAE rules and also has more supports connected to the front bulkhead than required by the FSAE rules. This means that the REV chassis will be much stronger in the event of a front-on impact than the FSAE rules require. An impact attenuator is also required by the FSAE rules to be mounted to the front bulkhead which dissipates some of the energy of the impact and reduces the accelerations. As discussed the use of square tubing in the side impact structure makes it much stronger than the minimum required by the FSAE rules.

The location of the batteries and the lack of a tall petrol engine mean that the completed car will have a very low centre of gravity, which means that it is highly unlikely the vehicle will roll over given that it only competes on flat tarmac surfaces. The roll hoop used in this chassis design is also larger than the minimum required by the FSAE rules and as such should be able to withstand a roll over if one were to occur. The design section of this document also shows that the designed roll hoop can withstand the force of a roll-over and should protect the driver. As shown in the weld testing section of this document, if a weld is stressed to its yield point, it undergoes ductile failure rather than brittle fracture. Ductile yielding is much safer than brittle fracture as if a chassis joint were to crack and fail in a brittle manner then the driver may be cut or impaled on the sharp fracture.

Torsion testing

To test the frame in torsion it must be stressed in the same locations that it would be stressed when in use. Loads in the chassis are induced by the suspension springs and rockers when the car is in use so the test should simulate the loading that the suspension springs and rockers would apply. To apply the load, three of the suspension supports should be fixed to pivots on a supporting rig and the fourth suspension support should be loaded by adding weight to the support. The displacement of the frame at the loaded suspension support is measured with a dial gauge and the torsional stiffness of the chassis can then be calculated by converting the applied load into a torque moment using the distance between the load and its adjacent support.

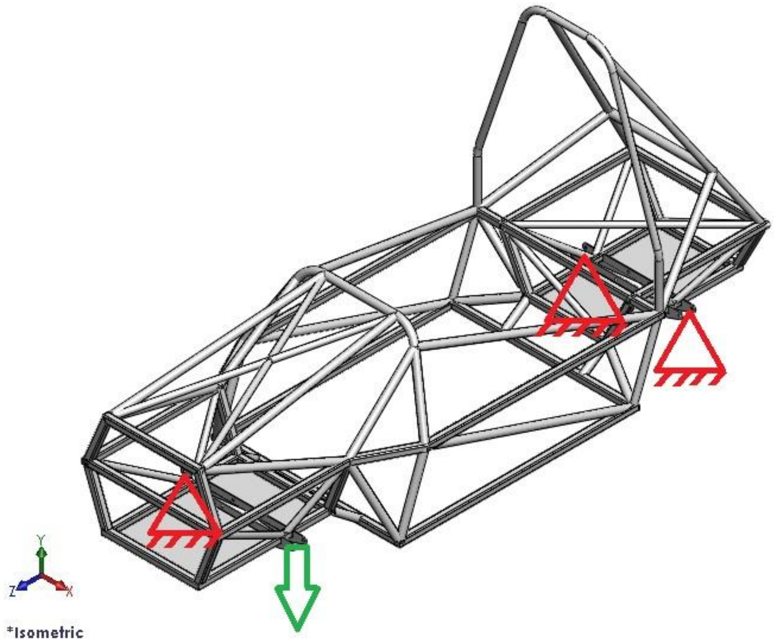


Figure 45 Torsion test procedure for competed chassis

Weld Testing

To ensure the structural integrity of the completed space-frame will not be compromised buy the welded joints it was decided that weld samples should be examined and tested. The welds are located at the nodes and corners in the chassis and as such are the most highly stressed parts in the frame (see Triangulation and Stressed Skins section). If there are any defects in the welds such as cracks, voids or porosity this could lead to failure of the frame. A weld failure is a serious safety concern, the consequences of a weld failure range from a decrease in frame stiffness to catastrophic failure of a safety component such as the roll hoop which could lead to serious injury to the driver.

Visual inspection and destructive testing of a weld sample is the cheapest and easiest way to check the quality of the welds. It involves a very small amount of material and very little time is needed to prepare the samples. To achieve the best indication of the welds in the chassis, the weld samples were welded by the same person that completed the welds in the chassis, using the same equipment and technique.

Two different samples were prepared and inspected, one wilt the square chassis tubing welded to itself, the sample consisted of the square chassis tubing welded onto the roll hoop tubing. Sample preparation for the square-square sample involved cutting a small length of the same tubing used in the chassis to size. The tube sample was then cut in half and the halves were then joined back together by welding. To inspect the welds a cut was made through the weld perpendicular to the weld and the cut face was then polished.

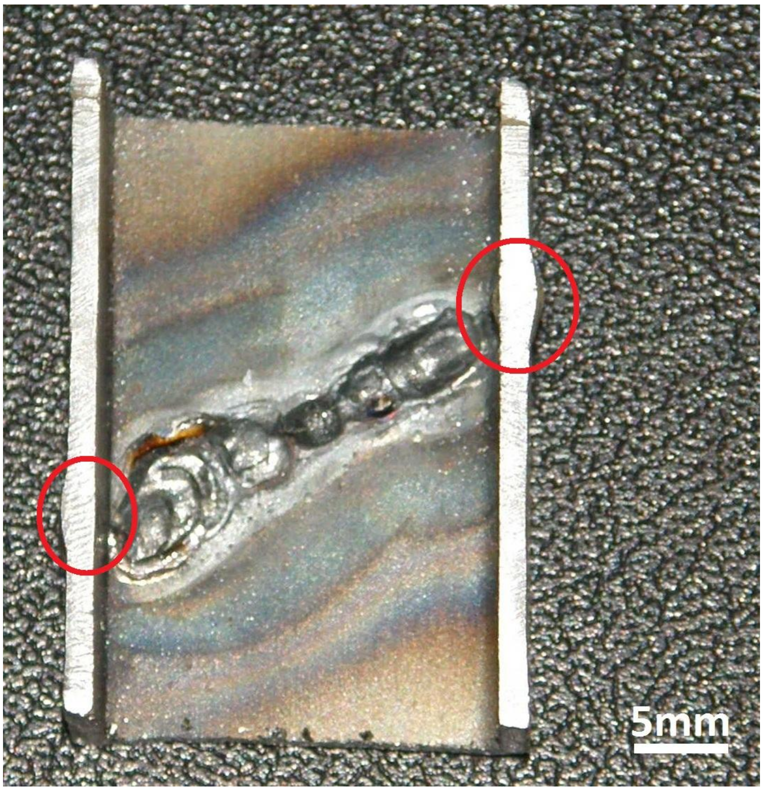


Figure 46 Weld sample, butt weld of square tube

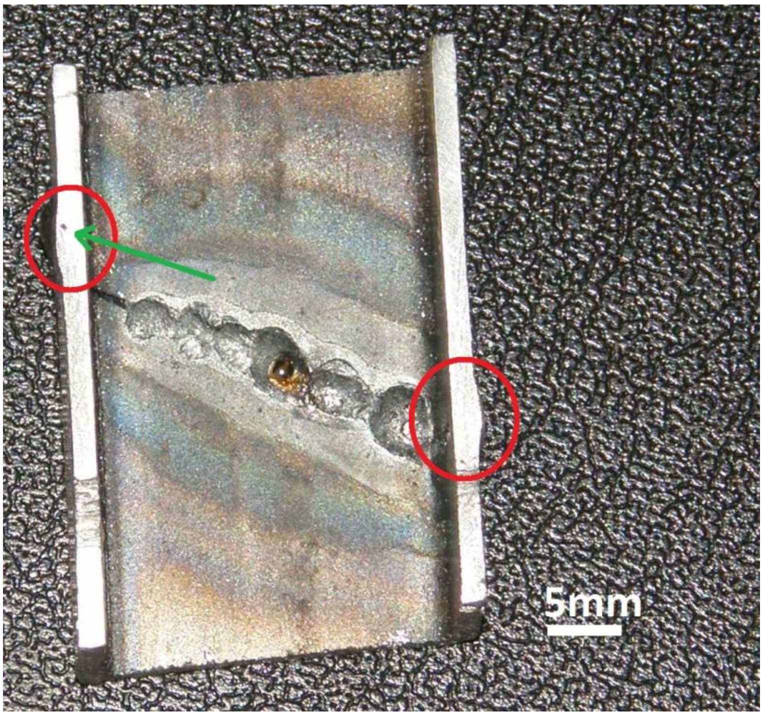


Figure 47 Weld sample, butt weld of square tube. Small defect indicated with green arrow

Figures 46 and 47 show the weld sample for the square tube butt welded to the same square tube. The weld has sufficient penetration where the entire wall of the tube has melted and fused across the joint. This is evident even on the un-cut part of the weld visible between the two cuts, thee weld was made on the opposite side of the tube but the weld has visibly penetrated the wall and protrudes out the other side slightly. In one half of the weld there is a small defect in the weld likely caused by an air bubble that was trapped in the weld. This will weaken the weld but it is not likely to cause failure in the weld as the volume of metal in the welded joint is still greater than in the un-cut wall. The defect does show that the welds are not perfect though and hence the completed welds in the chassis should be checked with ultrasonic testing to ensure they are of sufficient quality.

To prepare the second sample, a piece of the square tube was cut to size and then notched with a tube notcher which makes semi-circular shaped cut in the end of the pipe, so it fits perpendicularly onto the roll hoop tube. This welded sample was then also cut perpendicular to the weld to examine for penetration and possible defects.

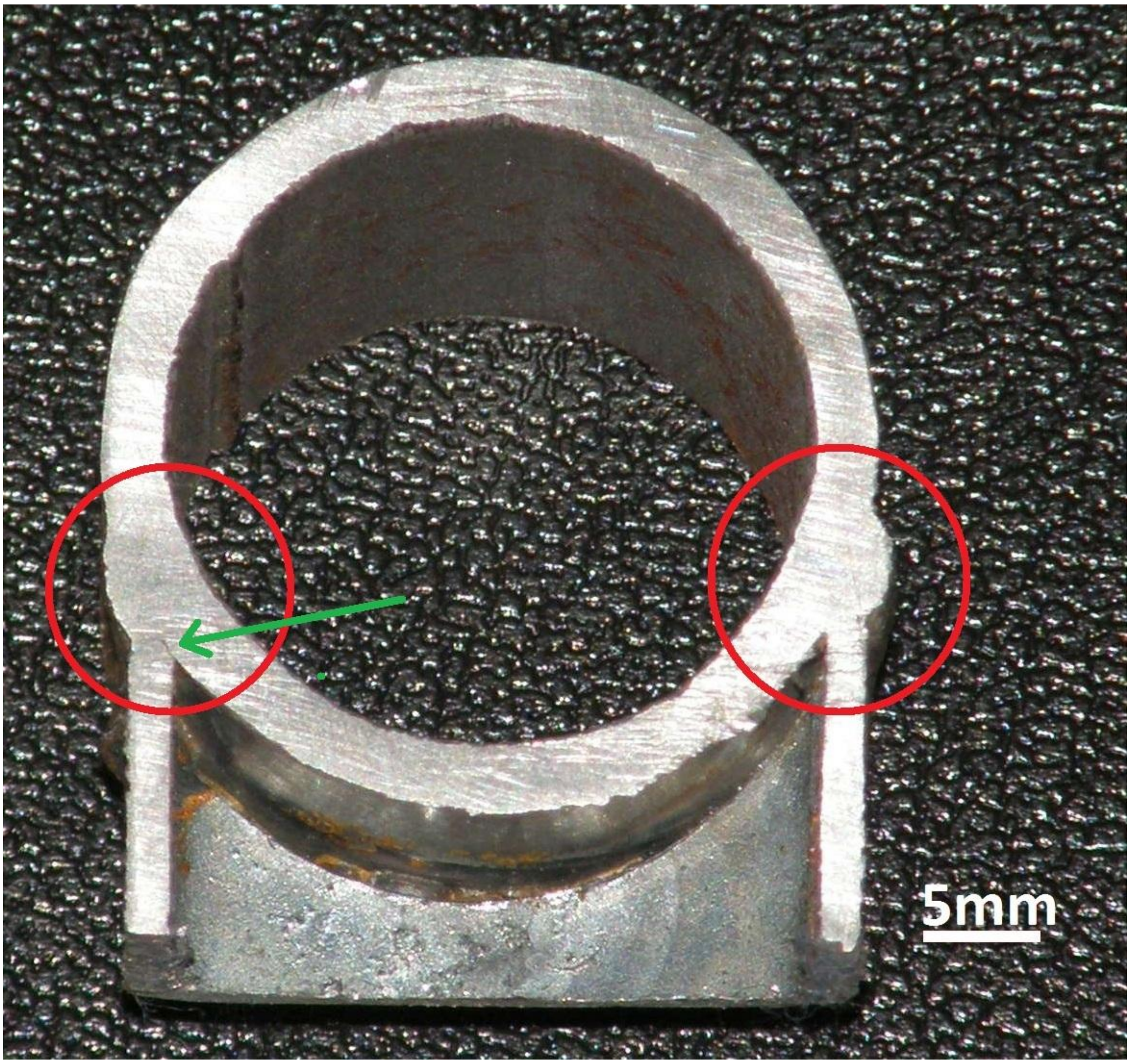


Figure 48 Weld sample square tube welded to roll hoop tubing. Incomplete fusion indicated with green arrow

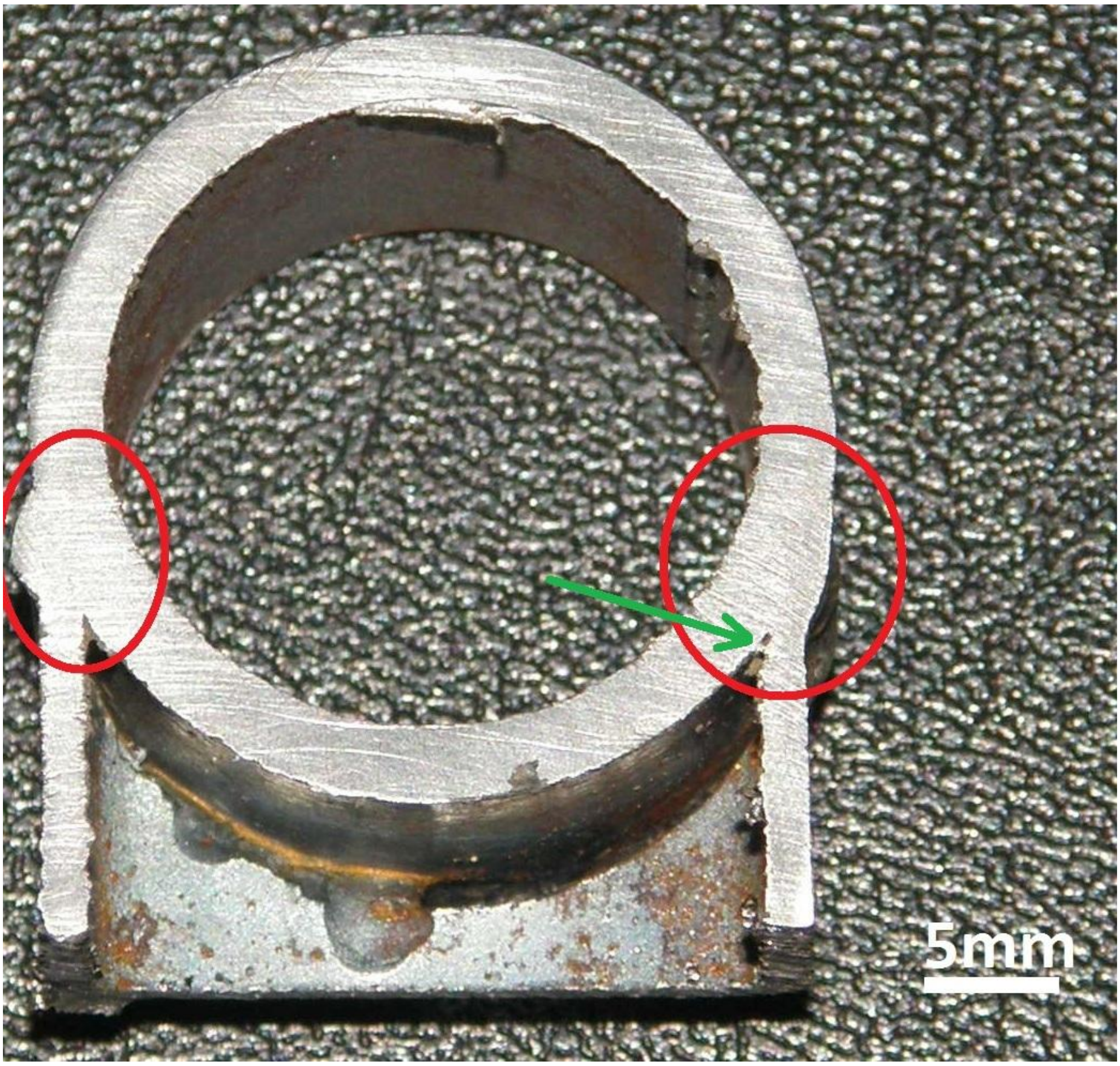


Figure 49 Weld sample square tube welded to roll hoop tubing. Incomplete fusion indicated with green arrow

There is no sign of porosity in the weld between the roll hoop and square tube however on one side of the weld it seems that there is not complete penetration along the tube/weld interface. This is much more serious than the small bubble found in the first weld sample, the defect has a sharp end which could potentially lead to cracking or more likely tearing in the weld as it is a ductile material. The weld on the opposite side to the defect is a much better weld with complete fusion between the two pipe sections.
To ensure a similar defect does not occur when welding the chassis, a higher weld current is used when welding members to the roll hoop material. A higher current melts a larger area of metal for better fusion between the two mating surfaces. More weld filler should also be used to increase the volume of the weld metal so if any defect is present there is more surplus material that can support any stress on the weld.

To test the mechanical behaviour of a sample weld it placed in a press for a three point bend. A three point bend is a good test of the weld as it introduces multiple types of stress into the weld which more accurately represents how a weld in the chassis will be loaded. The three point bend applies a compressive force to one of the weld faces, the reaction to this is a varying stress (from compression at the top to tension at the bottom) in the welds on the sides of the square tube and a tensile force in the weld along the bottom side of the tube.

The test was performed on a press with a pressure gauge that displays the force being applied however the gauge is not sufficiently accurate to calculate the exact stress being applied. Due to the gauge's inaccuracy the test was only intended as a qualitative test. In the test the press applied roughly 2 tonnes of force to the sample at the point of yielding. While this is not an accurate measure of the stress, the force applied is similar to what we would expect for an un-welded sample in the same conditions. So the sample has not been un-expectedly weakened significantly by the welding.

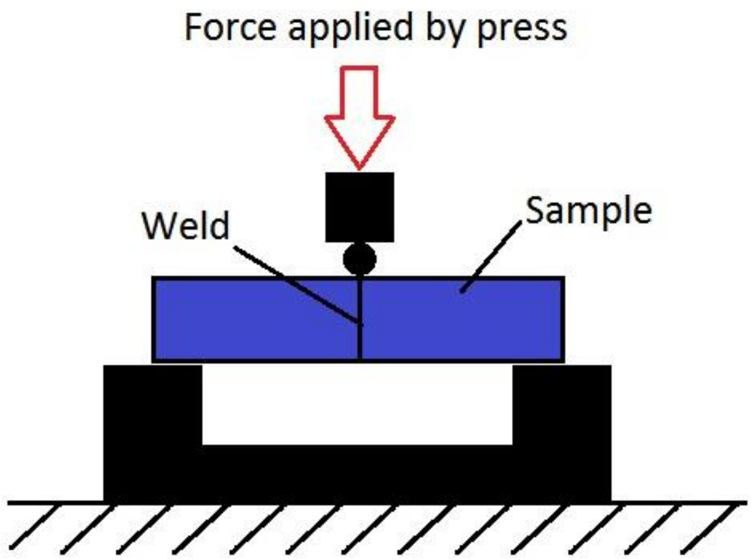


Figure 50 Schematic Diagram of 3 point bend test

Figure 51 Three Point Bend weld sample

Figure 52 Three Point Bend weld sample

Figure 53 Three Point Bend weld sample

The failure mode of the sample is buckling of the vertical walls, which is a ductile failure, a clear sign that the weld has not made the metal brittle. There are no signs of fracture anywhere in the sample and no cracks have formed in the weld/body interface area. This is important for the safety of the finished chassis and vehicle as it means that the chassis is not likely to fail in a catastrophic brittle manner. If the vehicle was involved in a collision or roll-over the chassis would undergo ductile yielding as the sample did, dissipating the energy of impact. If the weld had caused the metal to become brittle or if the weld itself wasn't strong enough a crack or tear would likely form along the weld at the bottom surface of the sample where the tensile stress is greatest in a three point bend.

Conclusion

This project achieves what it set out to do, a chassis design is complete and meets the FSAE rules. The chassis design is a unique one using the battery boxes as a structural component to stiffen the weaker, open cockpit section which has not been done before if FSAE. Construction of the design has progressed well and required only minimal changes to be made to the design. The welding technique used in the frame has been proven to be safe and will not undergo brittle failure. The completed space-frame weighs

Future work

Construction

At the time of writing, the majority of the space-frame construction has been completed. Some triangulating members need to be added to the frame and the sheet metal battery boxes and seat need to be bent into shape and welded into the frame. These will be completed by the end of 2011 however the car will no longer be entering the 2011 FSAE competition so the deadline is less strict now.

Chassis testing

The chassis testing mentioned in the safety section needs to be performed to measure the chassis' performance and to ensure it is safe. The torsional test will be performed on the frame both before and after welding the battery boxes into place in order to get an experimentally recorded value for the amount that they improve the stiffness of the chassis in practice.

Ultrasonic weld testing

To further ensure the safety of the chassis and the quality of the welds the completed frame should have the welds ultrasonically tested. This testing would have to be outsourced to a third party but would provide a very accurate way of testing the welds in the chassis itself. Testing of sample welds as mentioned is useful but does not guarantee the quality of the welds in the frame, even though the welds were completed by the same person with the same technique, many of the welds in the frame a in awkward positions with limited access which may have reduced weld quality. Ultrasonic weld testing can detect defects such as voids and cracks within the welds (Black, 2008) which could weaken the structure. If any welds are found to have large defects then they will be ground back and re-welded and re-tested.

Tuning

As the chassis will no longer be competing in the 2011 FSAE competition, there will be another year for the chassis to be tested by driving this leaves enough time to make changes to the chassis if necessary. It is unlikely that any significant changes will need to be made to the chassis but things like moving the batteries forwards and backwards in their boxes to adjust the car's centre of gravity can be done to try and make the car as quick as possible.

Future designs

If the REV team decides to continue with using hub-motor powered electric cars then the chassis designed in this project provides a good starting point for future designs. Due to the nature of the rules, it is unlikely that it would be possible to significantly lighten the frame or significantly increase its torsional stiffness. Investigations into the use of alternative materials may improve stiffness without increasing weight so this would be an area worth investigating. This design uses sheet steel stressed-skin panels in some areas, replacing these with carbon fibre composite panels would likely make the sections stiffer and lighter, the same can be said for the battery boxes.

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