Structural design and analysis of a lightweight composite solar car

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Declaration

I, **PD Brand 21140472**, declare that this thesis is a presentation of my own original work.

Whenever contributions of others are involved, every effort was made to indicate this clearly, with due reference to the literature.

No part of this work has been submitted in the past, or is being submitted, for a degree or examination at any other university or course.

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PD Brand

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Abstract

In 1987 the first world solar challenge was held in Australia with the aim of increasing the awareness of alternative energy transport and furthering the development of these technologies. One of the important contributing factors to the performance of a solar car is the weight, the largest of which is concentrated in the structure of the vehicle.

In 2012 the North West University made its first attempt at the South African Solar challenge by building its first solar car dubbed the Batmobile. During the race the poor performance of the car was attributed to a number of reasons of witch the weight was a large contributor. Thus the need arose for the development of a new frame and body that saves as much weight as possible without compromising the safety or reliability of the solar car.

Through the use of the finite element modeller Patran and the solver Nastran, a frame for a new solar car was designed and analysed to reduce the weight, while maintaining good reliability.

The method used to reduce the weight of the car is based on an iterative process of placing design loads on the structure and changing the geometry or composite material layup to reach a minimum weight and maintaining an adequate safety factor.

By the use of this design method a lightweight solar car frame was constructed with a weight of 65kg this equated to a 75kg weight saving over the old car of a 140kg. The new solar car completed the South African and Australian Solar challenges without any structural failures.

Key words: Solar car; Composite structural design; Finite element modelling; Light weight structure; solar vehicle structure.

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1. Chapter 1: Introduction

1.1 Introduction

In 2012 the North West University (NWU) competed in the South African solar challenge, with a car designed and built by pre-graduate students. This car was able to complete 1087 km of the 5300 km journey. Using inadequate solar arrays and construction methods the vehicle required several times more power than what was available to run. This can mainly be attributed to the weight of the car and the use of inefficient electric motors. The main components that make up the weight of the car are the body, the chassis, the motors, and the electric systems. The chassis and body were the largest contributing components. This was due to the design team's inexperience in the use of composite materials and its use in chassis design.

The focus of this study was placed on the chassis structural components of the solar vehicle and the optimization thereof. The new solar car has been designed with the reduction of weight as the primary design criteria. The reason for this criterion is based on the nature of solar power, which is severely limited and can range from 800W to 2kW.

Rolling resistance is a measure of the force necessary to move the tyres across a surface. The inertia of the car is another contributing factor to the force that had to be overcome to move and accelerate the car. Both of these forces are directly related to the weight of the vehicle. Thus if the vehicle is too heavy the power needed to move the car would exceed the energy supplied from the solar array.

The main objective of any solar car manufacturer is to design an efficient, "winning" vehicle. Design considerations included hundreds of trade-offs, but certain elements were essential, such as reliability which is an important design factor. A vehicle that performs well without any major breakdowns would cover the race distance in less time.

1.2 Problem statement

The NWU intends to continue its participation in the Sasol Solar Challenge with the ultimate goal of competing in the World Solar Challenge. With this in mind the need to design and optimise a new and improved frame was identified. During the 2012 Sasol Solar Challenge the weight of the previous car had been identified as one of the most important aspects that influenced the performance of the car and the total distance travelled in a day. Thus the need existed for a new chassis design with reduction in weight as the main objective, without compromising the safety of the driver and the overall reliability of the car.

The large surface area needed for the placement of the solar collectors; required some other aspects of the design to be compromised. The shape of the aerodynamic design will have to accommodate the maximum exposure to the sun; the aerodynamics of the vehicle is based on those limitations. The design of the frame is similarly dependant on the aerodynamic shape of the car and a suitable frame to be designed for the optimised shape.

1.3 Objective of this Study

The objectives of this project are:

- The development of a structure for the next solar car to compete in the 2014 Sasol solar challenge.
- Reducing the weight of the new frame to half that of the previous frame. To be competitive with international teams with frame weight of 70kg. The previous car had a frame weight of approximately 140kg.
- Maintaining the reliability and structural integrity of the solar car.
- The new frame has to comply with the regulations on design and safety for both the South African Solar challenge and The World solar Challenge.

1.4 Project motivation

This project can serve as a platform for continued development of new technologies and research opportunities. Due to the nature of competitive motor sport and the drive to gain an edge over the competition can stimulate the creation of innovative new technologies and evermore efficient systems.

Because of the media involvement of solar racing, large amounts of public exposure can be gained. This in turn provides financial support from industries and corporations as sponsors for the solar car project and other research projects. The stimulation of further cooperation between the North West University and these corporations can be expected.

Moreover the project can provide a test bed for new and existing technologies developed at the university. This can also serve as a showcase of these new technologies and innovations.

1.5 Limitations and scope

The constraints placed on the development team are some of the factors that can limit the overall performance of the solar car project. These factors can include budget and time constraints, physical and manufacture limitations. This can all define the development process of the solar car.

Budget constraints are a severe limiting factor in the development process of a solar car. The lack of required funds can prevent the development team from using the best technologies in the manufacturing process of the frame and substructures. This problem can be overcome by the development team with the intelligent utilisation of existing resources.

The time constraints available for the development of the solar car, is limited to the time between each racing event. The invested effort into each of the processes of the development has to be limited, to insure that a suitable car can be built and tested in time for the October 2014 solar challenge. This provided little less than two years for the development, manufacture and testing of the car for the event.

Large and expensive equipment will not be available to, or suitable for the manufacture of a solar car. Thus the construction will be largely based upon the hand-layup process of manufacturing, and requires the design to incorporate these into the process of development.

1.6 Background

History of Solar Racing

During 1983 Hans Tholstrup and Larry Perkins completed an epic trek from Perth to Sydney Australia in a solar powered car thus pioneering the solar racing as a sport. This event began the solar car races, and was designed to increase public awareness into alternative energy transport. [1]

The 1987 Australian World Solar Challenge saw 23 participants inaugurate the first such race followed by the European Tour de sol, the American Tour de sol, and the SUNRAYCE. Some spectacular corporate and college vehicles participated in these early events and examples are shown below.

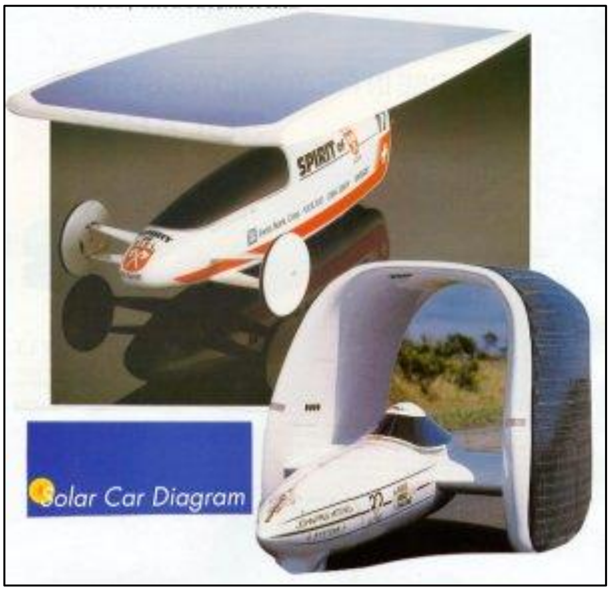

Figure 1: Solar car designs from the first solar races [1]

From 1987 the performance of the vehicles improved rapidly with average speeds increasing from 42 km/h to 76 km/h in 1996. The main concern of solar powered vehicles is the cost involved in the production of cars with higher average speeds. The main area of expense is the solar cells of which the top grade arrays are produced in laboratories.

These vehicles with top class solar arrays are not intended for commercial production, they are only for optimized performance and efficiency in the specialised racing cars [2]. The solar cars participating in these challenges are far too expensive for commercial use and require specialised equipment and personnel to maintain and operate. The goal of the competition is to stimulate development in solar energy to eventually create commercially viable solar vehicles.

Materials

From the study into different materials done for Ford by the University of Liege, the following cost to weight saving comparison was found and used as background to compare and evaluate different materials. From this one can see that composite materials and more precisely the fibre based composites poses the greatest weight saving properties with a potential weight saving of nearly 60%.

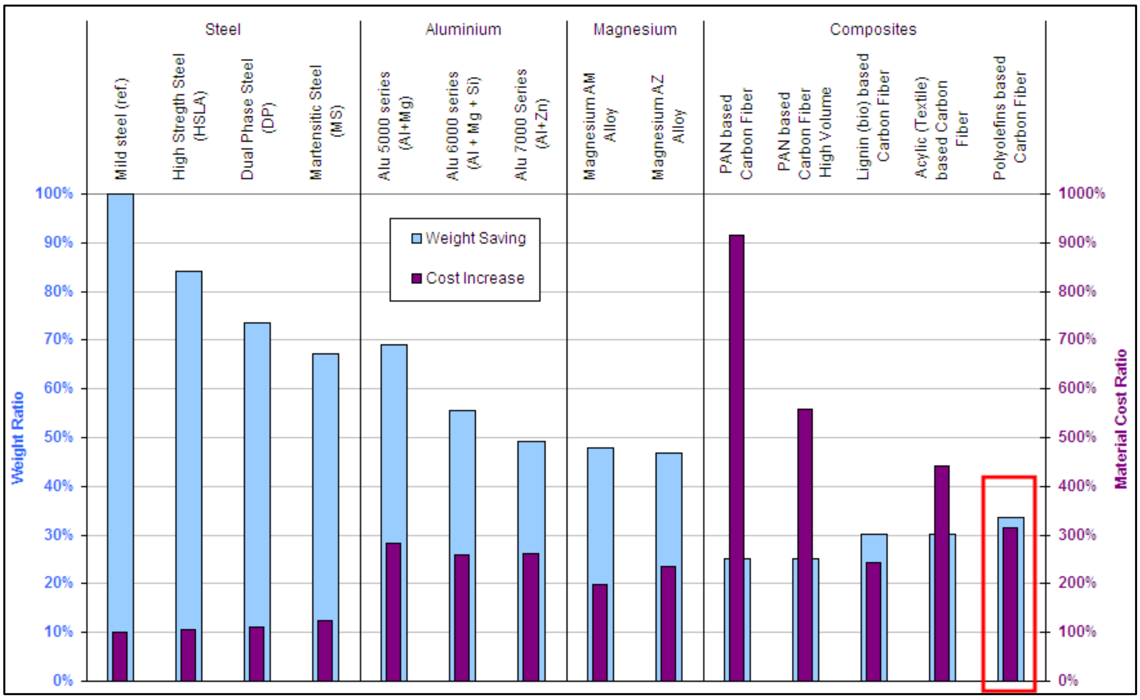

Figure 2: Cost to weight saving comparison [3]

Solar cars are built with a single purpose in mind - to race. As with any competitive racing sport the weight of the car is critical to performance. No expense should be spared to insure the car is as light and reliable as possible. Demonstrated in the following description - the vehicle mass is present in nearly all the resistive forces acting on the car, making it one of the largest contributors to energy used.

Solar cars power source (The solar array) has a limited maximum power output that can overcome the forces acting on the vehicle during motion. These forces are briefly summarised in equation 1.1 below as the drive force needed to overcome the resisting forces acting on the car.

$$F_{Dr} = F_{grade} + F_{rolling} + F_{aero} + F_{inertia}$$

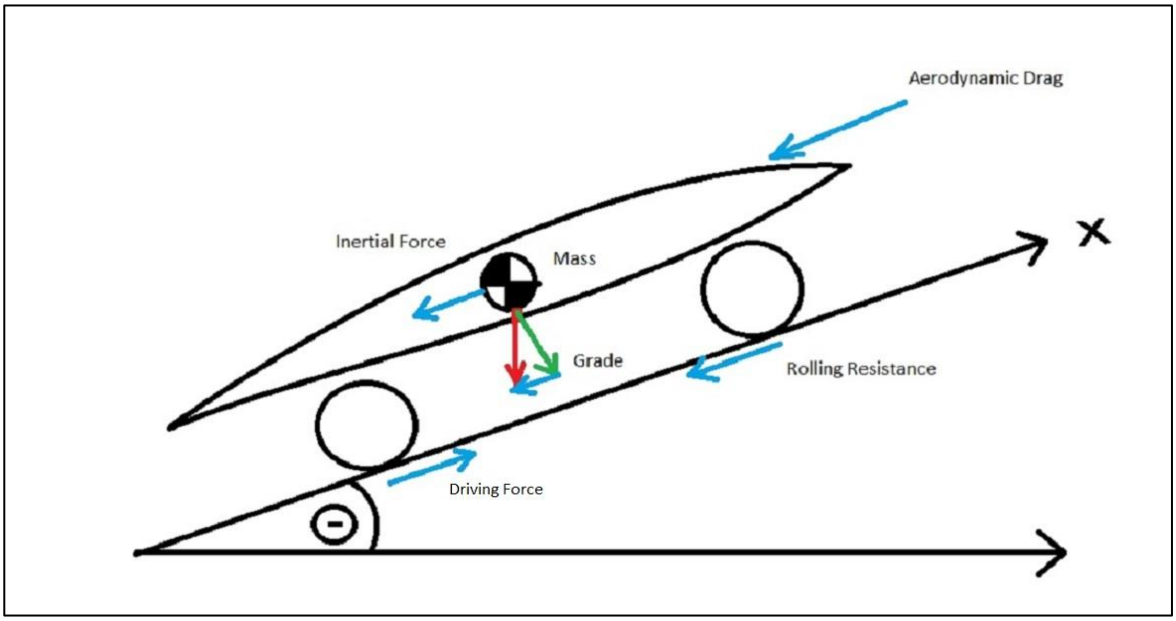

Figure 3: Tractive Force

The forces depicted in the figure above are considered the main forces that resist movement or acceleration. These are not the only forces acting on a vehicle during motion but (they) are the largest contributors thereof and are most commonly used in the calculation of the minimum force needed to move the vehicle. [4]

The following equations express the variables for each of the forces that make the minimum driving force required to move or accelerate the vehicle.

$$F_{grade} = mgsin\theta$$

$$F_{rolling} = c_{rr_0}mg + c_{rr_1}mgV$$

$$F_{aero} = \frac{1}{2}\rho C_D A_f V^2$$

$$F_{inertia} = mM_i\frac{dV}{dt}$$

The incline angle will not always be present when the vehicle is in motion, but does have an important effect on the energy consumption of the vehicle and should be accounted for. The rolling force, more commonly known as the rolling resistance, is a term that will always be present when the vehicle is moving.

The term aero is the force known as the aerodynamic drag experienced by the body of the vehicle as it moves through the air and it increases with the square of the speed of the vehicle thus increasing exponentially. The inertia term is the force dependant on acceleration and mass of the vehicle and needs to be overcome to accelerate the vehicle at a desired tempo. [3]

Use of composites

Team Helios of Lille France used cold curing epoxy system to produce its fourth vehicle. The car had to be produced from lightweight, but robust parts that are tough enough to withstand the environmental conditions encountered - such as very high temperatures. The body also had to be strong enough to support the weight of the solar panels and be able to withstand the stresses put on the vehicle during the race. To make the body of the car, a foam rubber scale model of the vehicle was produced from a computer model of the car. Fibre glass was then placed on the model before a vacuum pump was used to form the mould. Carbon fibres are placed on the negative mould. A vacuum pump is then applied to the mould and once the carbon fibres have dried, the composite part is turned out of the mould. [5]

Figure 4: Team Helios solar car [5]

What is composite material?

The most basic composite is one which is composed of two or more element`s working together. This produces a material with properties that differs from the elements singular properties when used on their own. Composites in practice, mostly consists of a bulk material (Matrix Element), and a reinforcing material of a different element. The second material is added primarily to increase the strength and stiffness of the matrix. This reinforcement is usually in fibre form.

The most common composites can be divided into three main groups:

1. Polymer Matrix Composites (PMC’s) – These are the most common form of composite forms. Also known as Fibre Reinforced Polymers (FRP) – these composites use a polymer-based resin as the matrix and a variety of fibres such as glass, carbon and aramid as the reinforcement. This will be the subject of discussion in this report.
2. Metal Matrix Composites (MMC’s) – Increasingly found in the automotive industry, these composites consist of metals such as aluminium, reinforced with particles such as silicon carbide.
3. Ceramic Matrix Composites (CMC’s) – These materials are commonly used in high temperature environments, using ceramic as the base and reinforcing it with short fibres such as those made from silicon carbide or boron nitride. [6]

Polymer Composites

Resin systems have a limited use in the manufacturing of structures due to the fact that they do not have good mechanical properties, even far less when compared with other materials such as metal. Resin has other desirable properties in the manufacturing process; the ease of forming into complex shapes is one of the desired properties.

Materials such as aramid, glass, and carbon have extremely good mechanical properties, such as high tensile and compressive strength. The drawbacks of these materials are the fact that these sought after mechanical properties are not very apparent in the solid form of the material. This is due to the fact that the material when stressed forms random surface flaws. This will cause the material to fail well below its theoretical strength. One way of overcoming this flaw is to produce it in fibre form. This will exhibit the materials theoretical strength better. The same random flaws will still occur, but will be restricted to a small number of fibres with the remainder in the bundle still intact. This will better exhibit the desired mechanical properties of the material. However, fibres can only exhibit tensile properties along the length of the fibre, much the same as cables. [6]

When combining the resin systems with reinforcing fibres such as carbon, one can obtain the mechanical properties of both the materials. The resin, which acts as a binder, distributes the applied load to the fibres in the composite and provides the fibres with protection against abrasion as well as impact. The high strength and stiffness, ease of moulding complex shapes, high environmental resistance, all combined with low densities, make the resultant composite superior to metals for many applications. [6]

The combination of the fibre with the resin creates a composite material with elements of the individual properties of the fibre and the resin. [6]

Chassis properties

The chassis of a car must be able to achieve several goals to be considered for use in vehicle design namely:

- Be structurally sound for the expected life of the vehicle. This means not breaking in normal operating conditions
- Provide mounting locations for the suspension and other components to ensure the handling is safe and consistent under operating conditions
- Provide support for body panels and passenger components
- Provide protection for the occupants from external intrusion
- Be as lightweight as possible

Structural stiffness is what makes a good chassis. It defines the handling, integrity, and overall feel of the car. Different chassis designs each have their own strengths and weaknesses. Every chassis is a compromise between weight, component size, complexity, and ultimate cost. Strength and stiffness can vary significantly even within basic design methods, depending on the details. [7]

Solar cars have several unique shapes. The following figure shows the most famous and well-known shapes:

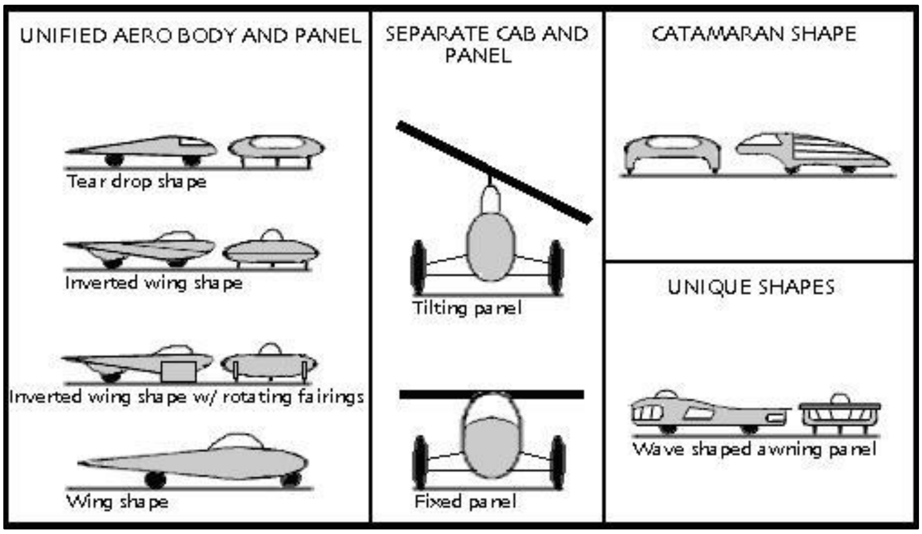

Figure 5: Basic solar car design

2. Chapter 2: Literature Review

2.1 Introduction

The world solar challenge has had a large influence in the stimulation of new technologies and innovations in the alternative energy industries. By creating a need to gain a competitive edge over the competition, the organisers of the world solar challenge have created an environment in which the alternative energy technologies can be developed and tested at an accelerated pace. Through this competition, industry leading corporations and centres for higher education and research have had an opportunity to work together on a mutually beneficial partnership. This partnership has helped in the development and showcasing of new and more advanced technologies.

In this chapter some of these technologies and methods will be reviewed and evaluated for the use on the North West University solar car, while considering the overall objective of this study. In this review the function of a chassis in a solar car, and the different types of chassis and materials was investigated for use in the new NWU solar car.

2.2 Vehicle chassis

The chassis of a solar car is the main structural frame of the vehicle. It connects the various components like the suspension and electronics to the car. There are four aspects that makeup the chassis of a solar car.

- It has to provide mounting locations for the different components of the car.
- Provide a stiff framework for these mounting points.
- Insure the safety of the occupant.
- Most importantly - provide a large area for securing the solar array to the body.

The different components that are important for vehicle operation are connected to the frame. The frame serves as a rigid structure for the mounting locations; this is to prevent large deflection of the components. Large movements of the components may cause interference and prevent it from functioning as intended. To evaluate the rigidity of the frame, the torsional stiffness can be used as an indicator. The torsional stiffness is the degree of twist the frame undergoes when one end is under an applied load and the other is fixed [8].

Poor torsional stiffness of the chassis can have a negative effect on the handling of the vehicle [3]. This is apparent in the setup of the suspension of the car. The suspension can perform as intended, if the frame does not act as an unknown damper. If less force is absorbed in the deformation of the chassis, the loads can be better distributed to the suspension for improved handling [8].

The vehicle chassis provides a safety element to the occupant. It acts as an energy absorbing structure in the event of impacts and rollovers. By increasing the energy absorbing abilities of the frame, the energy transferred to the occupant can be reduced, thus lowering the possibility of injury [8].

2.3 Types of chassis

In this section a few of the different types of chassis will be discussed and their respective properties mentioned.

2.3.1 Ladder Frame

Early motor car designs made use of the ladder frame upon which the passenger compartment was placed. The bodies of these cars did not contribute much to the vehicle structure. These cars relied mostly on the ladder frame to provide all the stiffness (Bending) to the structure of the vehicle [9].

The frames are called the ladder frame due to the fact that they resemble a ladder with two diagonal beams and two or more cross members, as shown in the figure 6.

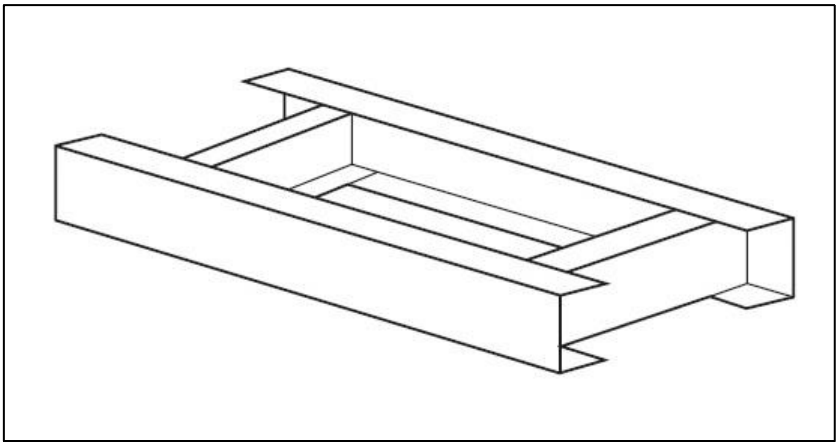

Figure 6: Ladder frame [9].

The main advantage of this frame type is its ability to adapt and be compatible with a large variety of body types. This fame can provide very good bending strength and stiffness using different configurations of beam cross-sections, allowing an efficient use of materials. The problem with these frames is the low torsional strength and stiffness they provide. This low torsional stiffness can be improved by replacing the open section beams with closed section box beams [3].

It is possible to improve the torsional stiffness of the ladder frame by incorporating a cruciform into the design as shown in the figure below. The cruciform frame is made of two strait members joined at the centre. The beams of the cruciform are only subjected to bending loads that are concentrated at the joints in the middle [9].

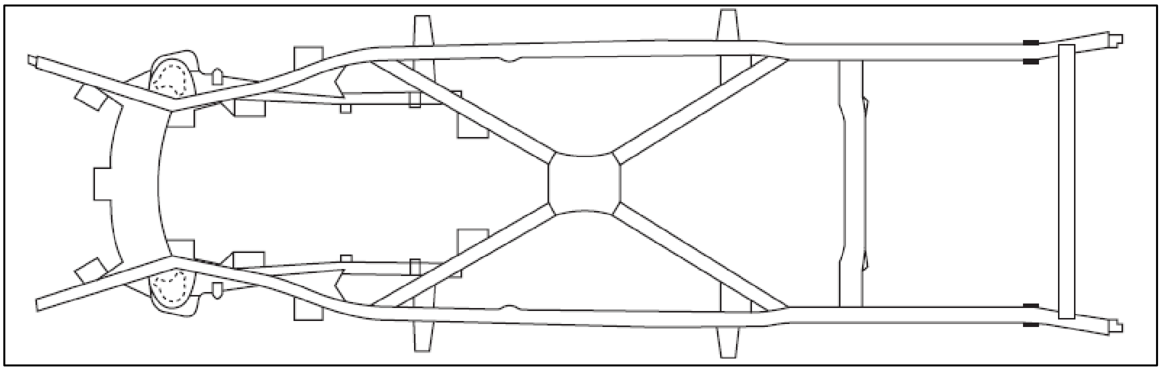

Figure 7: Early ladder frame with cruciform [9].

2.3.2 Torque tube (Backbone Frame)

Another form of chassis derived from the ladder frame is the backbone chassis, or the torque tube frame. This backbone design is formed out of a single structural beam running longitudinally down the centre of the vehicle, with outstretched lateral beams for the connection of the suspension and other components [8]. The backbone frame utilises the properties of a closed section tube for improved torsional stiffness as opposed to the open section of the ladder frame [9].

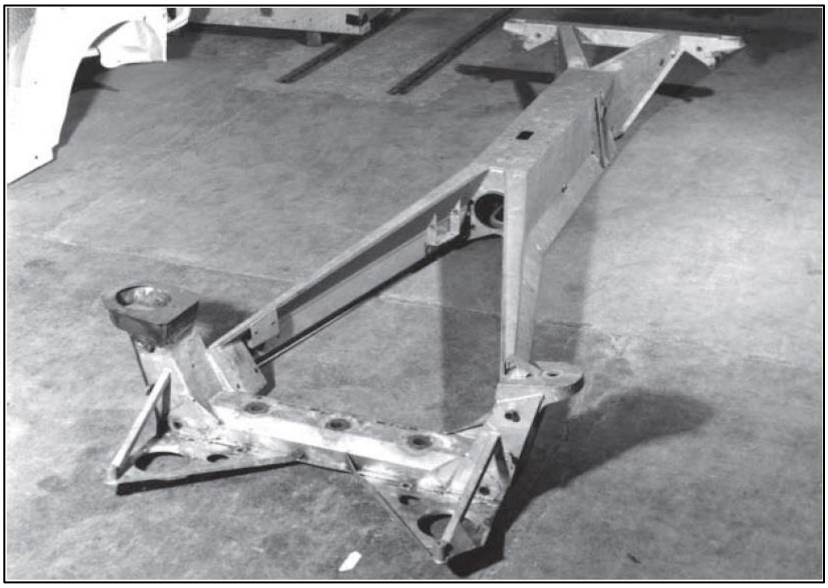

Figure 8: Example of a torsion tube frame [9]

2.3.3 Space Frame

By adding depth to the frame, the strength and stiffness can be considerably improved. All frames discussed, have less depth than length and width, essentially making them two dimensional structures. This lack of depth limits the overall stiffness the frames can achieve. By using three dimensional space frames, the strength and stiffness can be considerably improved by adding depth to the structure [9].

Space frames are constructed by joining together many tubes in a complex but light structure. Because of the triangular design, the amount of material used in the space frame is kept at a minimum. This design keeps the tubes under either tension, or compression and not torsion. The absence of torsion in the tubes allows for the reduction in the cross sectional area of the beams [8]. This design further improves the weight saving properties.

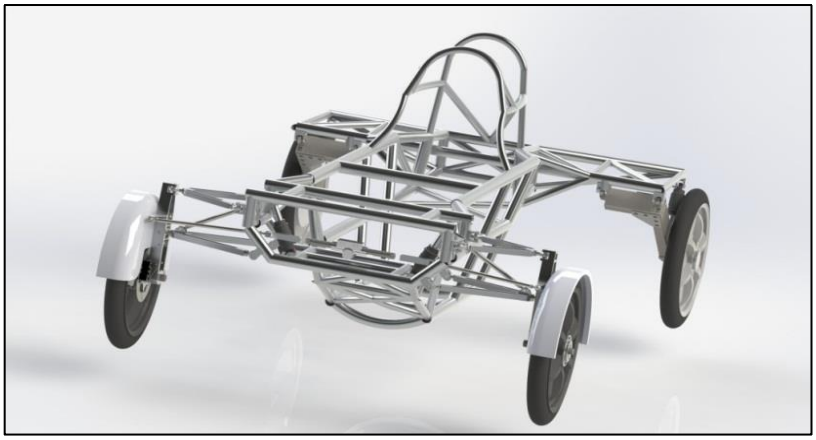

Figure 9: Zephyr aluminium space frame [10].

2.3.4 Monocoque unit body frame

The monocoque is a structure where the body and the frame are integrated to form one structure. The monocoque body is a complex structure, due to the integration with the body of the car. The easy mass production of vehicles makes the monocoque the frame of choice for major car manufacturers. Manufacturing is done by spot welding together metal sheets in integrated shapes, using automated processes. The monocoque frame requires a large amount of development and initial start-up capital investment. This limits its use to mass production [8].

By incorporating the roof (Upper part of the body) of the vehicle into the structure, the torsional rigidity can be significantly improved. This is done in a similar method to the space frame by adding depth to the structure [9]. This improvement in the torsional stiffness of the car can give rise to very good driving characteristics and handling [11].

To produce the stiffest frame available without drastically changing the design, the monocoque chassis can be constructed using carbon fibre. The carbon fibre chassis has a superior torsional stiffness and lightweight properties compared to other known chassis [8]. Figure 10 is an example of a carbon fibre monocoque chassis.

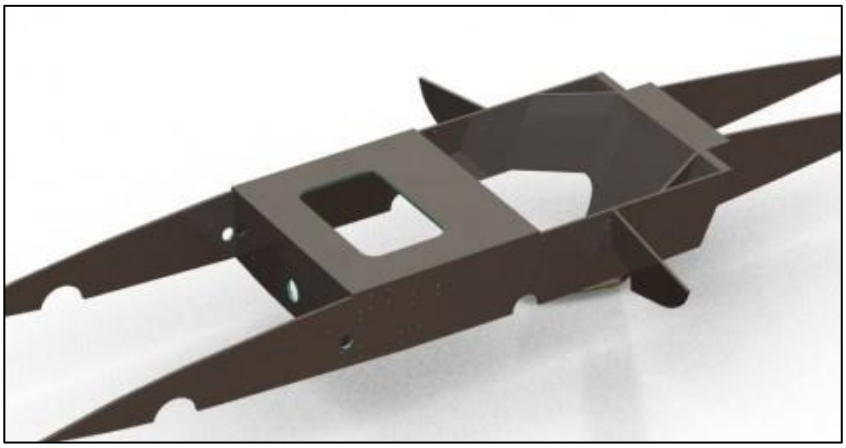

Figure 10: Infinium's monocoque Chassis [12]

2.3.5 Summary

Since the start of the World Solar Challenge in 1983 [1] the different design concepts mentioned have been used. Early into the history of the race, the composite monocoque chassis have been used by the majority of the teams competing.

From the limited space available in the body and aerodynamic design of the solar car it would prove difficult to use the ladder and space frame concepts. The ladder frame uses too much material with the majority of materials not performing any significant structural work in providing torsional stiffness. The space frame could provide the necessary torsional stiffness, but will prove difficult to assemble in the limited space inside the body of the solar car.

Thus it can be concluded that using the integrated body and frame (Monocoque) concept for its superior weight saving and structural properties is the right direction to move in.

2.4 Composite materials

The effective use of power in the solar car requires it to be as light as possible. This makes it impossible to use conventional structural materials normally used in vehicle chassis to build the solar car. It was thus decided to investigate the use of composite materials for this purpose. In this subchapter the different properties of carbon fibre composites will be discussed.

2.4.1 Definition

A composite is a combination of two or more distinct materials [13]. They can be identified by the following criteria

- Both materials must be present in reasonable quantities, larger than 5%
- The composite properties must differ from that of the individual materials
- The composite is produced by mixing the components in a matrix form

Following the previously mentioned criteria, plastics consisting of different fillers, cannot be considered a composite. Metals with a two-phase microstructure can also not be classified as a composite. In this project only the properties of a polymer composite will be investigated.

2.4.2 Polymer Composites

Resin systems have a limited use in the manufacturing of structures due to the fact that they do not have good mechanical properties, even far less when compared with other materials such as metal. But resin has other desirable properties in the manufacturing process such as the ease of forming into complex shapes are one of the desired properties [14].

Materials such as aramid, glass, and carbon have extremely good mechanical properties, such as high tensile and compressive strength. The drawbacks of these materials are the fact that these sought after mechanical properties are not very apparent in the solid form of the material. This is due to the fact that the material, when stressed forms random surface flaws and will cause the material to fail well below its theoretical strength [14].

One way of overcoming this flaw is to produce it in fibre form to better exhibit the materials theoretical strength. The same random flaws will still occur, but will be restricted to a small number of fibres with the remainder in the bundle still intact. This will better exhibit the desired mechanical properties of the material. However, fibres can only exhibit tensile properties along the length of the fibre much the same as in cables [6].

When combining the resin systems with reinforcing fibres such as carbon, one can obtain the mechanical properties of both the materials. The resin, which acts as a binder, distributes the applied load to the fibres in the composite and provides the fibres with protection against abrasion as well as impact. The high strength and stiffness, ease of moulding complex shapes, high environmental resistance, all coupled with low densities, make the resultant composite superior to metals for many applications [6].

The combination of the fibre with the resin creates a composite material with similar but enhanced properties of the fibre and the resin on their own in a matrix form [13].

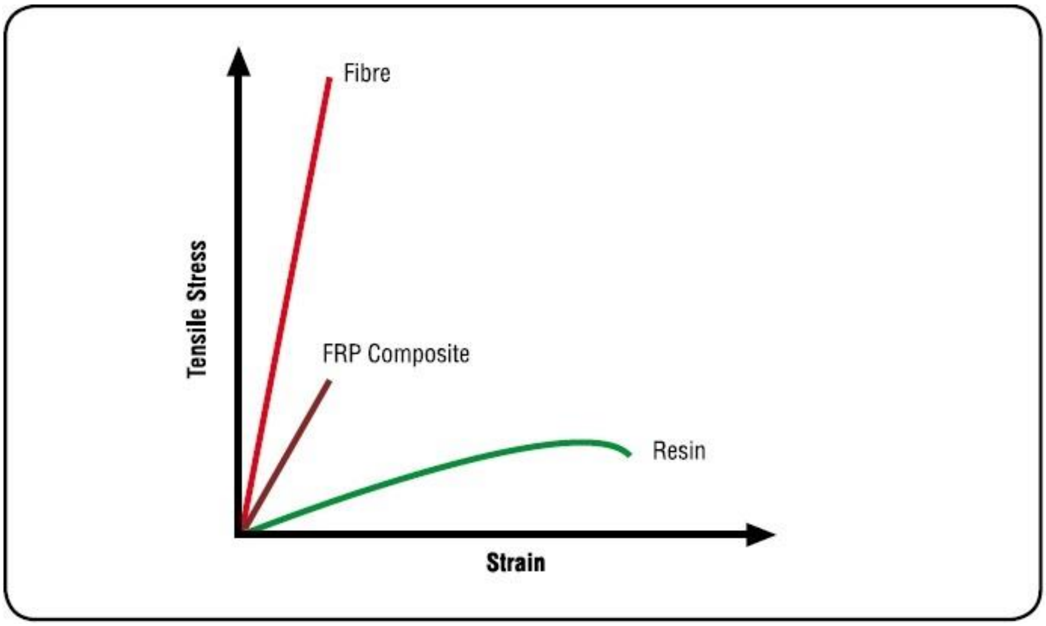

Figure 11: Composition properties [6].

2.4.3 Fibre Reinforced Polymer (FRP)

The fibre and matrix bond is created during the manufacturing phase of the composite part. This manufacturing phase has a fundamental influence on the mechanical properties of the composite materials [14]. It can thus be said that the material is made at the same time as the part. This can give greater freedom to the designer in optimising material distribution in the part, and allows for efficient weight reduction.

The fundamental difference between composites and metals are as follows:

- Composite material properties are decided by the manufacturer during the moulding process of parts, through the use of the directional properties of the composite.
- Whereas metals have a given strength as determined by the supplier. There is not much the manufacturer who fabricates the metal into a finished product can do to change these inherent properties.

The geometry of the fibres in the composite material is also very important; this is mainly due to the fact that fibres exhibit their highest strength along the length of the fibre. Thus unlike metals that have the same properties in any direction of testing, fibre reinforced composites are more likely to have several different properties depending on the direction it is tested in [14]. This means that it is very important to understand the magnitude and direction of the applied loads during the design stage when considering fibre reinforced composites. When taking these directional properties of composites into account, it can be very helpful in the reduction of weight. Placement of materials is only needed where loads will be applied and this will reduce the use of redundant material in the structure [14].

2.4.4 Composite Design

Stress considerations

The strength of a composite is described in the amount of load it can withstand before if suffers complete failure. This is the point where the resin breaks away from the fibre reinforcement and the part fails.

However unlike metal, the composite will not reach a yield point and then deform until braking. The composite will instead reach a stress level where the resin will crack away from the fibre reinforcement; this stress level is well below the ultimate strength of the composite. This form of cracking is known as 'transverse micro-cracking' and, although the material has not yet broken, the process of breakdown has already begun. Thus to insure a long lasting structure, the composite or laminate must not exceed this micro-cracking stress point during operation [14]. This point is represented in Figure 12 as case study and not actual values.

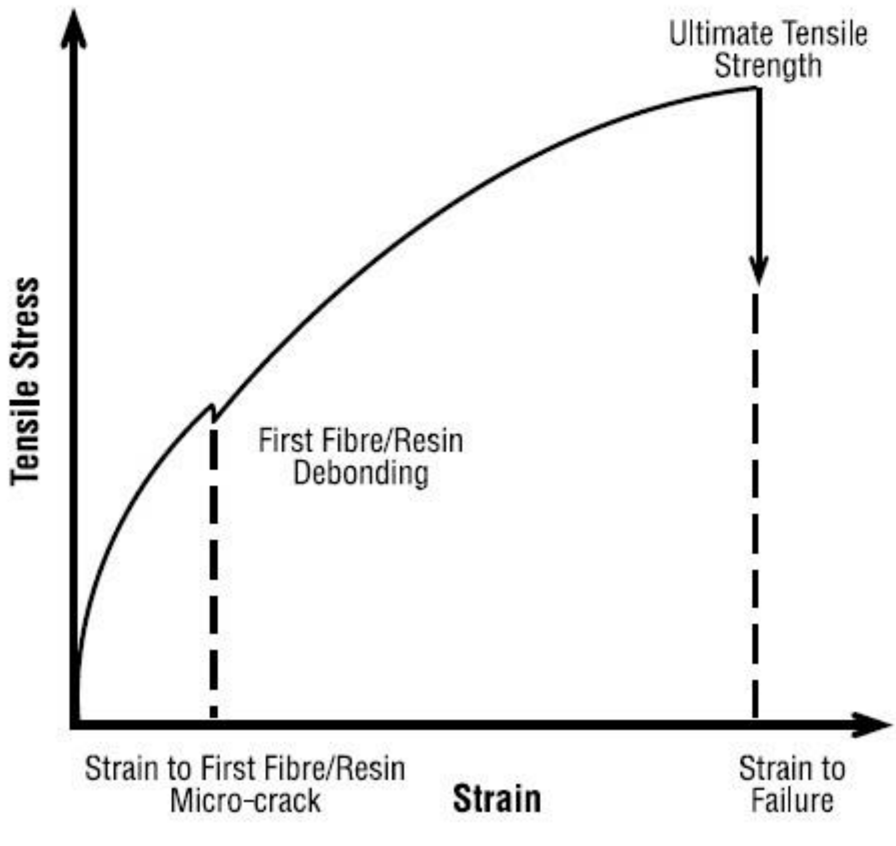

Figure 12: FRP Stress and strain representation [6].

Although micro-cracking does not reduce the ultimate strength of the laminate. This is because the strength is determined by the fibre reinforcement when in tension. However the micro-cracking does reduce the laminates resistance to environmental effects, such as moisture. The cracks will allow water to be absorbed into the laminate, more so than an uncracked laminate. This will allow the moisture to attack the resin and fibre agents present in the composite and lead to an increase in weight, the loss of stiffness, and with time the reduction in the laminates ultimate strength [14].

One way of overcoming the micro-cracking is to increase the resin's compatibility with the chemical surface treatments of the fibres. This is achieved through chemically altering the resin or using a different resin system with a higher ultimate strain to failure toughness. [6]

When using composites the only way to utilise the full extent of the fibres properties, when the composite is under tension, is to use a resin with at least the same or more deformation before failure properties as the fibre being used. This relationship is shown in the Figure 13.

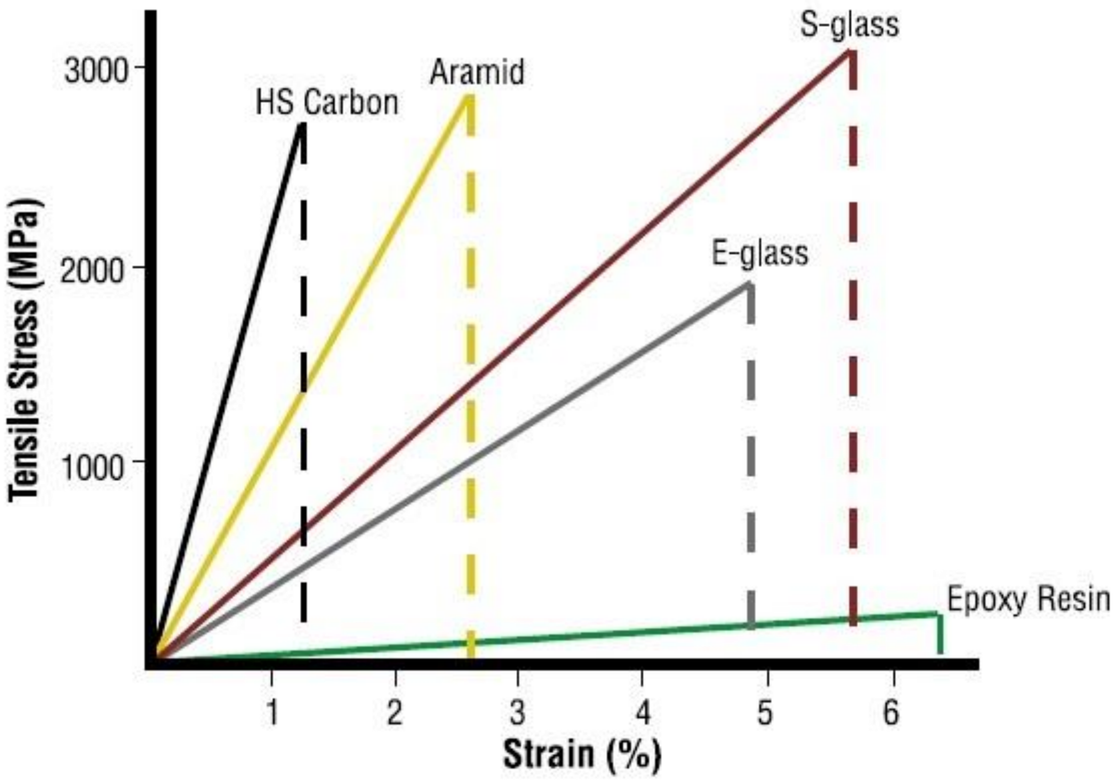

Figure 13: Strain Comparison of epoxy resin and fibre materials [6].

From the Figure 13 it is shown that epoxy resins are most suitable for almost all general fibre elements available in the manufacture of composite structures.

Fibre Orientation

The misalignment of fibres can cause a serious loss in mechanical properties, especially in compression loads, due to the increased likelihood of buckling. In practice it is very rare for laminates to have perfectly aligned fibres; this is because of the nature of the fibre products. Most fibres are available in woven fabrics; this introduces crimp to the fibres and can cause misalignment in the fibre directions. Even non-woven fabric can have crimping at stitch points [6].

When using unidirectional fibres extra care should be taken that the fibres are properly aligned during manufacture. This is to insure the loads are dispersed evenly and efficiently, in order to utilise the maximum potential of composite materials [6].

Fatigue Resistance

In general composite materials have outstanding fatigue resistance, more so than most metals. Small amounts of damage accumulated over n long period of time eventually result in fatigue failures. The resistance to fatigue of any composite is largely dependent on the resin properties, such as the resins ability to resist micro-cracking, and the amount of defects that occur during manufacture. When compared with other resins such as polyester, epoxy resin is the best laminate for fatigue resistance. It is for this very reason that epoxy resin is used in the aircraft industry [14].

Laminate symmetry

When stacking laminates it is important to maintain balance and symmetry, as shown in the Figure below. Maintaining symmetry about the mid plane helps prevent warping and bending and balancing the stack by using equal number of 45° plies, which reduce shear coupling [14]. The importance of symmetry and balance in layers to prevent bending and warping is also discussed in Gurit's guide to composites [6].

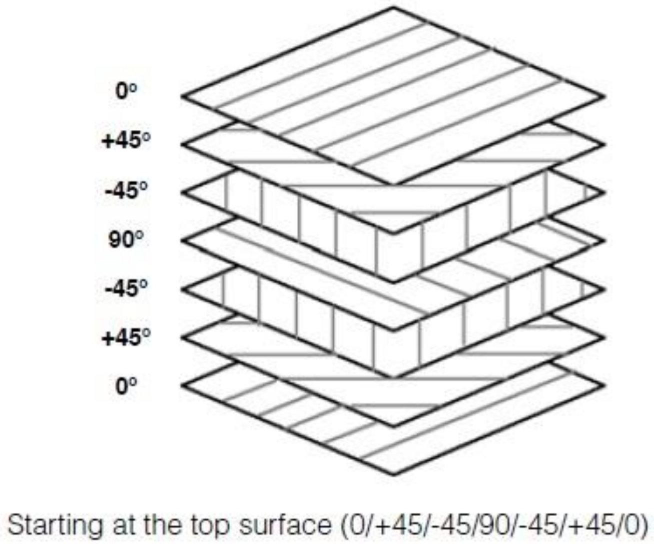

Figure 14: Stacking Example [6].

Sandwich panels

Laminates made up of a single skin are thin and although they are very strong they lack stiffness. One alternative is to add more skins or layers and stiffeners, but this ads weight, defeating the purpose of using composites. To overcome this, the use of sandwich structures and panels where introduced.

Sandwich structures consist of two skins separated by a core material. By adding a core material to the laminate structure the stiffness can be increased without dramatically increasing the weight of the composite or adding extra layers [6].

In essence the core material is similar to the webbing from an I-beam, where the core acts as the lightweight separator between the load bearing surfaces. Because the skin carries the main tensile and compressive forces the core can be relatively lightweight [14].

As derived from the following equation:

$$\sigma_{max} = \frac{Mc}{I}$$

Where

$$I = \frac{1}{12} bh^3$$

The flexural stiffness (I) of any beam is proportional to the cube of its thickness (h) multiplied by the width (b). This relationship is illustrated in the Figure 15.

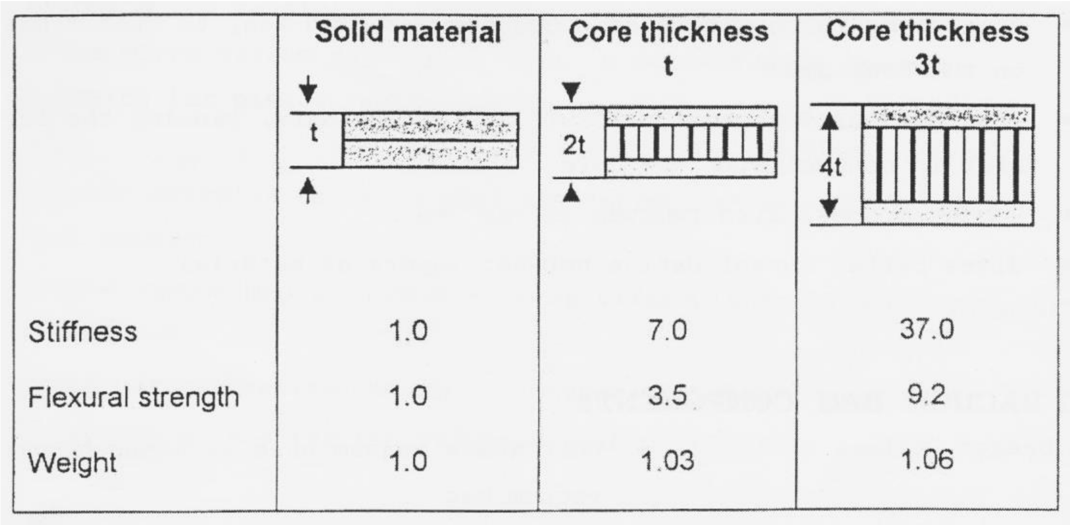

Figure 15: Stiffness to weight comparison of sandwich structures [6].

The Figure 16 shows a composite beam under bending load. In this loading condition it can be seen that the upper layer is under compression loading, the core material is being subjected to shear stress, and the lower skin in tension. Thus the most important properties of the core material are its shear strength and stiffness [6].

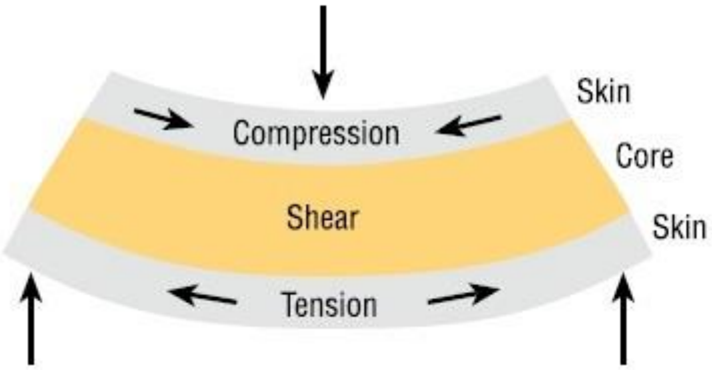

Figure 16: Sandwich beam load representation [6].

When using lightweight, thin laminate skins, the core must be able to withstand compression loads without failing prematurely. This helps to prevent the panel or beam from buckling [6].

2.5 Finite Element Modeller

The finite element modelling (FEM) software package used in the analysis of the structure will be the Patran as the pre- and post-processor along with the Nastran solver. This package is provided by MSC Software. Patran uses a number of finite element analysis codes to provide flexibility and integration. This includes the finite element codes for modelling laminated composite structures [15].

Unlike metals the fibre reinforced polymer (FRP) such as carbon fibre, is made during the manufacture of the component. This gives the designer increased freedom in the design phase of the component. It does mean that more attention must be paid to the process used during manufacture. The material can produce different properties, depending on the manufacturing method used to make the part or structure [16].

2.5.1 Classical analysis

Stress analysis techniques have been developed over many decades and can be satisfactorily applied to many different situations. These analysis methods produce a series of equations based on the equations of equilibrium and compatibility, together with the materials stress-strain relations. These governing equations must be solved to obtain the displacements and stresses of the given situation.

Assumptions such as one- or two-dimensional problems for beam and plates need to be considered respectively to obtain a solution. The material is often taken as isotropic but many methods exist for orthotropic materials, such as carbon and glass fibres. Classical methods are limited to simple geometries and structures. As the structure becomes more complex, the resulting equations become too complicated to solve and require more sophisticated mathematical techniques. In these cases the use of finite element analysis should be considered [16].

2.5.2 Finite element analysis

Finite element modelling (FEM) is just an alternative method of solving the equations of a more complex structure. Thus FEM and classical methods will produce the same results for the same problem if it is applied correctly.

The FE method consists of dividing the structure into discrete parts or elements, which are then assembled to represent the distortion of the structure under the applied loads. Care should be taken in the selection of an appropriate element distribution and size, to properly represent the given structure.

The FE method was initially developed for the application on isotropic materials; to apply the technique to FRP, requires different element formulations that represent the orthotropic, stiffness and strength as well as the laminated configuration of the FRP composite [16].

2.6 Leading Solar racing teams

Based on the results of the 2013 World Solar Challenge the best solar racing teams can be identified as the Nuon Solar Team, Tokai University and Solar Team Twente. These teams have a long history of competing in solar car challenges and between them have a large amount of accumulated experience. By studying the top racing teams in the wold and looking at their cars designs, the concept development process can be done while avoiding unnecessary or impractical chassis designs. These teams will be briefly described below as they were observed by members of the NWU Solar team.

2.6.1 Nuon Solar Team

Figure 17: Nuon Solar Team; Nuna7 2013

In 2001 the Nuon team, then known as Alpha Centauri, entered the World Solar Challenge (WSC). The first Dutch solar car named Nuna taking first place, surprising everyone in the solar racing community. The team continued winning the subsequent WSC under the name Nuon Solar Team. This was upset in 2009 when the Nuna5 suffered a tire blowout and was damaged in an accident a few weeks before the WSC, placing second after being repaired. The team was only able to regain the title of World Solar Champions in 2013 with the Nuna7 [17].

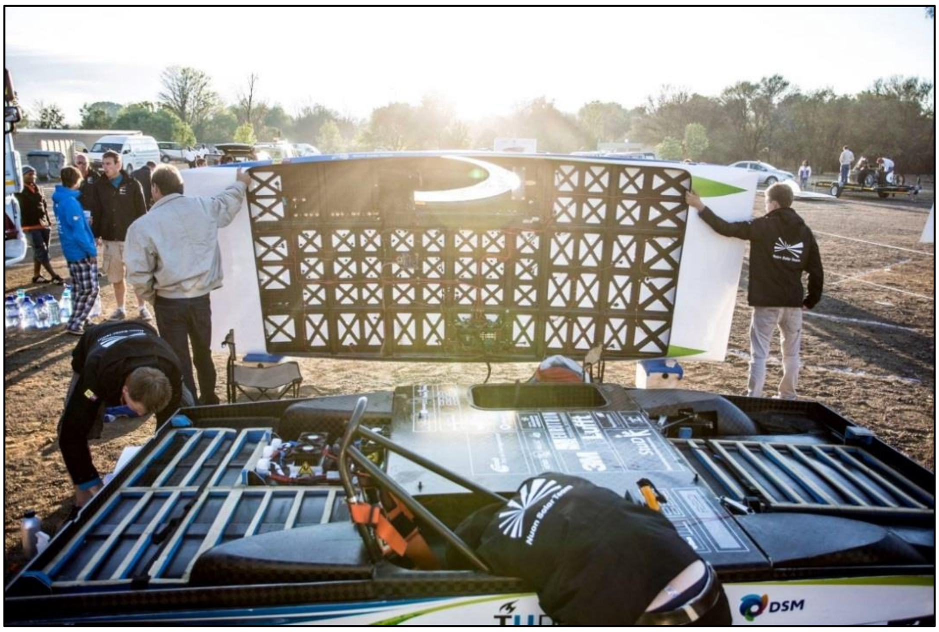

Figure 18: Nuon Solar Team; Nuna7 2013

The Nuna7's chassis is based on a compact monocoque frame located in the central section of the car body. The frame is integrated into the lower body of the car making it a semi-monocoque chassis, built from lightweight carbon fibre composite onto which the components such as the suspension and steering are attached. This type of frame made the design of the steering and front suspension very complicated and in turn caused some minor stability concerns. The vehicle weight was measured at 227kg without the driver this was observed at the start of the South African Solar Challenge 2014.

2.6.2 Tokai University

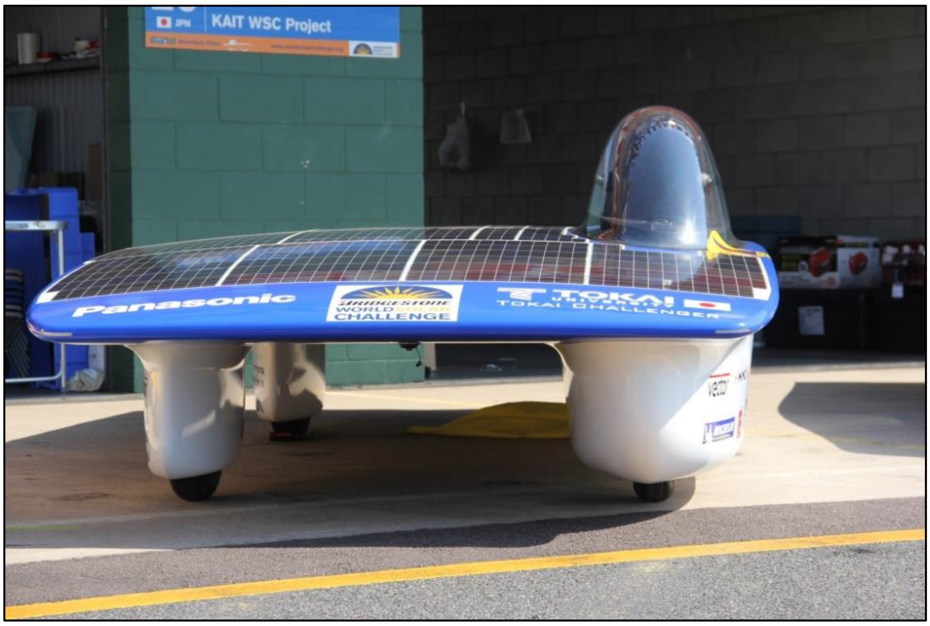

Figure 19: Tokai University; Challenger 2013

The Tokai University from Japan started competing in the WSC in 1993 placing in the top 20 teams until 2001. The team did not compete in the WSC for eight years after 2001 and only restarted participation in 2009 when they placed first with the car named Challenger. They managed to repeat this result in 2011 [17]. During the WSC 2013 Challenge they placed second. This race was the first time where the regulations required the main competing vehicles; the challenger class; to have four wheels to be eligible for the world title [18].

Figure 20: Tokai University; Challenger 2013

The 2013 Challenger frame is made from carbon fibre composites formed into a central box chassis combined with the bottom half of the car body making it a semi-monocoque frame. The frame provides the mountings for the suspension, electronics, batteries and the other subcomponents of the car. This frame provides the necessary rigidity to withstand the loads imposed on it during normal operation. The design allows for the steering and suspension subcomponents to be of a simple, but reliable design for improved stability and maintainability.

2.6.3 Solar Team Twente

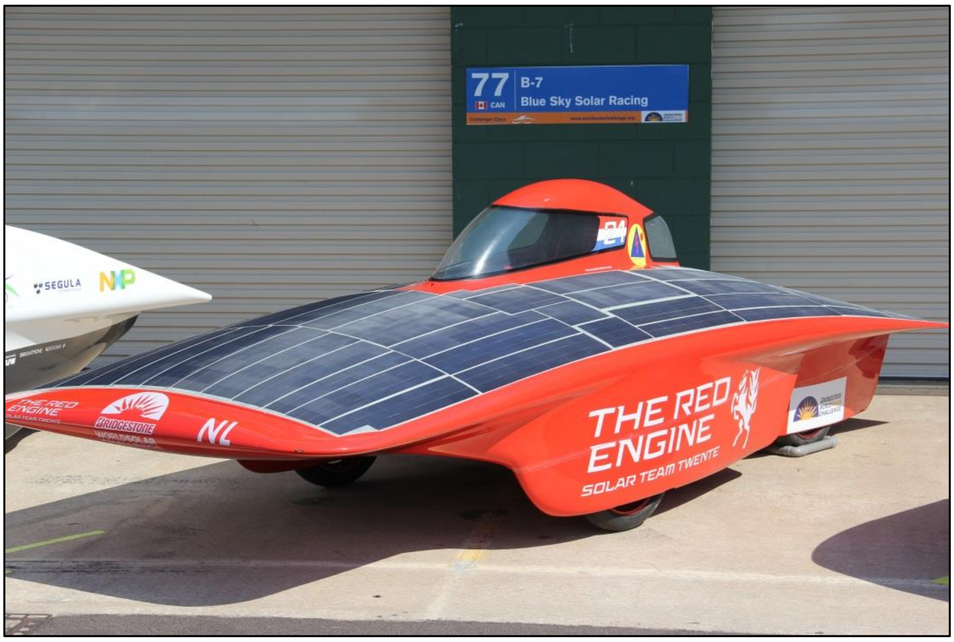

Figure 21: Solar Team Twente; the Red Engine 2013

The SolUTra was the first car entered in the WSC by Solar Team Twente in 2005. The team prides itself on using new and innovative ideas to gain better performance from their cars. This dedication to pushing the limit of their creativity has ensured that the team has always been in the top 10 of the WSC despite having an accident in 2009 and still finishing in 8th [17]. In 2013 the teams focus was mainly on saving weight and reducing the aerodynamic drag of the RED Engine over the previous car, gaining them the third position overall.

Figure 22: Solar Team Twente; the Red Engine 2013

The RED Engine design was mainly focused on saving weight by building it as a full monocoque body. This incorporated the top and bottom body panels in to one load bearing structure saving weight by fully utilising the shape of the body and the material properties. The material used to form the chassis and body structure consisted of carbon fibre composites. This allowed the construction of a lightweight car that had sufficient rigidity to withstand the loads imposed on it and carry all the components of the solar car.

2.7 Summary

In conclusion of this literature review it was shown that the use of a semi-monocoque frame and body would be preferred. This allows for the effective use of space and materials in the construction of the solar car. The semi-monocoque shape was chosen due to the need for easy access to the interior of the solar car. Carbon composite materials were identified as the most commonly used building material for solar cars in the world solar challenge. The material properties of composites and their advantages was discussed along with the design consideration that need to be known to work with carbon composites. The use of FEM for solving the structural loads in composite materials and how it speeds up the process was mentioned. The leading solar car teams in the world had a brief description on their history and types of structures and materials they currently employ.

3. Chapter 3: Methodology

Design can be described as an iterative decision-making process.

- The first step is to identify the needs and specifications of the product, such as the vehicle dimensions.
- Next is the iterative process of seeking a solution to the design problem and satisfying the specifications set in the first step of the process.
- The final step is a detailed description of the product and processes used in the design and analysis.

These are the three phases of the design process as described by Current and Future Research in the Conceptual Design of Mechanical Products [19].

3.1 Design specifications

The first step in the design process:

To identify the required specifications from the FIA [20], WSC regulations [18] and the Sasol Solar Challenge [21] on solar car chassis.

The requirements defined by the team itself for the frame of the car in precise yet neutral terms. These specifications can be identified by the following points and will be discussed in further detail in later chapters of this document:

- Dimensional constraints depending on the class of solar car being developed
- The type and amount of solar cells to be used
- Seating position of occupants
- Driver protection in the event of a rollover or side impact
- Roll bar that can satisfy the FIA specifications on load bearing capabilities
- Number of wheels and the position of the wheels
- Location of subsystems and the necessary attachment points
- Safely withstand induced loads
- Accessibility to components
- Minimum weight constraints

3.2 Conceptual design

The conceptual design phase consists of generating solutions for the design specifications [19]. Each of the concepts generated during this phase can be motivated as to why it was proposed as a possible solution to the design specifications.

The next step in this process is to select one of the concepts and motivating in clear terms as to why the selected design was decided on, based on the design specifications and discussions with the team.

3.3 Detail design and analysis

The detail design phase consists of finalising the shape, dimensions, material and component positioning. These decisions can be influenced by the manufacturing processes and strength requirements produced by the analysis done on the frame for specified loads.

The frame selected from the concepts is further developed to insure that the known subcomponents, such as the steering, battery, suspension and control systems will fit in the car when completed.

The chassis is then subjected to a finite element analysis to determine the correct material composition for a selected safety factor while aiming for the lowest weight attainable for the selected design configuration.

The finite element analysis package used in this study is the pre- and post-processor of MSC's Patran and Nastran. This analysis programs has the ability to analyse composite structures and giving detailed results pertaining to the structure strength, such as calculating the safety factor for the composite layup.

This analysis is based on load cases that will be discussed in the detail design chapter.

4. Chapter 4: Validation

The finite element modelling method needs to be validated before the detail design and analysis of the car structure can begin. This is to prove that the model gives an accurate representation of reality. This was done by constructing a simple test sample and subjecting it to a deflection load test. The test data was then compared to the finite element model data to insure the accuracy of the modelling technique.

4.1 Process

The first step was to define a FEM (finite element model) with the same properties as the material that will be used for the final design and analysis of the vehicle structure. This model should be of such a nature that it is easy to manufacture and subjected to the same load case as in the finite element model.

The model that was used in this analysis is a composite I-beam configuration. The beam was constructed using the same vacuum bag wet layup method that will be used on the car itself. The beam was post cured over the course of three days with very low temperature ramp rate. This is to insure proper material properties of the resin used in the composite [14].

The material properties improvement is also evident from the resin product sheet describing different material strengths at varying curing temperatures [22]. This is to insure the properties are as close to the final product as possible.

The layup consisted of four layers of carbon fibre in the web with a 0° and 90° layup symmetrically about the middle plane. The flange of the I-beam was made up of three layers with the outermost layer being a 90° layer.

The next step was to subject the I-beam model to a deflection test. The deflection test was conducted by applying a point load on the beam midpoint and supporting the beam on the sides using sharp edges at an equal distance from the middle. The deflection was measured at the midpoint where the point load was applied. The analysis was repeated for an incremental increase in the load to generate plenty of data points for comparison with the test data. The test sample was subjected to the deflection test using different weights as well but not as many. This is due to the test bench not supporting large quantities of weights and reducing the time necessary to test the sample. The test sample process was repeated several times to insure no significant measurement error were recorded.

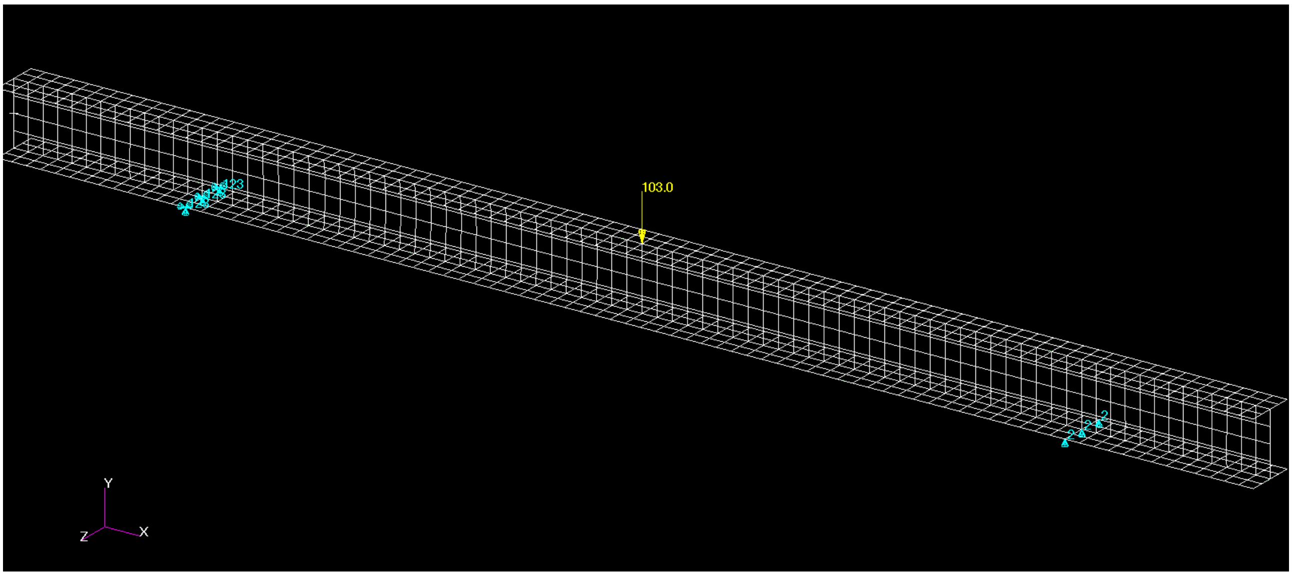

Figure 23: Validation mesh

The finite element model was setup the same way as the test sample. With the point load at the midpoint with the constraints an equal distance from the mid-plane. The only difference to the test beam setup is the constraint on the left side of the model. Unlike the real test, the one constraint is a fixed point that only allows rotation but no translation. Whereas the constraint on the right side only prevents translation in the Y-axes this is due to the solver requiring a fixed point of reference to calculate the strain and deflection of the beam.

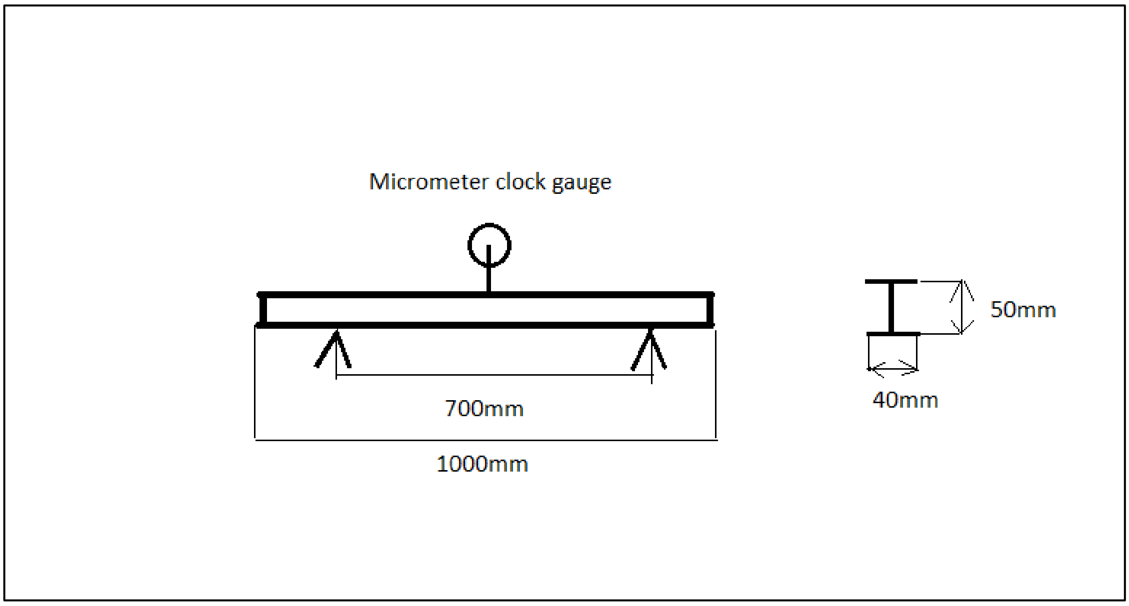

Figure 24: Validation model setup and dimensions

The mesh of the beam can be created in two different ways using the Patran processor.

The first method is to create the mesh entirely through manual inputs. This method uses mesh seeds to create the mesh on each surface individually. This is the most time consuming way to create a mesh and is generally used only if the other method fails to work, this does not happen often. The manual method is mostly only used for controlling the mesh size on individual surfaces.

The second method was to use the auto surface mesh function. This method considerably reduces the time to mesh the structure. It works by generating the mesh for the surfaces, by using user defined element sizes and mesh properties. The mesh was generated using quad elements of 10 mm in size creating the mesh as seen in Figure 23.

4.2 Results and conclusion

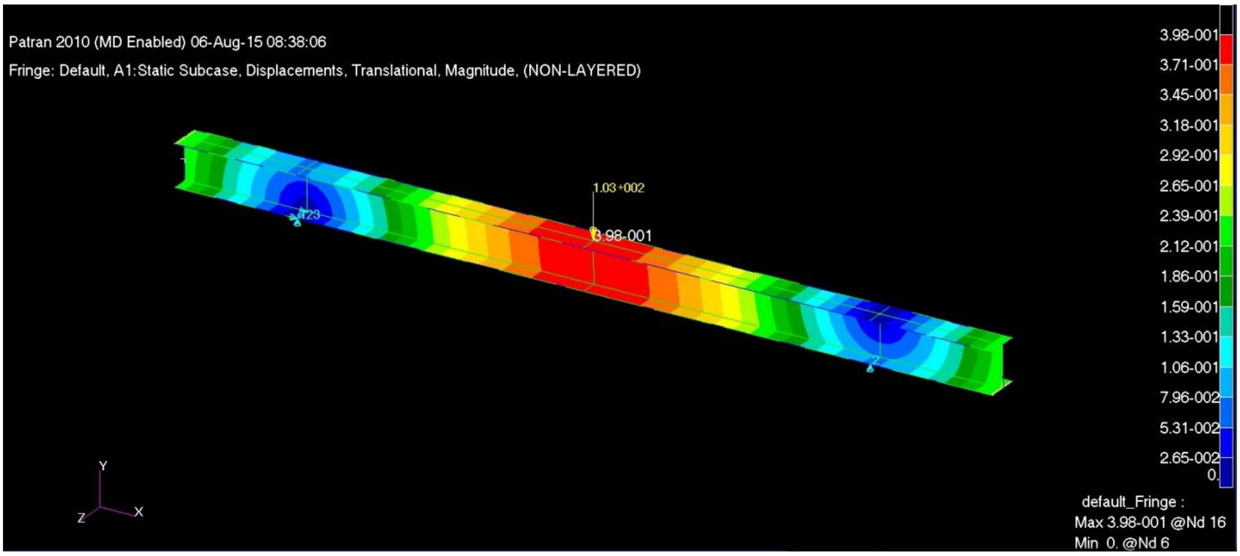

Figure 25: FEM Deflection result

The test results revealed a good linear relationship between the deflection and load for both the test sample and the finite element analysis. A variation of 1.5% existed between the result of the analysis and the practical test. This demonstrates that both tests were executed correctly with proper mesh type and size selection. This comparison was done for both the meshing methods mentioned and the results were the same for both; thus using the auto surface meshing of Patran is the preferred method for being the faster method.

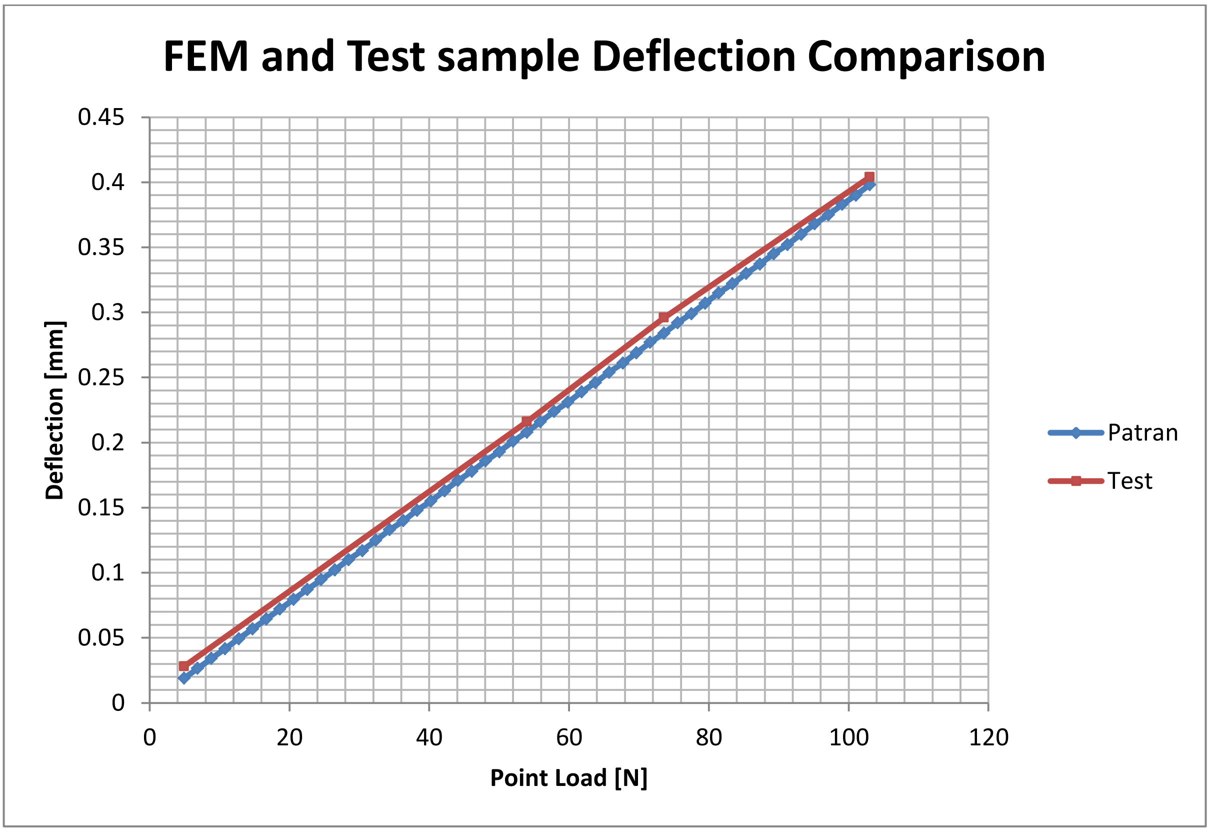

Figure 26: Deflection comparison of simulation and practical tests

By comparing the results of the finite analysis to the practical test, an average of 1.5% difference existed overall, indicating a good similarity between the test and simulation data.

With this result it can be concluded that the analysis method used to analyse the sample is an accurate representation of the practical test and can be used to analyse the design of the new solar car frame.

5. Chapter 5: Concept Evaluation

During this step concepts were developed that satisfy most of the identified specifications. The concepts were then evaluated by the team to select the one that best satisfy the need for each of the subcomponents that will be used in the completed solar car.

5.1 Vehicle specifications

The first step in the design process is to identify the required specifications from both the FIA regulations on solar car chassis and the requirements defined by the team itself.

These specifications can be identified by the following points:

- Maximum dimensional constraints based on the challenger (World Solar Challenge) or the Olympia (Sasol Solar Challenge) class of solar car and the type of solar cells to be used (Length 4.5m, Width 1.8m, Height 1.6m, with $6m^2$ silicon solar array).
- Seating position of occupant, the driver backrest angle must not exceed 27° from vertical.
- Seatbelt anchorage points that comply with the FIA technical regulations
- Driver protection in the event of a rollover or side impact (specified by FIA)
- Roll bar that can satisfy the FIA specifications on load bearing capabilities
- Number of wheels and the position of the wheels(4 wheels symmetrically about the centreline)
- Location of subsystems and the necessary attachment points
- Safely withstand induced loads (reliability)
- Minimum weight constraints of 190kg in the racing configuration and driver included
- Easy maintenance access to the interior

The specifications mentioned here are difficult to apply to the concept phase of the design.

Only the dimensional constraints, wheel position, subsystem location and the maintenance access will be considered for the concept selection.

These where identified by the team as the most important aspects of the early design to make work on the car easier at a later stage.

Based on the literature study done during the initial stages of the project it was identified that the use of a monocoque structure when working with composite materials will benefit the ultimate goal of reducing the weight of the car by combining the body with the chassis.

It was then decided to present the team with a monocoque and semi monocoque frame design.

5.2 Concept 1

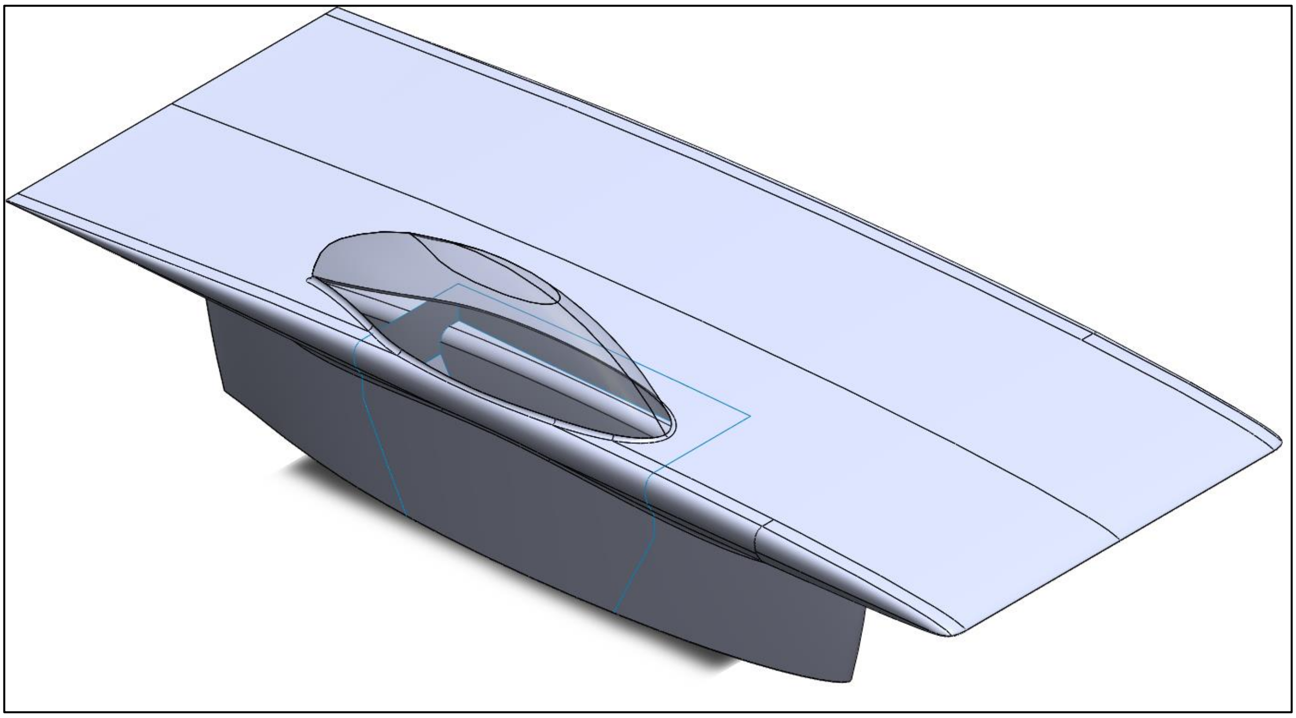

Figure 27: Full monocoque Body

The first concept considered was the full body monocoque frame. This is due largely to the fact that the body of the solar car has very limited space for a frame.

The full body monocoque frame uses the aerodynamic profile of the car as the subcomponents supporting structure. The full monocoque frame provides a very good stiffness for the least amount of material and additional structures for a solar car frame. By distributing the composite materials only where it is needed for the required strength the weight of the frame can be minimized.

Figure 28: Solar team Twente the Red Engine

In section 2.6 it was mentioned that one of the leading solar racing teams in the world utilises the full body monocoque frame design. The team from Twente built the Red Engine using this concept for minimizing the weight of the car by using the body as the loadbearing structure.

This type of frame design is not without some flaws. The weight that can be saved from this concept is easily negated by additional structures that are added out of necessity. These structures include supports for the access hatches to the interior of the car.

The walls are added in the interior of the body to isolate different electrical components and to stiffen the outer body shell. This is due to the requirement for the battery to be isolated from the rest of the car in case of a fire. It can also include the supporting structure for the steering and non-loadbearing sections of the body such as the fairings and the trailing edge. This is to prevent any deformation of the aerodynamic shape or vibration.

The major concern raised by the NWU team after considering the full body monocoque frame was the difficulty of maintenance and access to the interior of the solar car. The reason given, was the time it would require to repair or maintain the car during the race, would greatly affect the overall results of the race. The maintenance or repair work on solar cars is not due to poor reliability of the car, but (due) to the high sensitivity of the equipment that require constant attention for optimum performance. The failure of components is not unheard of either, as this is a competitive motor sport. Teams will use the equipment in the car to the limit of its endurance. It is important to be able to replace and maintain these parts as fast as possible. To remedy the monocoque design for maintenance and access negates the benefits of the reduced weight of this concept.

5.3 Concept 2

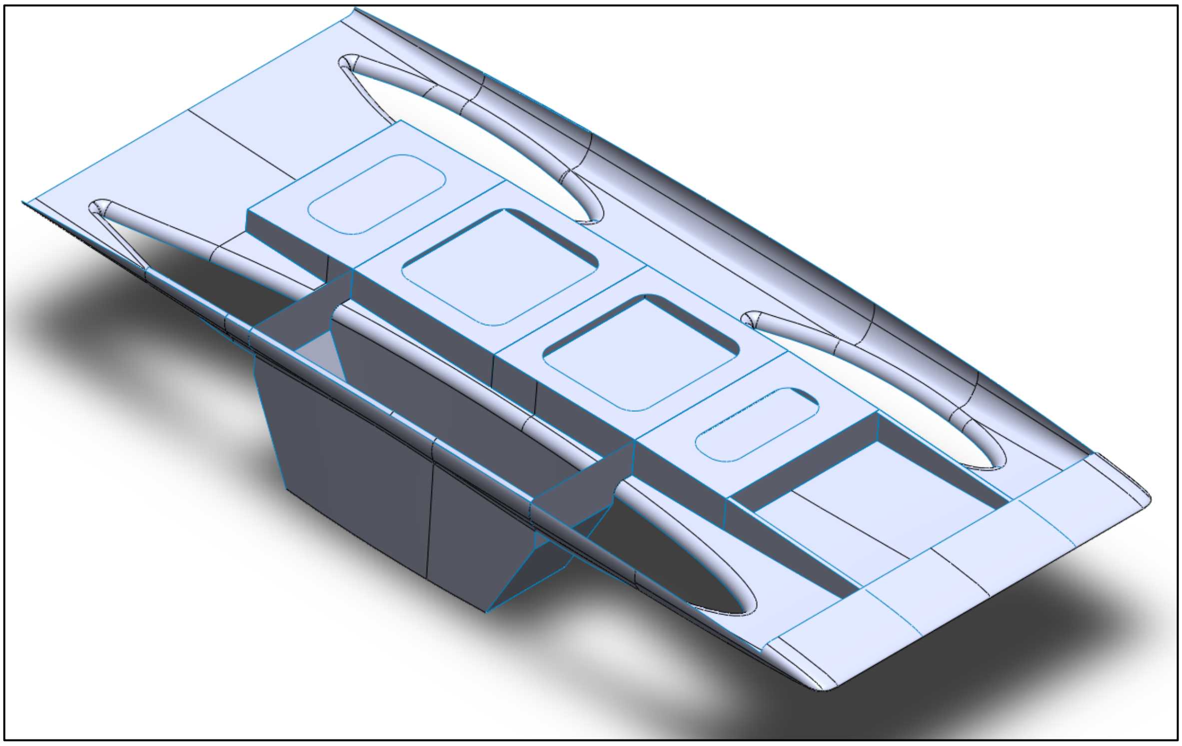

Figure 29: Semi-monocoque body

The next concept proposed to the team borrowed the same basic idea from the full monocoque frame, using the body of the car as part of the loadbearing structure.

Instead of being completely enclosed, it only uses the bottom half of the body as a supporting structure, therefore permanently incorporating the frame into the body of the car.

This type of frame incorporates additional structures to strengthen the body, in order to withstand the load it has to carry. By adding more structures over the full body for increased strength of the monocoque frame, a small increase in weight can be expected.

By adding more hatches and internal structures to the full body monocoque frame to accommodate the need for interior access and to support other subcomponents, the weight saved is easily lost. But this is only true if it did not require easy access to the interior of the body.

The nature of being easily opened and already having internal structures, the semi-monocoque frame already provides easy access to the car’s interior and mounting locations for subcomponents. Using the already existing structures of the frame as compartments for the battery’s isolation and electronics, no additional structures are needed to serve this purpose. This allows for an effective use of space and material in the overall design of the car.

Figure 30: Tokai University; Challenger 2013

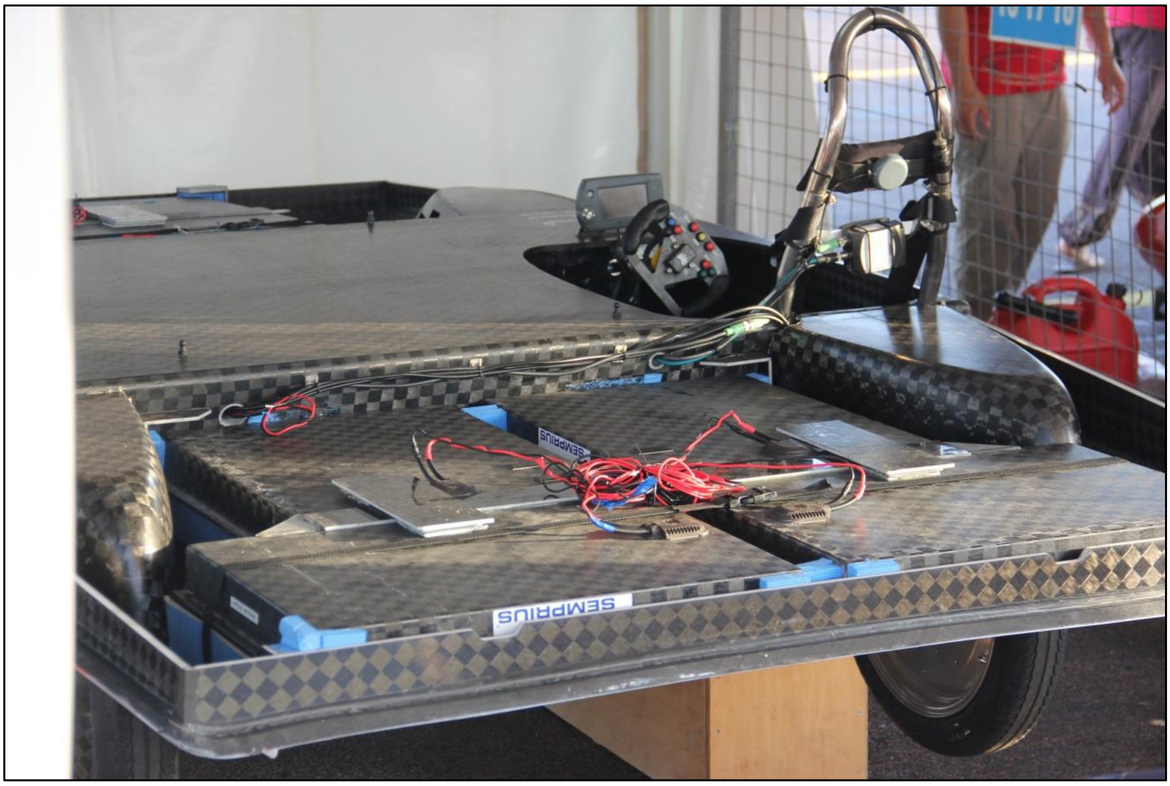

Figure 31: Nuon Solar Team; Nuna7 2013 interior

The semi-monocoque frame type is the most commonly used form of frame in solar racing. This is most evident in the top 5 teams in the world, all implementing this type of design.

5.4 Summary

Table 1: Concept evaluation summary

Concept	Dimensional constraints	Wheel position	Subsystem locations	Maintenance access
1	Easily complies with race regulations	No limitations on wheel positions	Additional structures required	Difficult without more additional structures
2	Easily complies with race regulations	No limitations on wheel positions	No additions required, use of existing frame possible	Easy, requires no additions

In conclusion, both frames would be able to provide the necessary strength and support needed by the solar car and effectively use the materials available to achieve this.

The full body monocoque frame has the potential to be the lighter of the two concepts. But the requirement of the team to have easy access to the interior of the car during the race, makes the semi-monocoque frame the more practical option for the design of the North West University solar car.

By using the interiors of the solar cars effectively and using the frames additional structures for multiple purposes, the increase in weight can be limited.

Therefore team concluded that the easy access semi-monocoque frame was to be used and justified it by stating that the car will be used for future testing of subcomponents.

6. Chapter 6: Detail Design

After the concept selection was done, based on the literature study and the preferences of the team, the next step is the design and analysis of the structure.

To do this, an understanding of the operating loads it will be subjected to, will be discussed in this chapter. The loads are used to analyse the structure in order to define the composite material layup. The shape of the frame to be integrated into the body will be defined in this section, with motivation for its use.

6.1 Load cases

The first step to designing a vehicle frame, or any structure, is to understand the different loads acting on the structure [23]. The loads imposed on the vehicle are formulated by considering the normal running conditions of the car as described in [9] and [11] by defining the loads in the list given below. The load cases can be formulated for the analysis of the frame.

The following list can be used to define the load cases for the analysis of the solar car frame:

- **Vertical bending:** The vertical bending acting on the frame is due to the weight of components and the driver in the interior of the car body. This force is always present even if the vehicle is not in operation making it the least critical of the loads acting on the frame.

- **Torsional loads:** Torsional loads on the frame are due to any road imperfections encountered during the normal operation of the solar car. These imperfections can include potholes and road bumps that cause one wheel of the car to lift higher than the other wheels or to leave the surface of the road inducing a torsional load on the chassis.

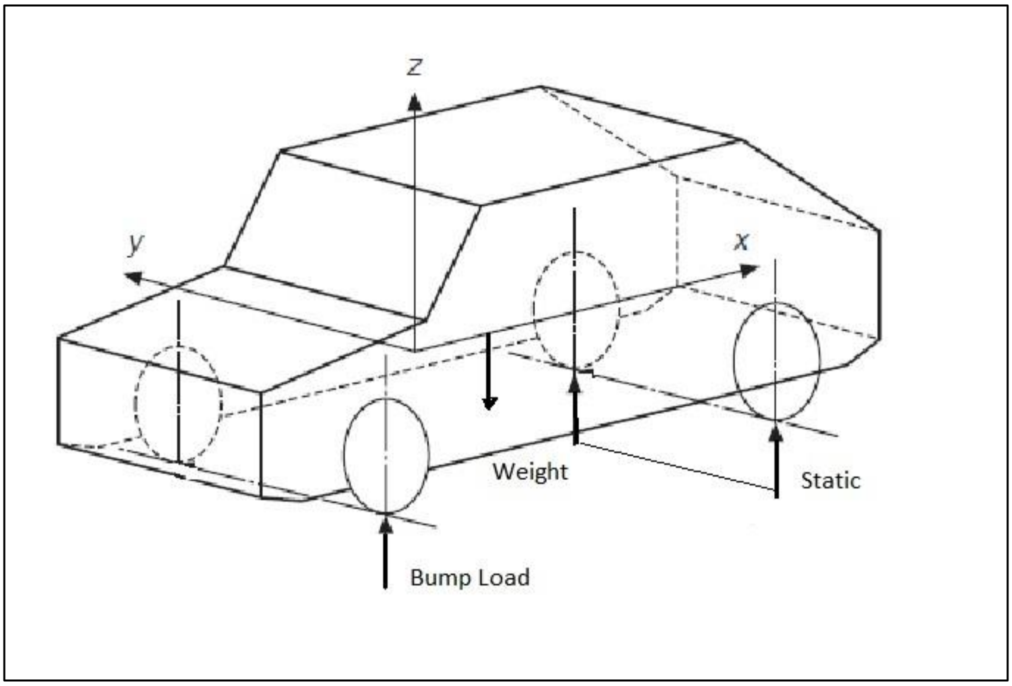

Figure 32: Combined bending and torsional load

- **Vertical loads:** The vertical loads are caused by road imperfections at the suspension mounting locations. Imperfections such as bumps in the road surface, also known as bump loads.

- **Lateral loads:** The lateral loads on the vehicle are caused by the car turning around a corner or by sliding across the road surface.

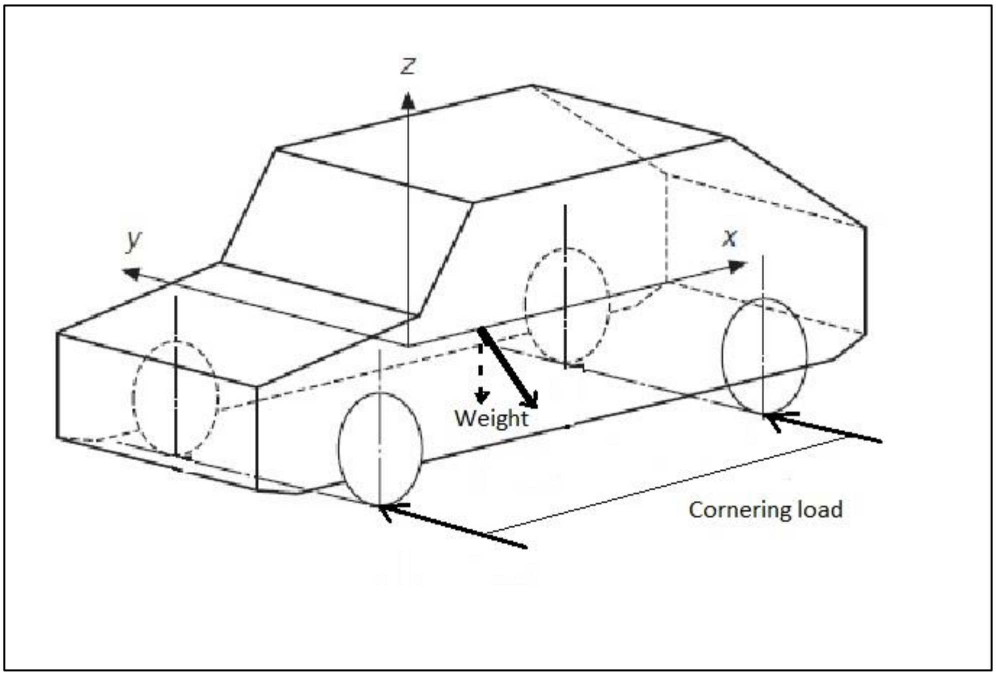

Figure 33: Lateral loads

- **Longitudinal loads:** These loads are induced by the vehicle during acceleration and breaking. The loads act on the mounting locations of the suspension in a forward or aft direction.

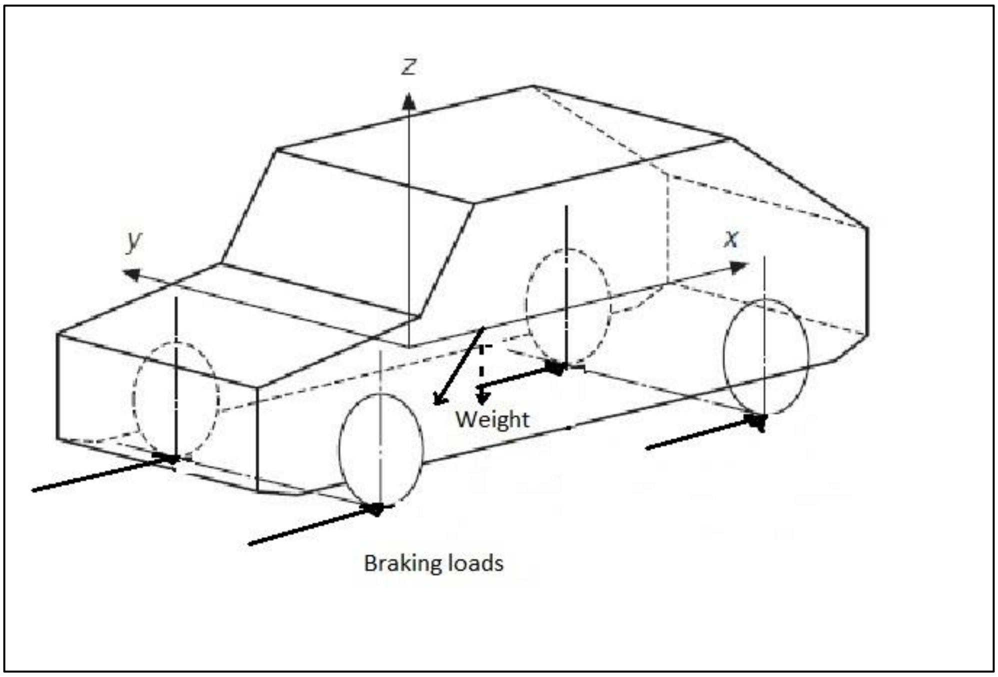

Figure 34: Longitudinal Loads

- **Impact loads:** Impact loads are mainly considerations for the event of an accident, where the car may experience impacts from the front, rear, or sides of the vehicle. These are provided by the race organisation as multiples of the car weight.

By calculating the weight distribution of the vehicle, the load cases mentioned can be expressed as multiples of the weight on the individual wheels or application points of the frame [9] and these values comply with SAE (Society of Automotive Engineers) standards and are discussed by Carrol [24]. These values are given in the table below along with the loads supplied by the race regulations to insure the safety of the roll bar:

Table 2: Loads and dynamic load multipliers

Bump load vertical	4
Bump load longitudinal	3
Cornering load	1
Braking and acceleration	1
Front impact	5
Rear impact	5
Side impact	5
Roll bar vertical [N]	16300
Roll bar horizontal (Fore and aft) [N]	12300
Roll bar lateral [N]	3300

The body of the vehicle receives punishing treatment with a variety of use and abuse. This is why a combination of load cases had to be considered to find the worst case scenario for a realistic use in the analysis. To use the various load cases a calculation of the weight of the car as well as the distribution of the weight had to be estimated from previous experience.

Table 3: Weight estimation

Components	**Weight estimation [kg]**
Body/Fairings/Frame	80
Battery	30
Suspension	30
Steering	15
Solar cells	10
Electronics	20
Driver	75
Motors	30
Total	290

In order to calculate the weight distribution the centre of mass needs to be determined. This requires the approximate location of the internal components to calculate the centre of mass and the weight distribution. To do this the shape of the car must be completed in order to estimate the locations of known components like the battery and suspension.

6.2 Shape design

Defining the shape of the frame is the next step in the design process.

The semi-monocoque frame design was identified in the previous chapters as the type that best satisfies the requirements set out by the team. This type of frame also allows for the easy accommodation of interior components by inherently providing attachment points.

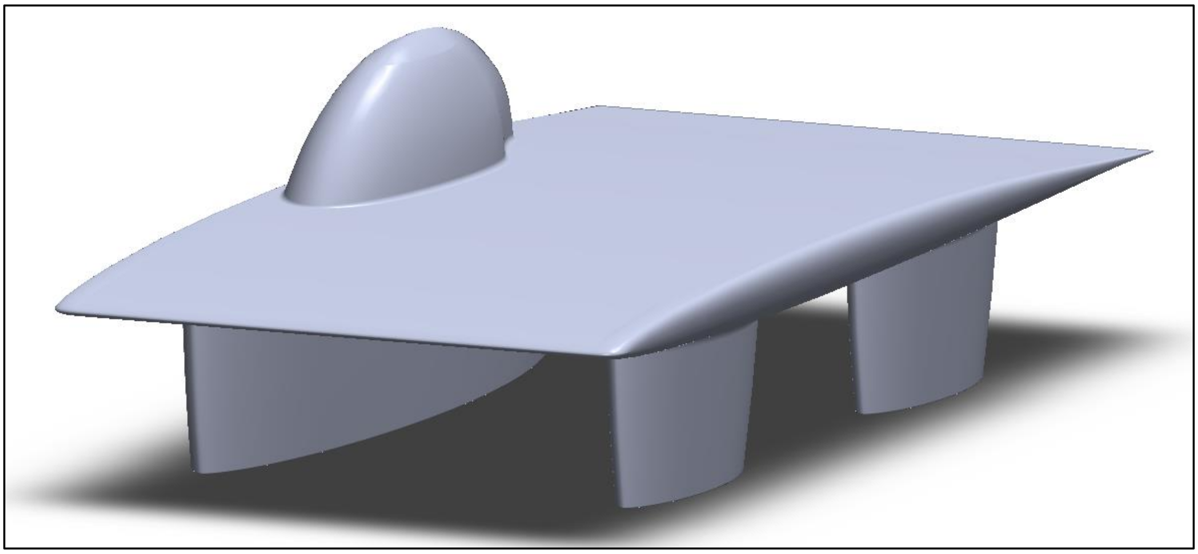

Figure 35: Aerodynamic design input

The aerodynamic design output is the main contributing factor to the shape and space available for the design. The space available in this body shape is very limited and makes it difficult to fit a large and complex frame. The placing and shape of the internal structure is therefore very important and the mounting locations had to be identified.

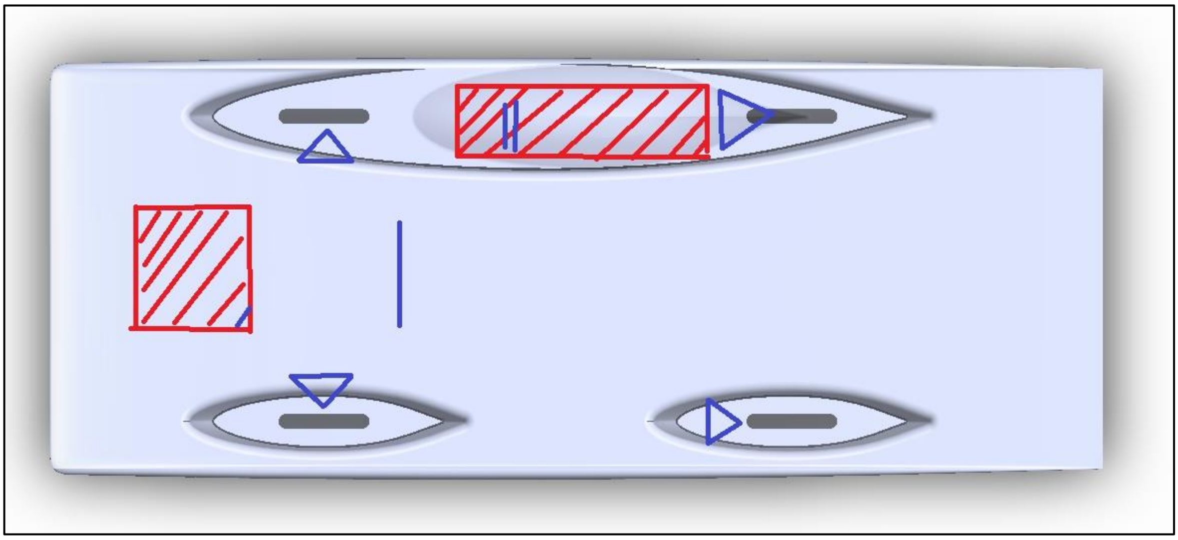

Figure 36: Loading and mounting locations

The locations of the large weights that will be present in the car, is shown in red in Figure 36. These figures represent the driver and the battery pack. The region in blue are the required mounting locations for the suspension and steering in the car.

Other weights and mounting point will be necessary for electronics, seatbelts and telemetry etc. These mounting points are more widespread and can be mounted inside or to the frame without much difficulty. This does not require visual representation, as it would clutter the image.

6.2.1 Shape design process

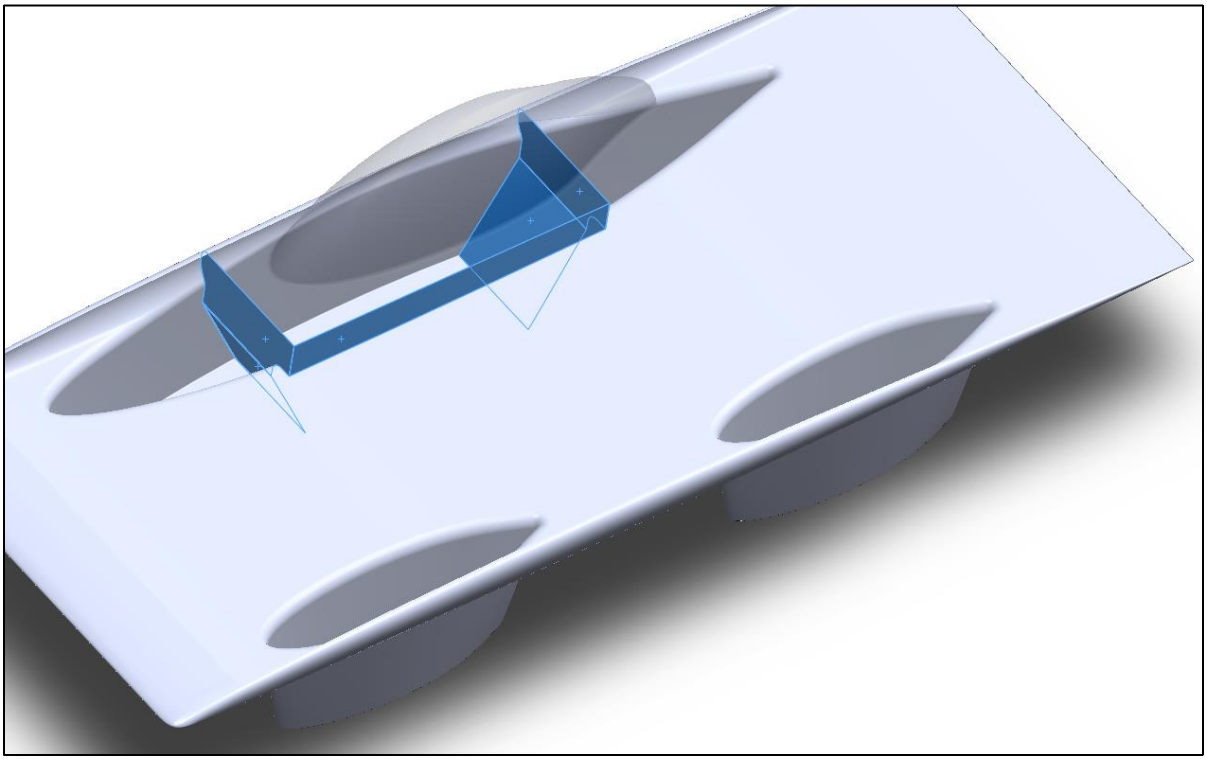

Figure 37: Driver compartment

1. The first step in the shaping of the frame was the compartment for the driver. Due to the regulations on ergonomics, described in [20] and [21] of the driver seating position and the limited space available, the shape is mainly fixed to the boxed design. The seating position of the driver is limited to an inclination no larger than 27° from the vertical. This is to prevent excessive driver fatigue during the long periods of time spent in the vehicle. The driver's heels may not be higher than the bottom of his seat when in a driving position, thus a level surface was given with no elevation or depression. The elevation of the heels of the driver lowers the seating position, therefore creating a lower centre of gravity.

   The level surface provides the lowest seating position possible, without infringing on the regulations. This also allows the driver to sit with eyelevel at a height of 700mm above the ground, as required by the regulations.

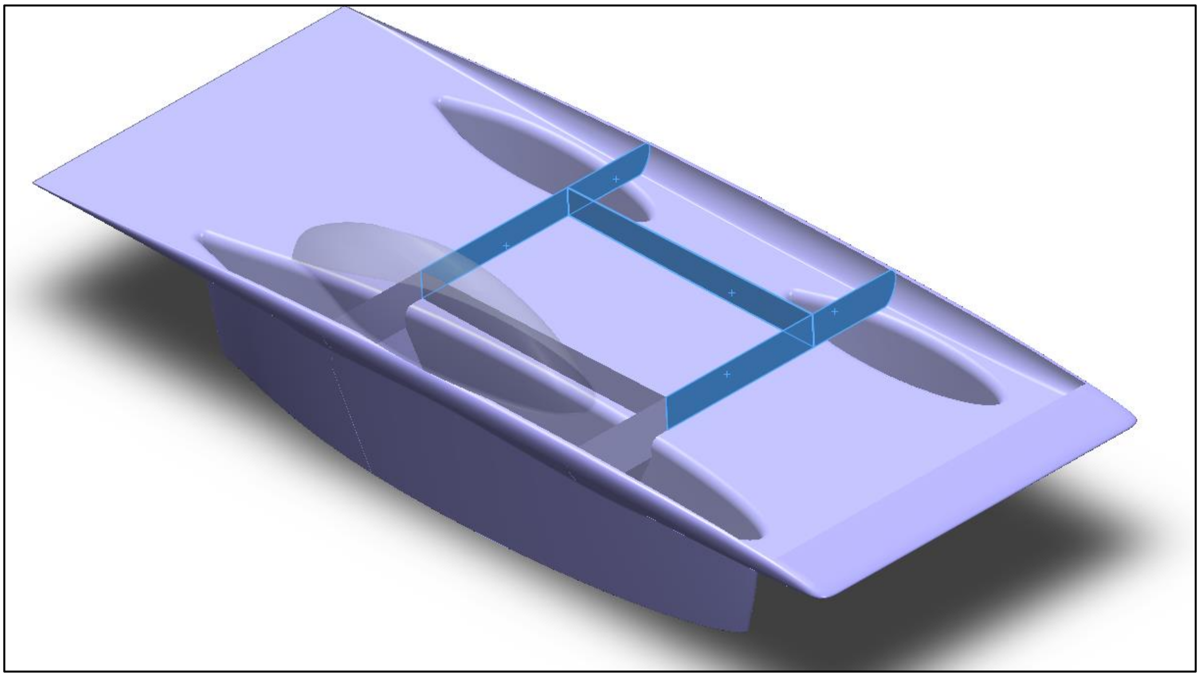

Figure 38: Central frame

2. The central section of the lower body is stiffened by connecting it to the driver section. This also allows the rear part of the diver seat and the rib in the back, to serve as mounting points for the rear suspension. The frame was drawn with 20mm or more space under the top body skin to insure enough room for the skin thickness of the body and wiring.

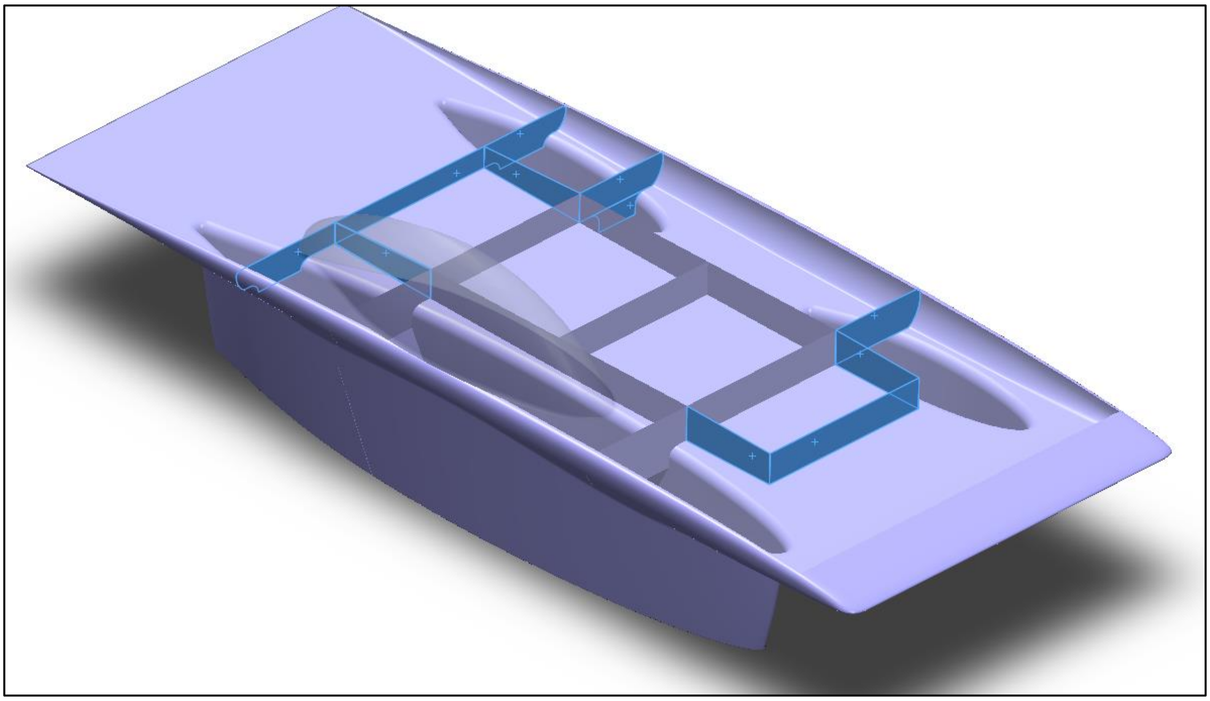

Figure 39: Central frame extension

3. Next step is to connect the front suspension mounting location to the rest of the frame configuration. This is done by extending the front of the frame forward. The remainder of the body is further stiffened by adding cross members to the centre of the frame. The rear body was stiffened by extending the frame and adding cross members to the rear wheel wells. This is to prevent flex in the wheel well due to the placement of the removable fairings.

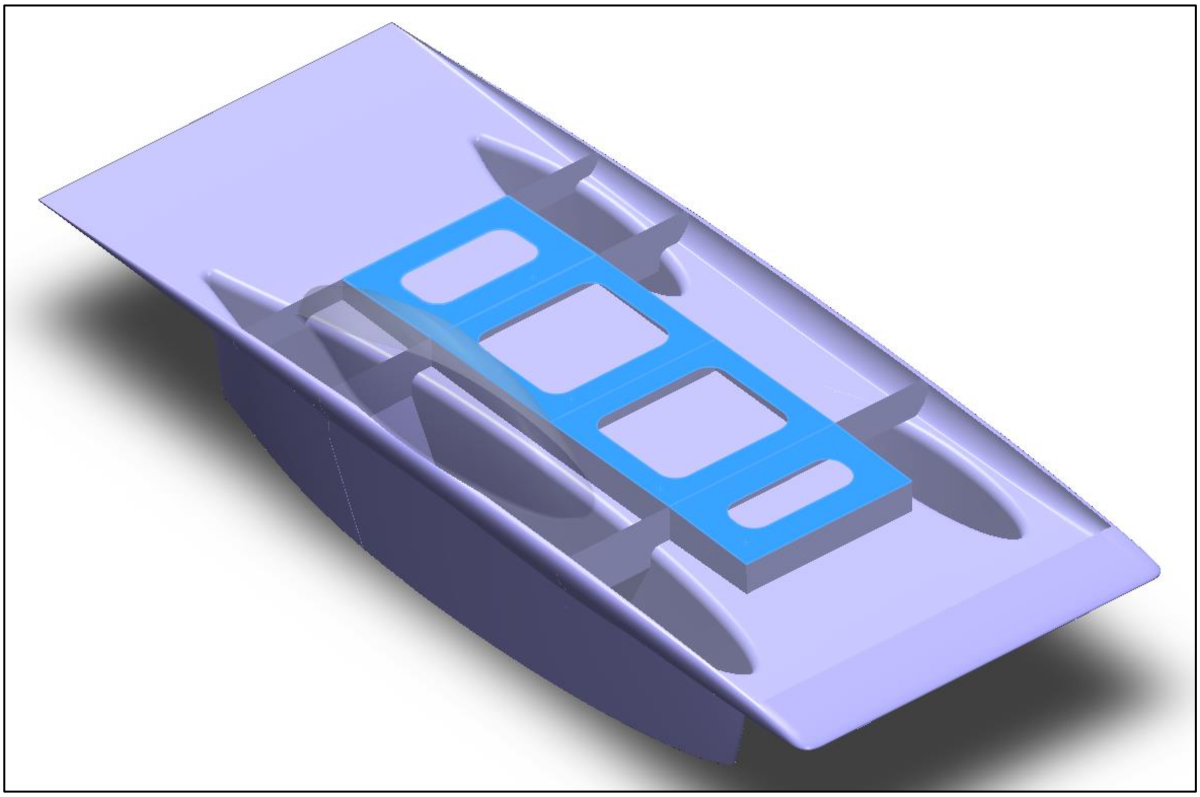

Figure 40: Frame stiffening

4. Enclosing the frame like a box would be very effective to increase the torsional stiffness of the structure.

   However this will increase the weight considerably. The same effect can be achieved by adding flanges to the top of the beam members, but for less weight.

   The exact size and thickness of these flanges will largely be dependent on the analysis of the frame under different load conditions. This was determined during the combined bending and torsion load analysis of the car frame.

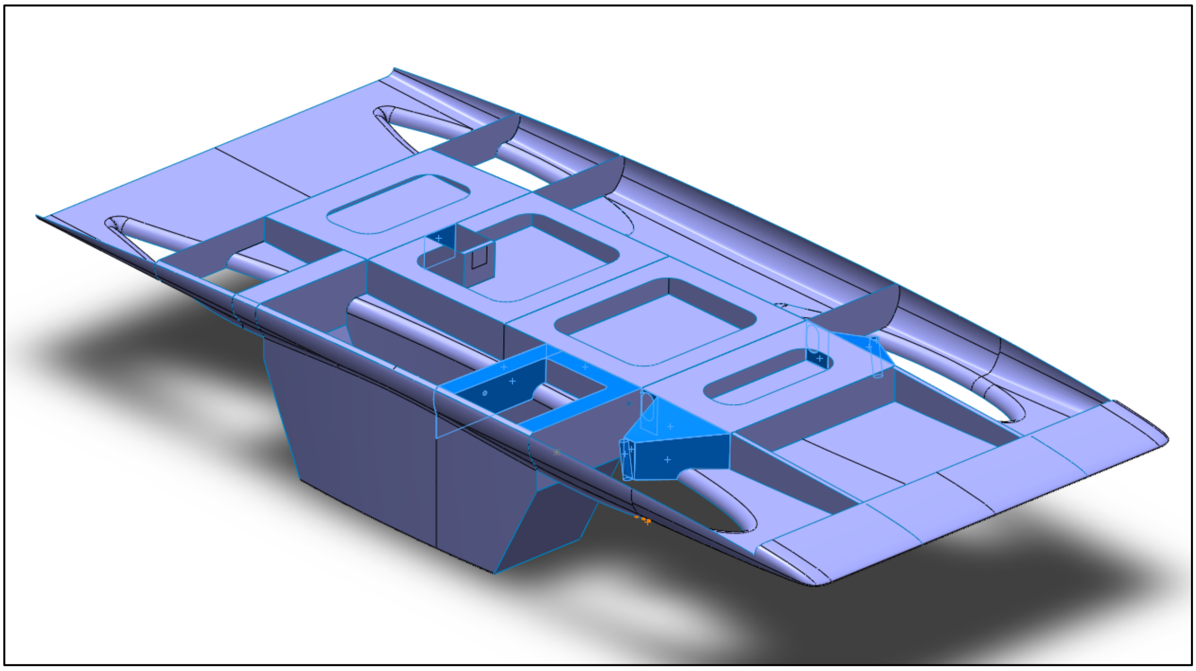

Figure 41: Frame design

5. Lastly the supporting rib for the steering wheel and telemetry is added at an appropriate distance from the driver seat, to ensure a comfortable driving position. Openings in the frame for the steering and suspension elements are made, for more accurate representation of the final structure in the finite element analysis.

The front triangular structure is added to support the front suspension. The front suspension is based on the headset of a mountain bicycle. This gave rise to the shape of the supporting structure.

6.2.2 Weight distribution

With the shape completed, the weight distribution can now be estimated. To do this the centre of gravity has to be calculated. The centre of gravity has an influence on the load calculations. The analysis on the structure was to be done later.

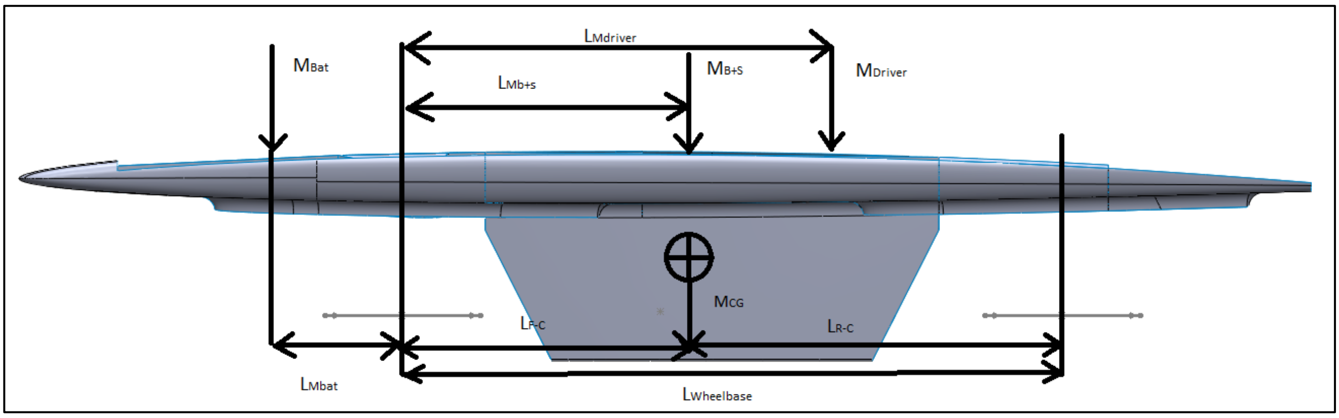

Figure 42: Car weight distribution

According to Carrol [24] the horizontal centre of gravity can be calculated with the following equation.

$$L_{F-C} = \frac{\sum M_n \times L_n}{L_{Wheelbase}}$$

With the weight distribution calculated as follow.

$$WD_{front} = \frac{L_{Wheelbase} - L_{F-C}}{L_{Wheelbase}} \times 100\%$$

And

$$WD_{rear} = \frac{L_{F-C}}{L_{Wheelbase}} \times 100\%$$

Using the equations for weight distribution on the estimated locations and weight of internal components, the calculated loads and centre of gravity location are summarised in the tables below.

Table 4: Weight Distribution

Weight distribution	
L_{F-C}	0.701m
L_{L-C}	0.849m
WD_{Front}	65.1%
WD_{Rear}	34.9%
WD_{Left}	34.7%
WD_{Right}	65.3%
Load front axel	1852N
Load rear axel	992.64N

Table 5: Suspension static loads

Suspension static loads		
	Front	**Rear**
Left	642N	344N
Right	1210N	648N

With the load calculations completed, the frame analysis can be done in order to define the material layup of the frame and body of the car. This can now be accomplished by using the load multipliers on the suspensions static loads, as previously mentioned.

6.3 Analysis

During the design process the analysis of the frame is used to define the composite material layup. This is to ensure the structure is strong enough to withstand the loads imposed on it by normal operating conditions, but still maintaining the priority of keeping the frame as lightweight as possible.

Low weight permits faster acceleration, lower tyre rolling resistance and higher hill climbing speeds. Therefore, the weight is one of the main contributing factors that influence the hill climbing and handling performance of the solar car.

It has been estimated that for a speed of 70 km/h on a level road, a 1 kg increase in weight will require an additional power about of 1.5 Watts as stated in [25].

In order to maintain a frame that is as light as possible, a minimum safety factor needs to be defined. By consulting Julian Happian-Smith [9] on vehicle design it was found that:

$$Static\ load\ \times dynamic\ load\ factor\ \leq \frac{2}{3} \times yield\ stress$$

This basically translates to the worst possible dynamic load case not exceeding 67% of the material yield stress. Alternatively this equates to a 1.5 safety factor against yield for the worst possible load condition.

The worst load cases were identified as the following, and will be discussed in the detail design that follows.

- Front, rear and torsional bump loads
- Cornering and braking as a combined load case
- Impact loads on the front, rear, left and right side of the car frame
- Roll bar loads as stated by the FIA regulations

Many other smaller loads are present and it was seen fit to analyse them as well. The previously mentioned load cases are the main contributing loads to the overall material requirements of the frame. The other loads, such as the battery compartment load and deflection are small and do not contribute much to the overall safety or reliability of the solar car. Thus any additional load analysis are not mentioned, but was added to the appendix for further information.

6.3.1 Finite element mesh

Depending on the modeller package being used, it has to be insured that the model is in the proper unit of measure and that a sufficient mesh size has been selected for the meshing process. As with the validation chapter, the processing program used to analyse the structure is the MSC Patran and Nastran processor and solver.

The same method of defining the mesh, with the auto surface meshing function, was used as with the validation. To ensure an accurate result, the mesh size for the analysis of the car must be determined. This is to ensure the results given by the analysis are independent of the mesh element size. To determine if the results of the analysis are independent of the mesh size, a mesh independence study had to be done. To accomplish this, the frame of the car was subjected to a load case analysis with all the variables kept constant, except for the mesh that was varied, to find the desired mesh size. This is to find the smallest element size and to eliminate any influence it may have on the analysis results.

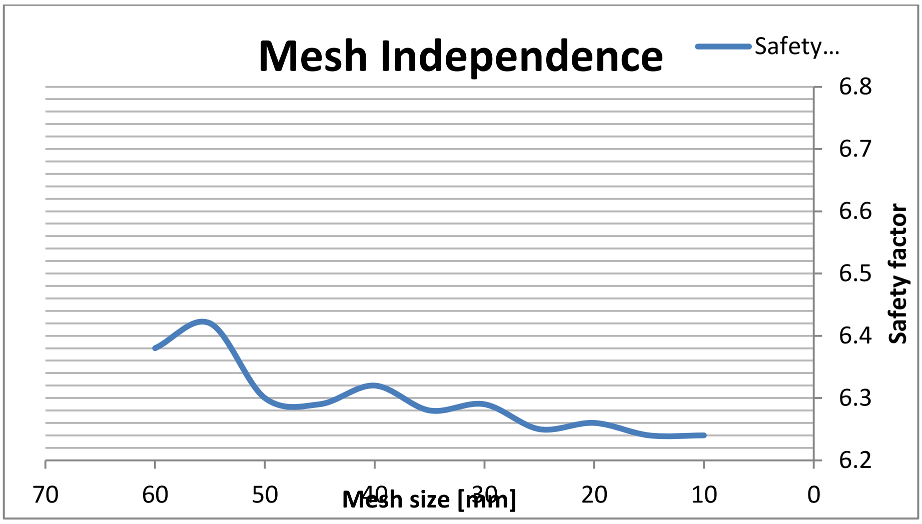

Figure 43: Mesh Independence

In order to eliminate the effect of the mesh element size on the results, an analysis was done on part of the frame to determine the largest usable mesh. From the results of the analysis, it was found that the results stabilised after the mesh element size was 30mm or smaller. With an overall difference in results of 2.52% from a mesh size of 60mm to 10mm.

The conclusion was to use a mesh size of 20mm to 15mm for the analysis of the solar car frame and body. This is based on the fact that the processing and memory requirements increase exponentially with the decreasing mesh size, therefore increasing the solving time of each analysis. This decision was based on the fact that the change in results between 20mm and 10mm was only 0.32%, making the difference in results negligible. The difference in memory requirements for 20mm is only 900Mb whereas the memory requirement for 10mm mesh element size was 4000Mb. Making the use of the 20mm mesh size more preferable than the 10mm.

The use of a mesh smaller than 30mm, even when it delivered results very similar to 20mm was mainly due to the model geometry. The solar car frame has some features that are smaller in dimension than the 30mm mesh size, but can use the 20mm mesh. This allows for a better representation of the frame geometry without losing details of the frame. These details can include large radiuses between the surfaces of the body.

When using a model that consists of two-dimensional surfaces it has to be insured that the mesh of each surface sharing a border has the same element nodes. This will allow for the proper utilisation of the structure as a whole and not just local stress concentration, but a uniform stress distribution.

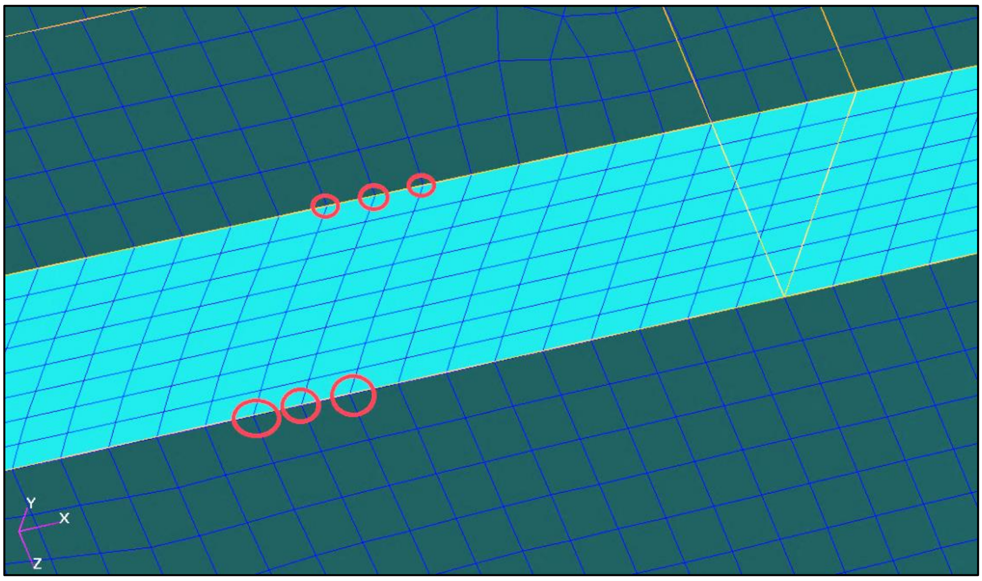

Figure 44: Mesh node alignment

In the case of mesh misalignment it can be rectified by a number of methods.

The main two are: - Increasing the auto surface mesh function's tolerance value.

- To redraw the section of the frame and to insure proper alignment of the edges shared between two or more surfaces.

6.3.2 Analysis method

In this design development it was decided that it will save time to define the model surfaces as the minimum amount of material practically possible for the construction techniques, used by the team's technical support. This layup consists of 4 layers of bidirectional carbon fibre with 3.5mm core, two on either side of the core. Using less than two layers on either side causes distortions in the plies that can have a detrimental effect on the structural strength of the body.

The initial material distribution was kept symmetrical throughout the thickness of the individual layups of the carbon fibre for each surface. The ply orientation can be either 90 degree or 45 degree plies. For the first run, the best results can be expected alternating between the two directions in a symmetrical form throughout the layup even when adding more plies.

The following steps are used to minimisation of the structures components:

Step 1

After the finite element model has been solved for the particular load case the next step is to identify the critical locations of the structure for that case. These locations can be identified by calculating the safety factor for each of the plies in the layup. Most modelling packages have the capability to do this calculation.

Step 2

After the critical components have been identified, the process of strengthening the structure can begin. This is done by adding core material and carbon plies to the layup of the critical components and re-running the analysis until the desired safety factor of 1.5 is reached.

Step 3

Once the specified safety factor has been reached, the theoretical weight of that component can be calculated. The goal is the weight minimisation of each component.

By reducing the thickness of the core and increasing the carbon fibre plies while keeping the safety factor the same as before, the new weight of the component can be calculated. Comparison between the first and the altered component is now possible.

If the result is favourable and the weight of the new configuration is less than the first, the process of replacing core thickness with carbon fibre plies can be repeated until the weight reduction equalises. At this stage the minimum weight of the component is achieved while still maintaining and withstanding the induced load strength.

If, on the other hand the weight increases, the amount of carbon fibre plies in the layup is too large. In this instance the opposite should be done. Increasing the thickness of the core while reducing the layup of the carbon fibre by one or two plies, still maintaining the symmetry of the layup.

Recalculate the weight after the specified safety factor has been reached and compare it to the previous weight calculation. Repeating the process of reduction in carbon fibre plies and increasing the core thickness until the lowest weight is reached for that structural component.

Furthermore, if a section of the frame was identified as a critical component in a previous load case analysis, it can only be strengthened by increasing the number of plies or increasing the core thickness. Reduction of the thickness and strength in this section could possibly compromise the previous analysis.

The weights of the components are calculated using the density of the respective materials used, such as the carbon fibre and Airex core material. This is possible because the surface area and thickness of the laminate and core material is known and the density of the core materials are given by the manufacturer. The density of the carbon fibre plies were calculated by using a sample manufactured by the team.

These guidelines were developed in this design and were applied to the various load cases during the analysis.

6.3.3 Front bump load

The front bump load was developed to analyse the frame strength when subjected to a bump load on one of the front suspension mountings. This can happen when the car encounters an imperfection or road bump during operation.

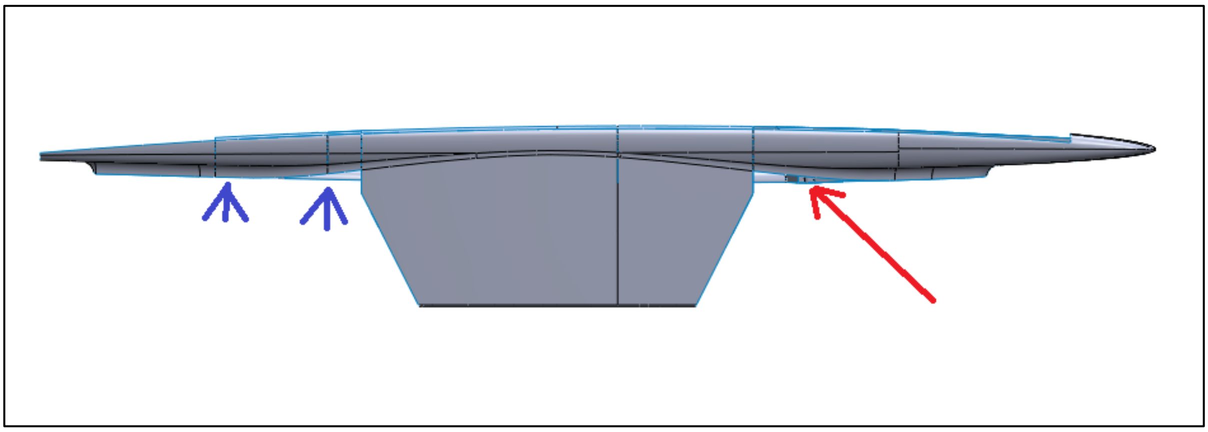

Figure 45: Front bump load

The front bump load was applied on the front suspension mounting location (red marker) on the one side as a combination of the vertical and horizontal static load, multiplied by the dynamic load multipliers for this particular case. The frame was constrained at the back (Blue marker); this was done to do a bending and torsional load analysis on the frame.

This serves as a worst case scenario load, to test the overall strength of the mounting locations along with the frame bending and torsional load strength.

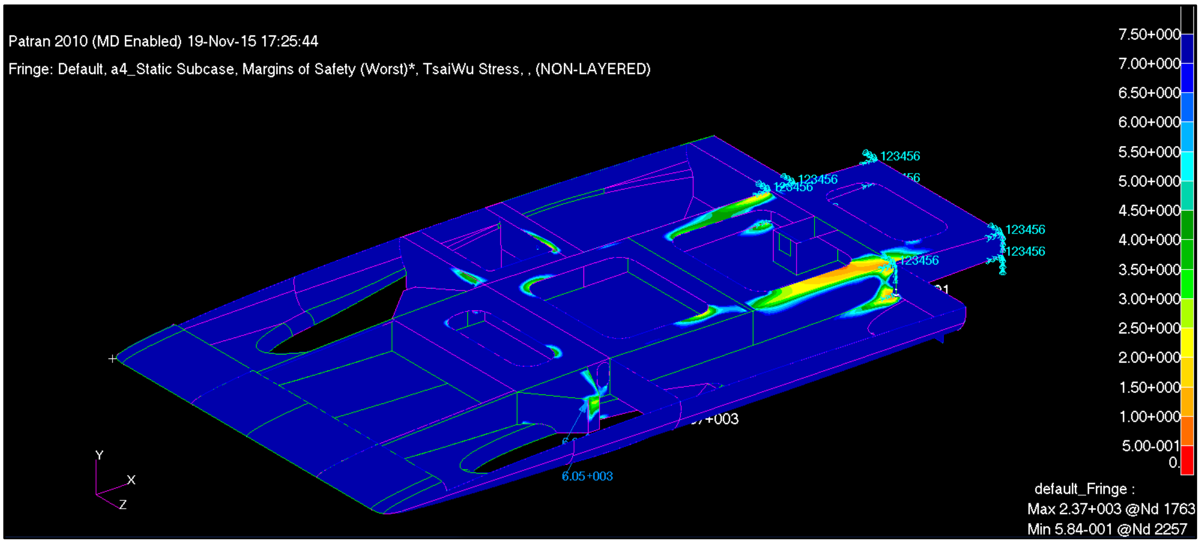

Figure 46: Analysis front bump one wheel

During this test the frame main beams and beam flanges were identified as the critical components requiring material strengthening. These sections are highlighted as the orange and green sections above. The flange width was adjusted in size as well, to find the lowest weight for this particular component. It was found that increasing the flange size only increased the weight of the components without any significant change in the safety factor. This resulted in the design above with a medium sized flange with the minimum safety factor of 1.584 at the intersection of the flange and beam.

Table 6: Front bump analysis results

Component	Carbon plies	Core thickness [mm]	Weight [kg]
Revision 1			
Beams	4	18	1.96
Flange	8	20	5
Revision 2 (6.3% weight saving over Rev 1)			
Beams	6	3.5	1.7

Flange	10	3.5	4.43

It can be concluded: For this load case that consisted of bending and torsion loads acting on the frame, that the revision 2 configuration of more plies and a thin core was the lightest.

After the frame was strengthened, the bump load was applied to both the front suspension mounts to test the strength of the local structure. The frame was constrained at the mid-section to find the local stress in the mounting structure.

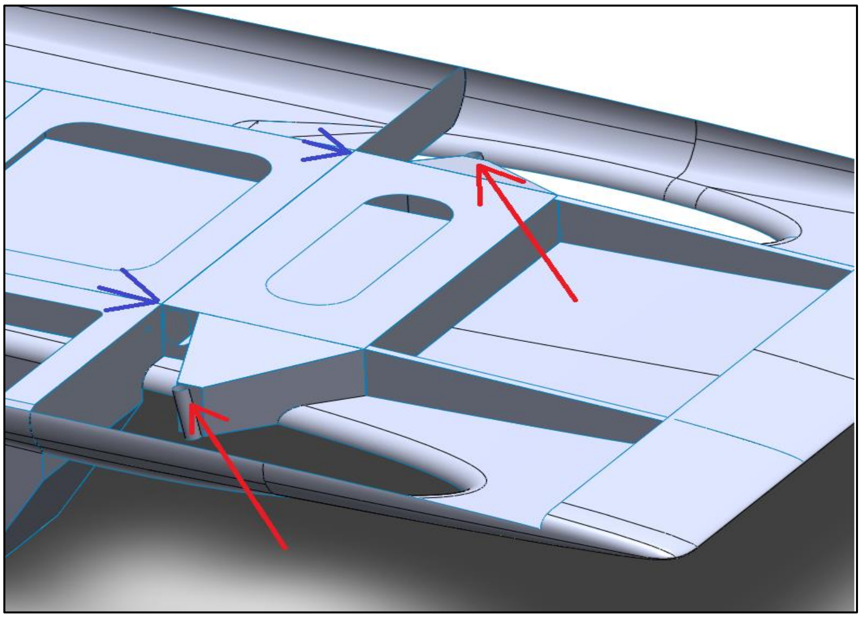

Figure 47: Front suspension mountings load

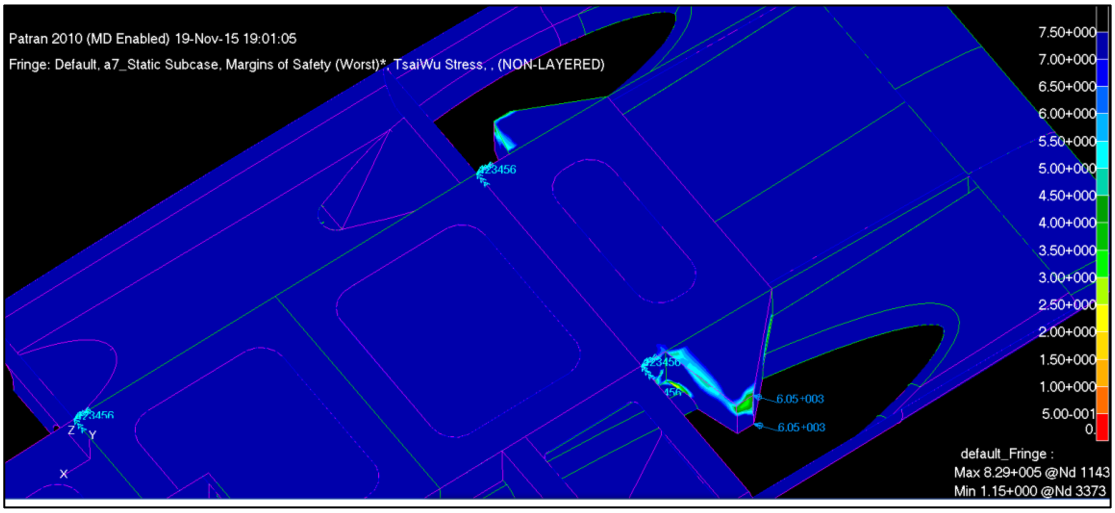

Figure 48: Front suspension mounting bump

The minimum safety factor for the front suspension mounting locations were found to be 2.15, therefore no changes were necessary.

6.3.4 Rear bump load

In order to strengthen the rear suspension mounting locations, the rear bump analysis was done.

The load was comprised of a torsional load. The torsional load was calculated from the vertical and horizontal loads that would act on the swing-arm suspension, to accurately represent the loads that were to be present on the mounts. This was due to the fact that the rear suspension consisted of a unique swing-arm torsion tube suspension. This type of suspension was conceptualised by the team to address the known stability issues of solar cars. Analysis on these subjects was done by the author of this paper but was not part of the thesis and will be added in the appendix for more information.

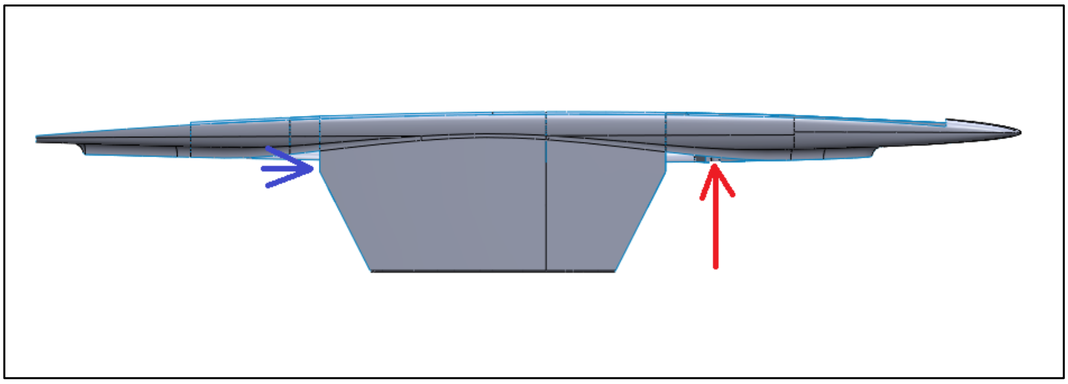

Figure 49: Rear suspension bump

To create this torsional load on the structure, the rear suspension mounting location was constrained and the load was placed on the front of the frame. This load was converted from the sum of the torsional load calculated and converted to a vertical load a certain distance from the rear mounting location.

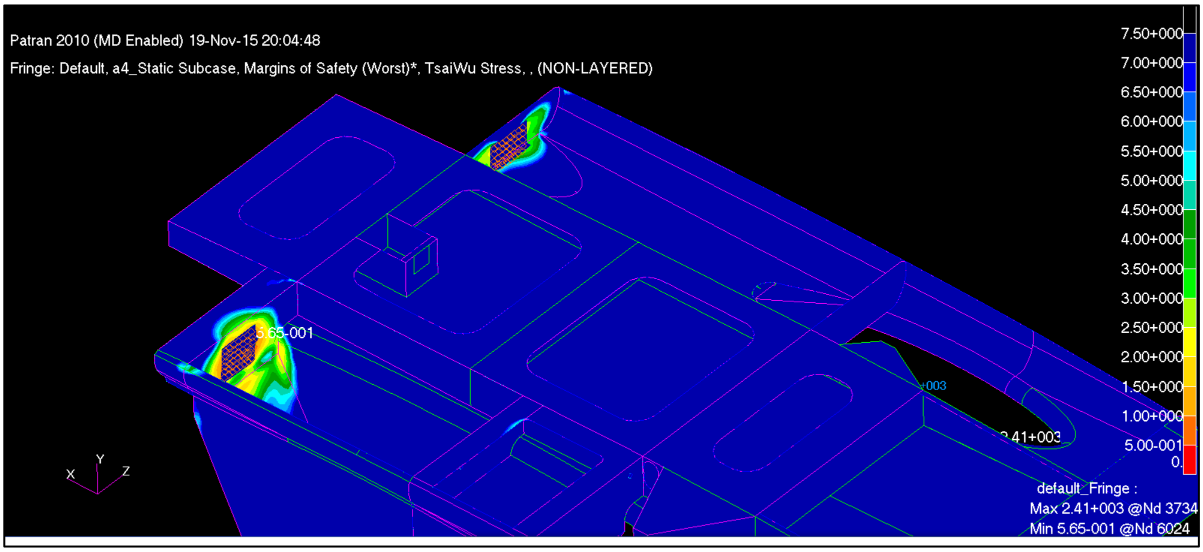

Figure 50: Rear suspension mount stress

In the analysis of the rear suspension mountings returned a minimum safety factor of 1.56 on the driver side. This can mainly be attributed to the stiffer structural shape of the mounting location. But it was decided to keep both mounting layup schedules the same.

Table 7: Rear suspension mounting stress

Component	Carbon plies	Core thickness [mm]	Weight [kg]
Revision 1			
Left and Right mount	12	13.5	1.034
Revision 2 (24% weight saving over Rev 1)			
Left and Right mount	6	15	0.637

From this analysis it can be concluded that the weight of the configuration can be significantly reduced by slightly increasing the core thickness and reducing the carbon fibre plies. It can therefore be concluded that the mounting structure only needed to be stiffened and not strengthened with more plies.

6.3.5 Cornering load

The next load to consider is the cornering loads on the suspension mounting locations. To accomplish this, the forces acting on the mounts were converted to a moment load. This moment load is represented by restraining the suspension mounts and applying a force on the frame to create the same loads that would be acting on the supports at the time of excessive cornering.

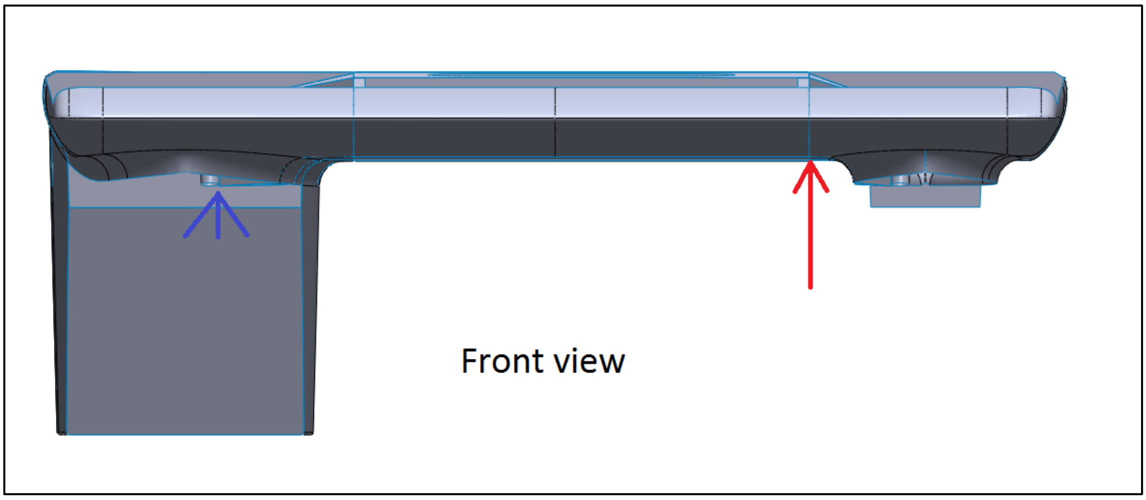

Figure 51: Front view cornering load right side

Both the left and the right side mounts are subjected to this load test to insure the supports are of sufficient strength.

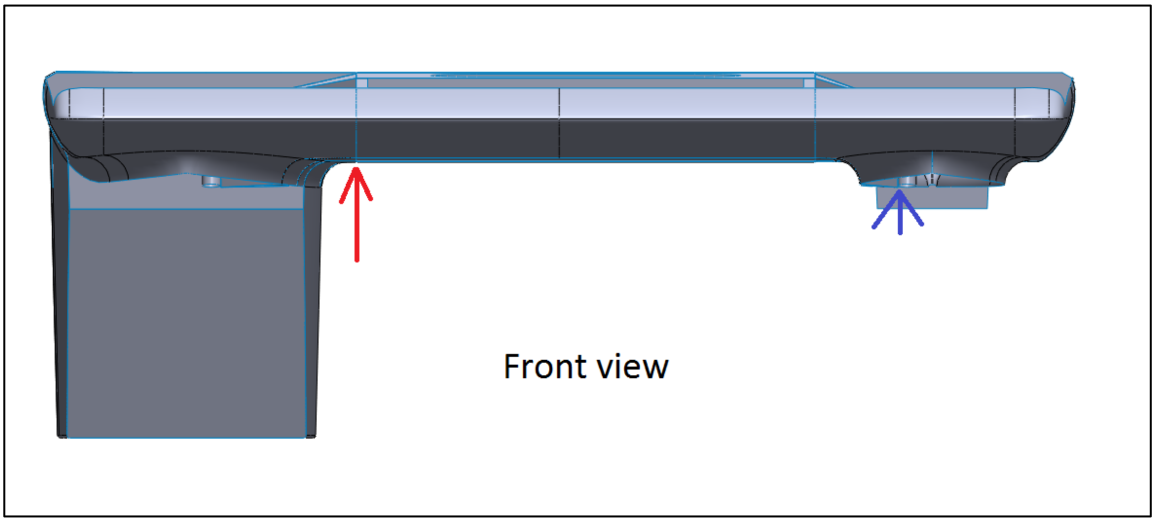

Figure 52: Front view cornering load left side

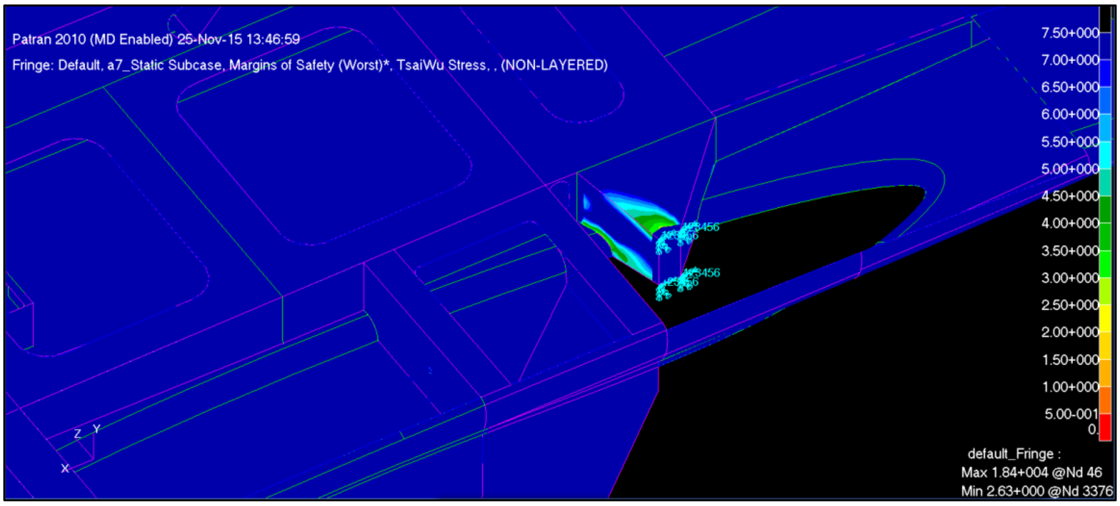

Figure 53: Cornering load analysis results

The cornering loads alone returned a minimum safety factor of 3.63 on the top and bottom parts of the suspension mounts. Similar results were returned by repeating the loads on the other suspension mounting points. Thus no changes to the material layup were needed, but the scenario of severe cornering is rarely ever done without applying the brakes as well. Therefore the need to combine the cornering and braking loads as one load case existed and will be investigated next.

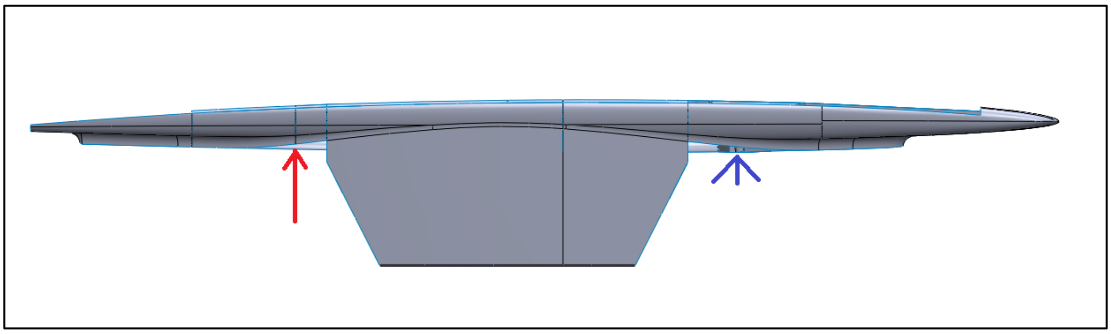

Figure 54: Braking load

In a similar way, the cornering load applied to the braking load, was applied to the frame. This load was added to the previous analysis to combine the cornering and braking loads into one combined load case. This is to insure that the suspension mounts can withstand severe control inputs during times of emergency.

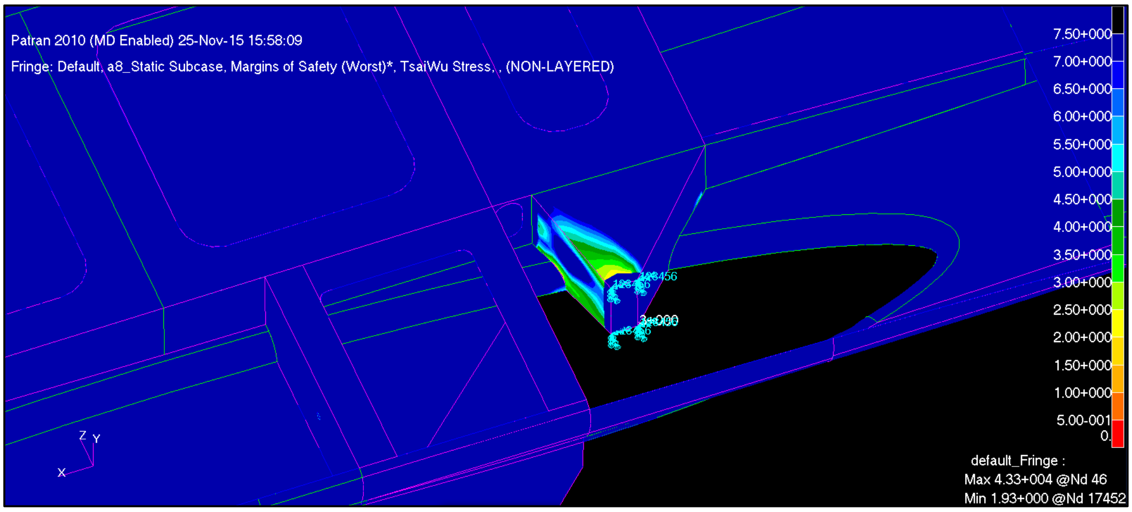

Figure 55: Combined cornering and braking load

The analyses on the frame suspension mountings under the combined braking and cornering loads have returned a minimum safety factor of 2.93. The right front side mounting location was identified as the point with the lowest safety factor. The other locations were analysed in a similar fashion, and returned higher safety factors as the right front mount. This being the point with the largest load as calculated from the weight distribution, it can be assured that the mountings have theoretically sufficient strength to withstand the loads required without changing the composite material layup. Any further weight reduction would be unnecessary due to the fact that the layup does not change from the minimum material layup as described by the analysis method in section 6.3.2.

6.3.6 Impact loads

The impact loads on the frame of the solar vehicle were prescribed by the organisers of the event. These loads were defined as 5 times the weight of the car as a static load on the frame and driver compartment.

Front impact load

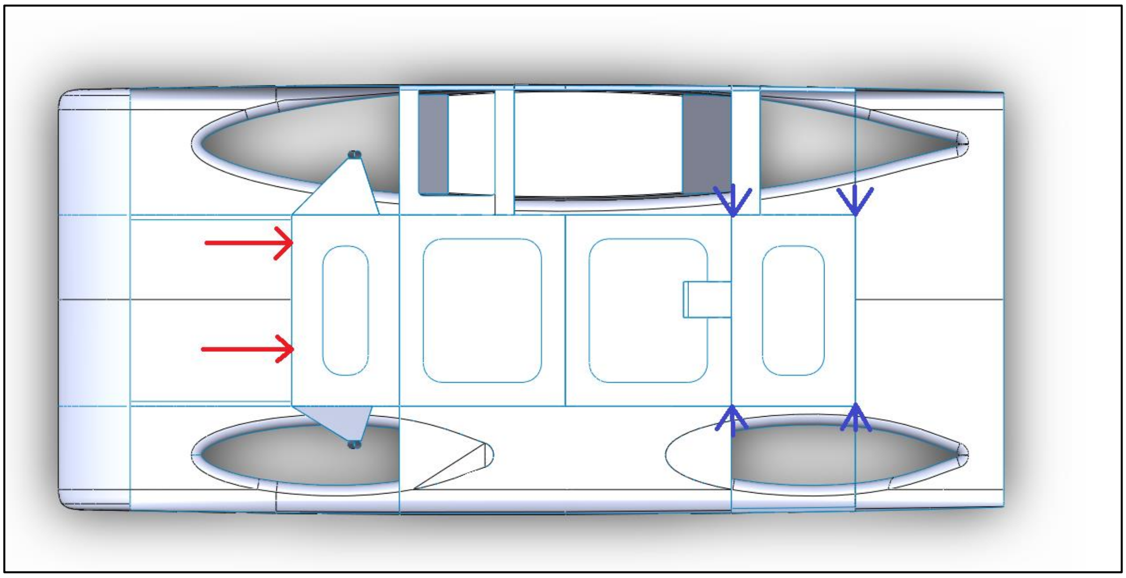

Figure 56: Front impact load

The front impact load was applied across the frontal area of the frame to test for sufficient strength as demonstrated above in red. The chassis was constrained at the rear of the frame as shown in blue in Figure 56.

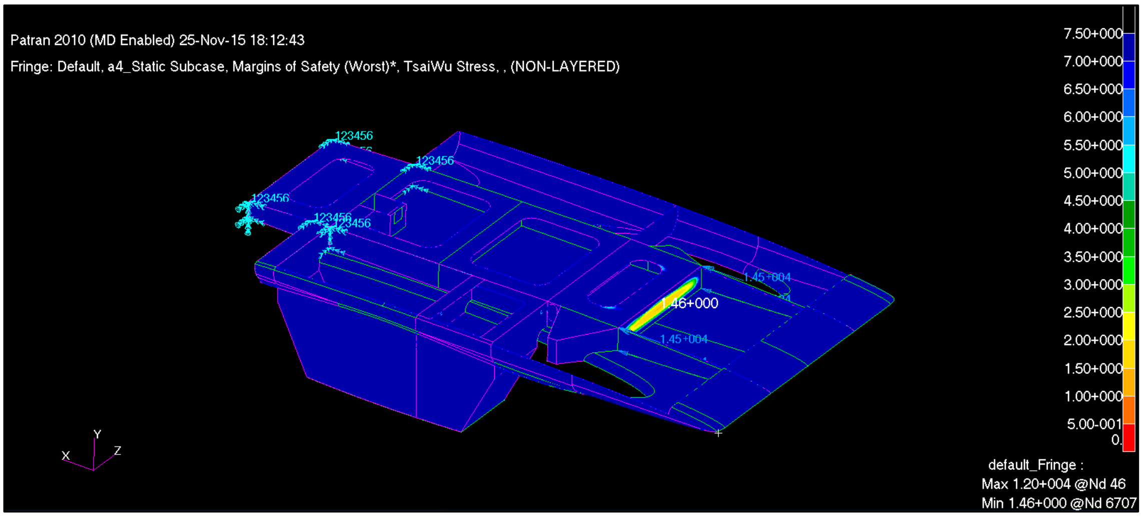

Figure 57: Front impact load analysis

The analysis on the frame's frontal impact load returned a minimum safety factor of 2.46, thus no changes were necessary. This demonstrates that the frame would be able to withstand a moderate impact from the front even at the cost of losing the nose and battery compartment. This ensures that the frame is not compromised during an accident and endangering the driver.

Rear impact load

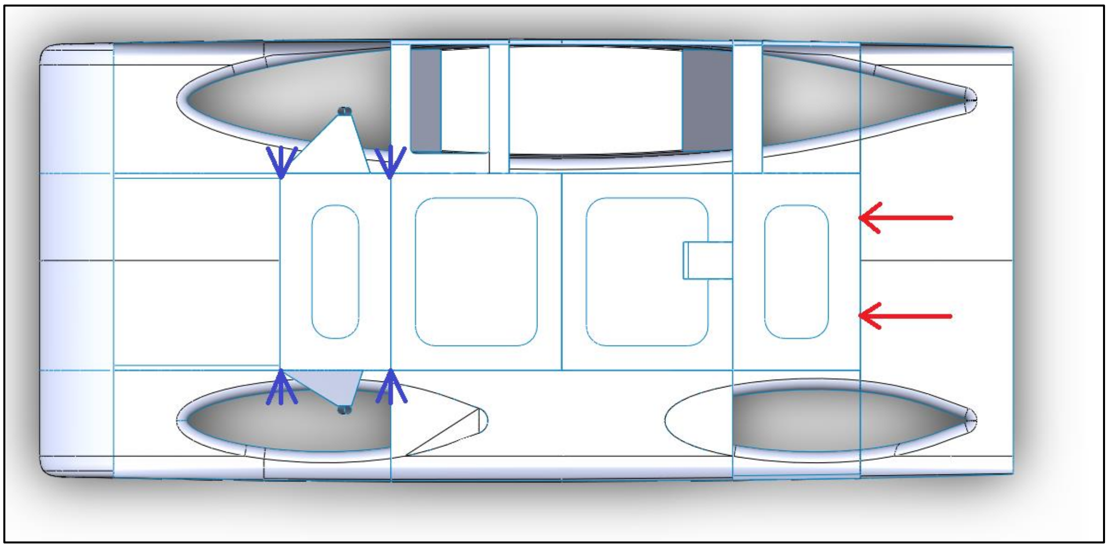

Figure 58: Rear impact load

Same as with the front impact load, the frame was constrained at one end and the load representing the impact load was applied to the rear surface of the frame.

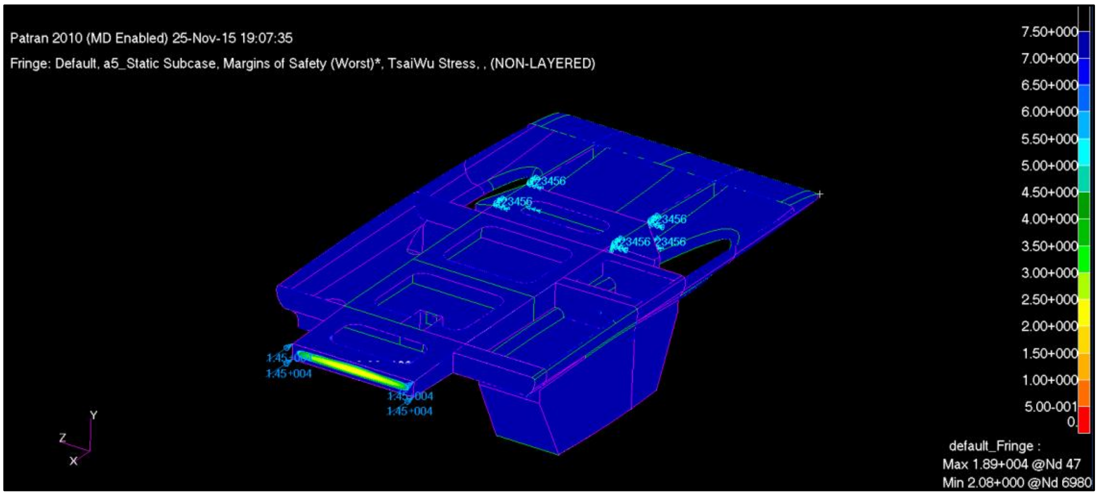

Figure 59: Rear impact load analysis

The minimum safety factor of the frame in the event of a rear impact is 3.08, therefore no changes to the material layup was required.

Left side impact

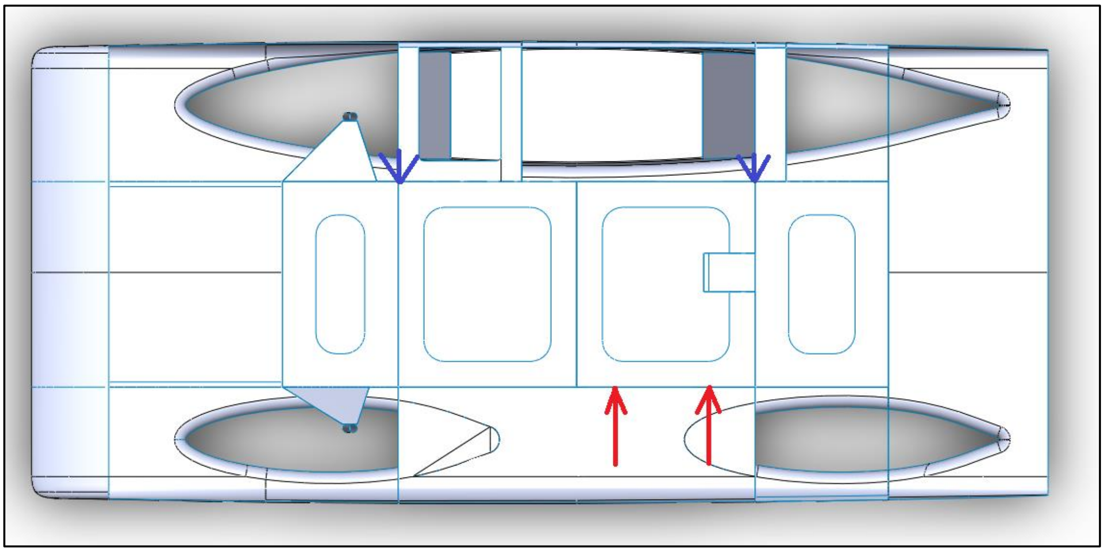

Figure 60: Left side impact

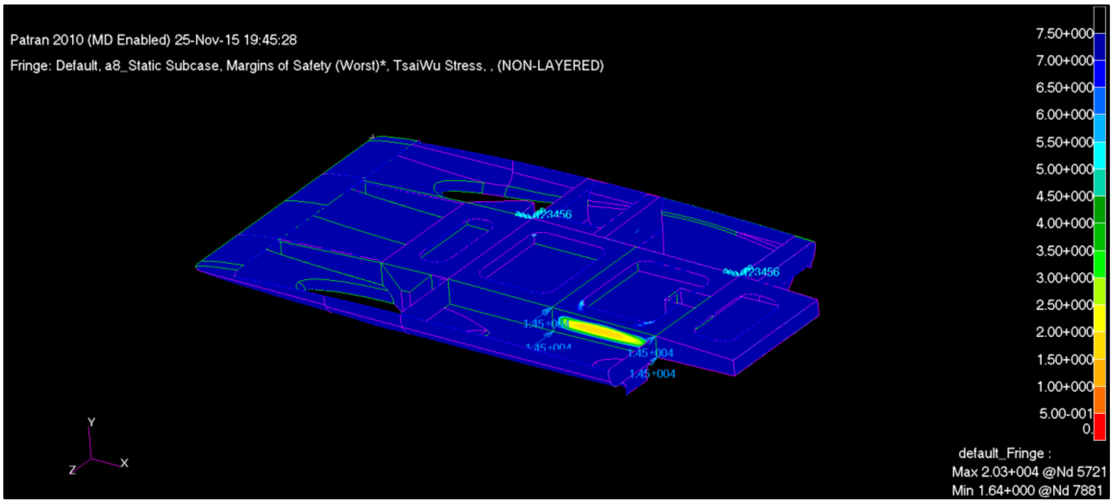

Figure 61: Left side impact analysis

The left side impact analysis was applied to a portion of the frame on the left side, returning a minimum safety factor of 2.64. The frame required no changes to strengthen it.

Right side impact (Driver compartment)

The last impact load analysis was on the right side of the solar car. This is where the driver is located and one of the most important factors in the impact load analysis on the car.

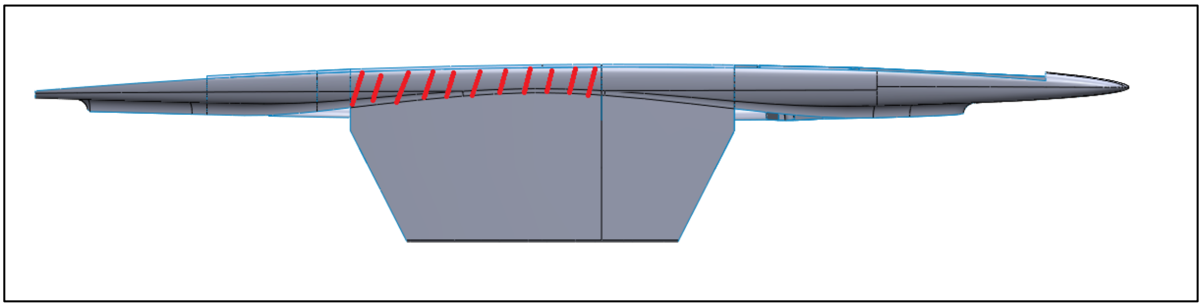

Figure 62: Driver side impact bar

To protect the driver without drastically increasing the weight of the body on the right side, only a portion of this side will be strengthened. The indicated part of the body in the above figure will be used as the side impact bar. This impact bar is at a good height to protect the driver’s upper body from an impact on the right side of the solar car.

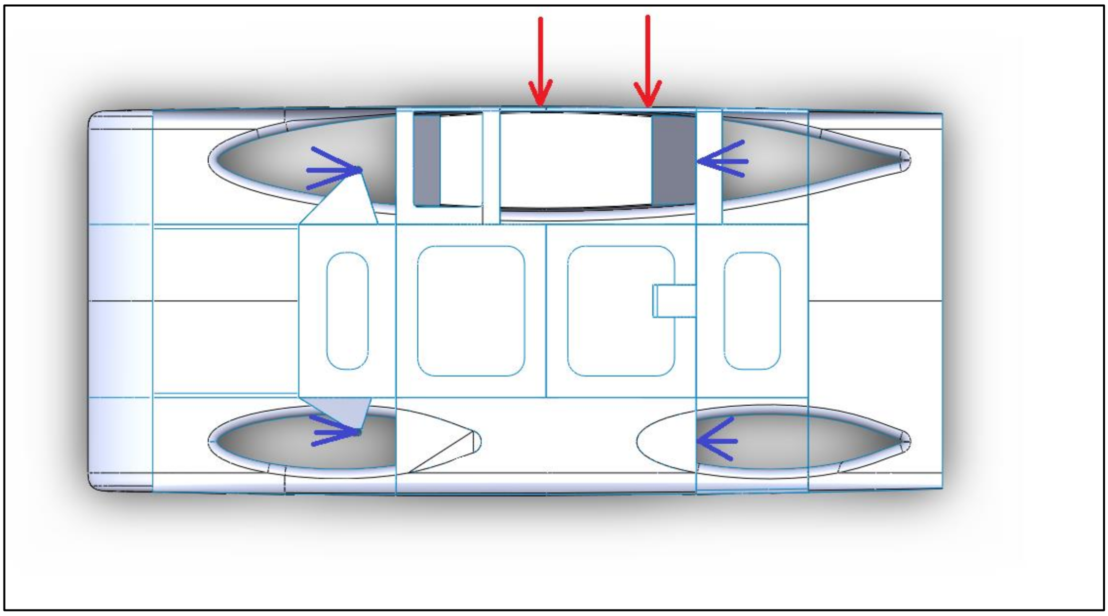

Figure 63: Driver side impact load

The frame was constrained at the suspension mounting locations in order to test the strength of the side impact bar. The impact load was applied across the side of the body along the impact bar. The purpose is to protect the driver, as illustrated in Figure 63.

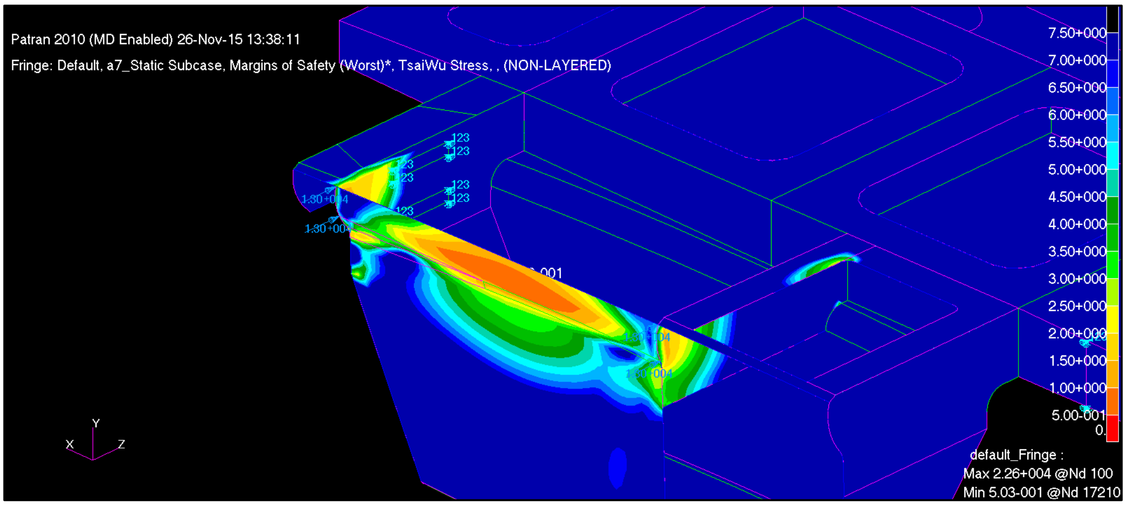

Figure 64: Driver side impact analysis

The analysis revealed that strengthening the side beam and front supporting rib in the centre of the driver compartment was required. This was done by following the same method as described in the analysis method section.

Table 8: Driver side impact analysis results

Component	Carbon plies	Core thickness [mm]	Weight [kg]
Revision 1			
Side impact beam	14	33.5	0.775
Front support rib	4	23.5	0.355
Revision 2			
Side impact beam	12	40	0.751
Front support rib	6	10	0.323
Revision 3			
Side impact beam	10	50	0.754
Front support rib	8	16	0.454

The results from the analysis method returned a side impact beam with a minimum safety factor of 1.503, therefore revision 2 was used. Additional changes to the beam material layup would negatively affect the weight of the beam and intrude further into the driver compartment.

6.3.7 Roll bar loads

The next loads that were analysed was the roll bar loads. These were given by the regulations as described in the FIA documentation [20]. In the regulations the horizontal load had to be applied in the forward and aft direction, with all the other loads acting on the roll bar at the same time. This created the need to analyse the roll bar structure in two stages.

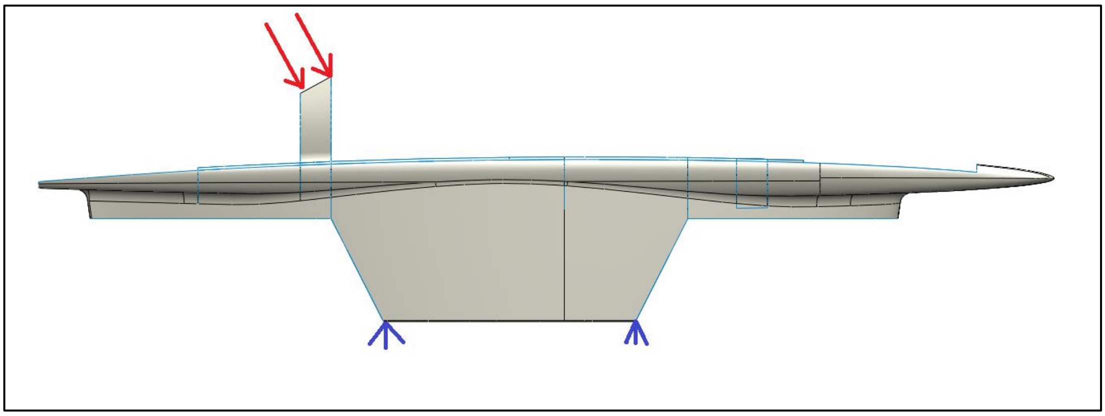

Figure 65: Roll bar forward loads

For the first forward load the body was constrained at the bottom of the driver compartment. The loads were applied at the top of the roll bar simultaneously.

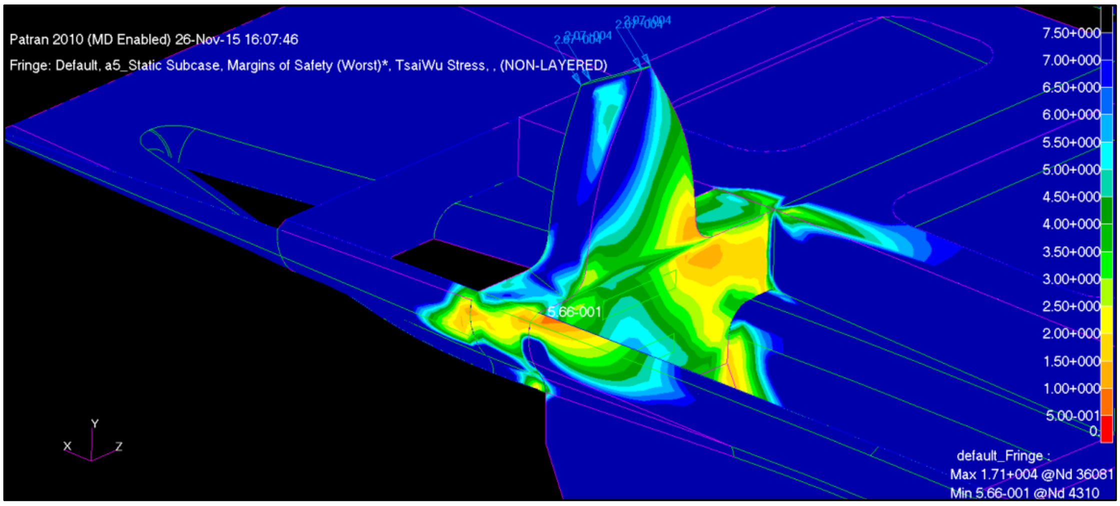

Figure 66: Roll bar forward load analysis

In the forward load analysis the minimum safety factor was 1.56 for revision 2. The critical structures were the roll bar, the right side suspension mount plate, and the roll bar base plate.

Table 9: Roll bar analysis

Component	Carbon plies	Core thickness [mm]	Weight [kg]
Revision 1			
Roll bar	10	30	1.1
Roll bar base plate	8	20	0.374
Right side suspension mount	6	40	0.583
Revision 2			
Roll bar	14	3.5	1.01
Roll bar base plate	10	8	0.36
Right side suspension mount	8	23.5	0.525

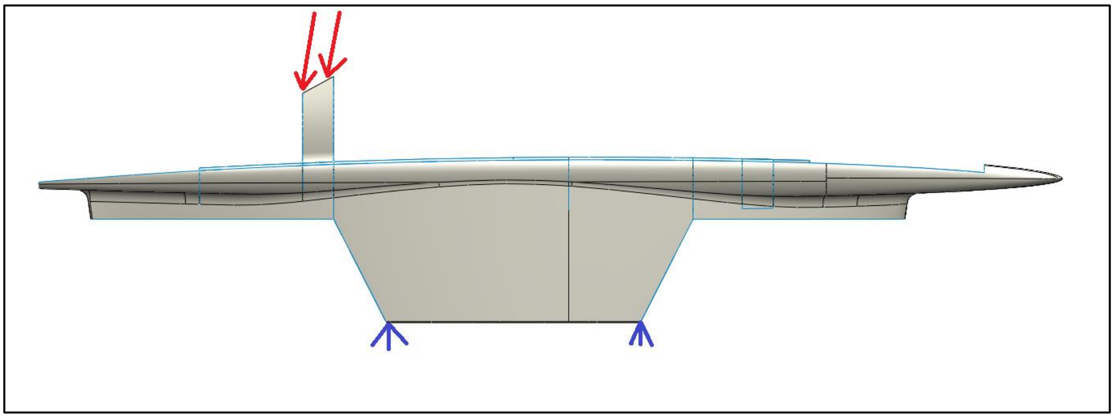

Figure 67: Roll bar aft loads

In exactly the same way the forward loads were applied, the aft loads were analysed on the roll bar structure. The same constraints and application region was used for this load analysis.

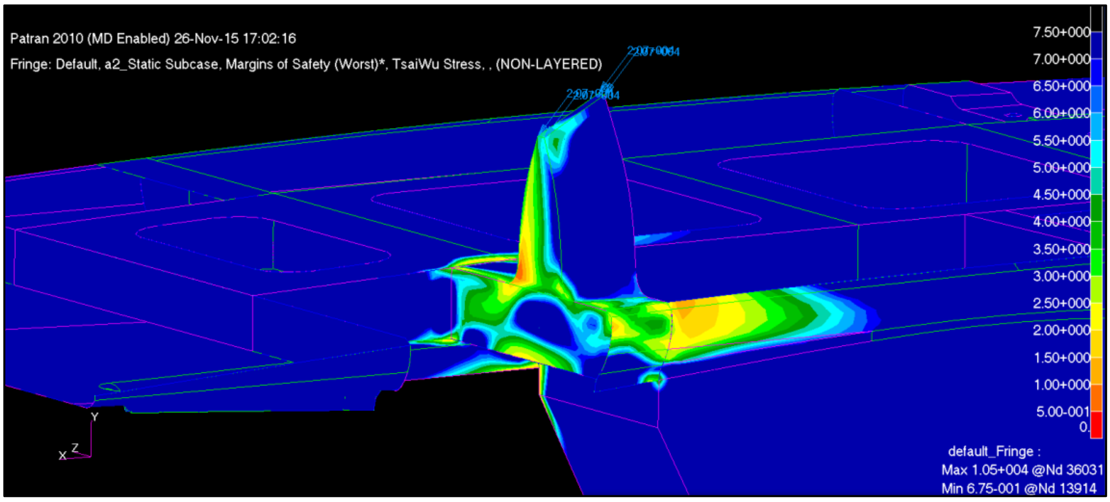

Figure 68: Roll bar aft load analysis

In the aft load analysis, the roll bar material layup stayed the same. The only structure that needed strengthening was the rear supporting beam connected to the frame. The beam was strengthened resulting in a minimum safety factor of 1.67 at the connecting point between the beam and roll bar structures, highlighted with orange in Figure 68.

The regulations also placed a maximum deflection constraint on the roll bar at 50mm, but after the structural analysis was done the maximum deflection of the roll bar was shown as 19.5mm, therefore satisfying this requirement as well.

6.3.8 Rear shock absorber load

A final last minute addition to the frame was a rear shock absorber mount plate. The plate had to be able to withstand the loads of both the rear wheels. This is due to the fact that the rear wheels were connected with an axel through the body of the car, as shown below. This design was selected to improve a known problem in the handling character characteristics of lightweight solar vehicles.

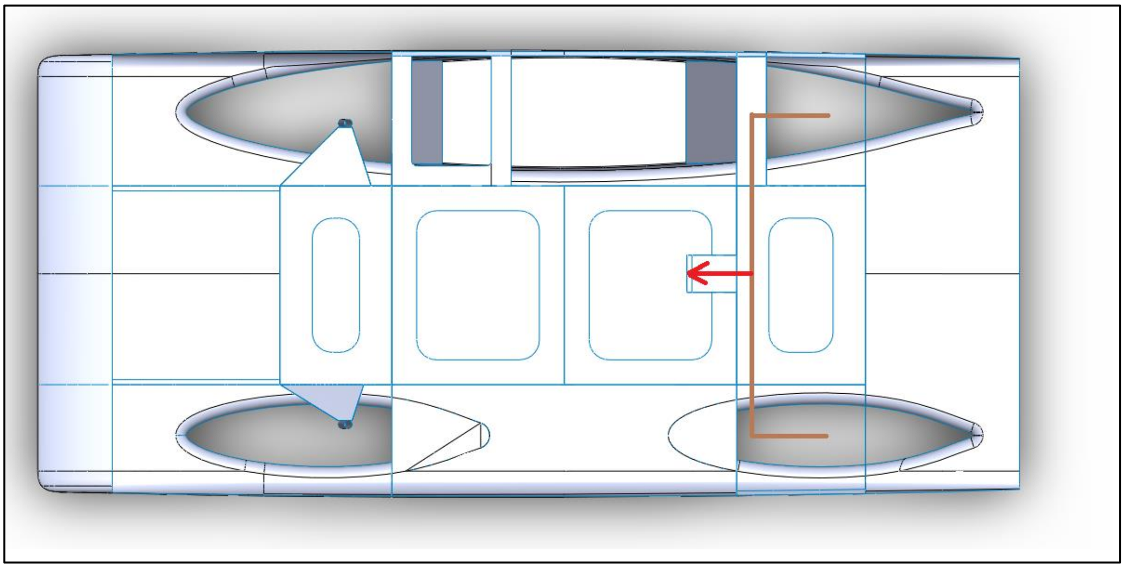

Figure 69: Rear shock absorber axel load

The load of the axel on the support plate was calculated using the bump loads of the rear wheels as a moment around the axel, as seen in Figure 70.

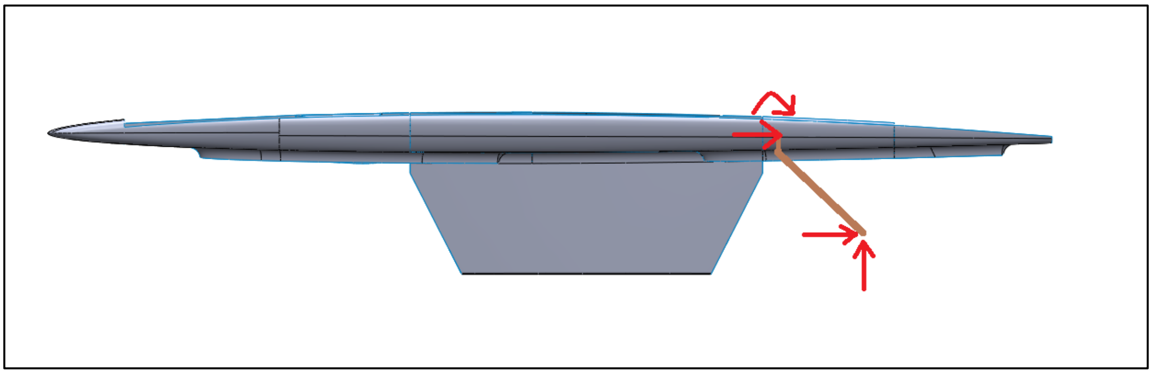

Figure 70: Rear shock absorber bump load

The load on the support plate was calculated at 15400N after converting it to a linear load. This load was applied to the support plate as shown in Figure 70.

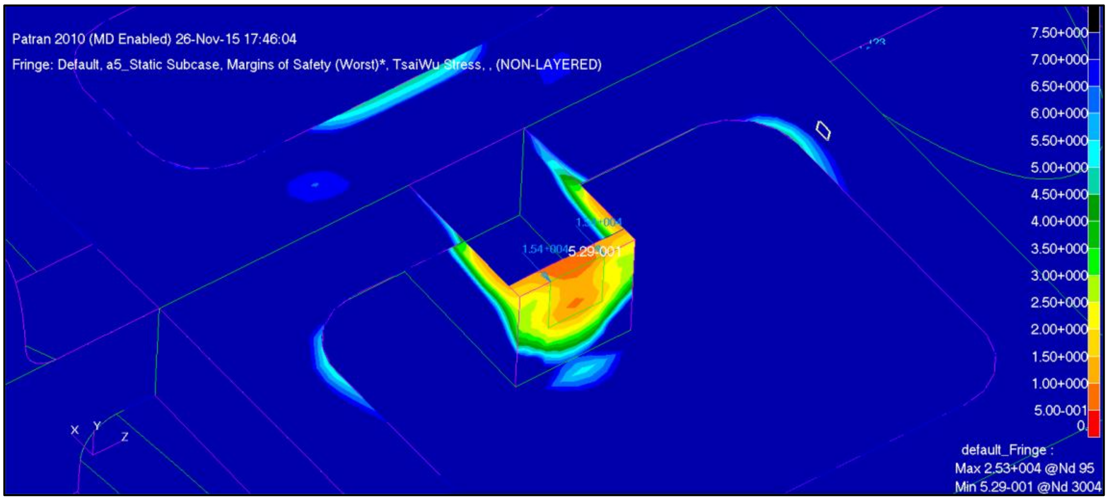

Figure 71: Rear shock absorber mount

The analysis on the support returned a minimum safety factor of 1.53 on the base plate of the shock absorber. This area of minimum safety factor is shown in the figure above as the orange highlighted section.

Table 10: Shock absorber mount analysis

Component	Carbon plies	Core thickness [mm]	Weight [kg]
Revision 1			
Base plate	12	20	0.348
Revision 2			
Base plate	14	6	0.185

From the results it can be seen that the base plate for the shock absorber required a fairly large amount of layup of carbon fibre plies. The sides of the box only required the minimum amount of carbon fibre plies. Carbon fibre is better at withstanding tension loads rather than compressive loads. This is supported by the material properties included in the appendix.

6.4 Summary

The main loads on the frame was defined and analysed for strength and safety. The shape of the body of the solar car was determined and the frame designed, making provision for the positions of the suspension and internal components. The most important loads were analysed to ensure that the frame is reliable during normal operating conditions.

The World Solar and Sasol Solar competition imposes regulations regarding impact zones and the roll bar safety, to insure the safety of the driver in the event of an accident. The loads on these impact areas and the roll bar safety zones were analysed.

Sections of the driver compartment that were not affected during the analysis on the frame have been stiffened by increasing the core thickness to 10mm. This was done to prevent any excessive deflections when the driver sits on the seat or steps on it when getting in or out. This also served to give the driver a sense of security inside the solar car.

After the layup of the frame and body was completed the theoretical weight of the frame and body was calculated. This was done by calculating the weight of the carbon fibre and core material used in the design. The theoretical weight was calculated at 56.5kg for the body and frame, this is 23.5kg less than what was estimated at the start of the chapter. The table containing the layup and the weight calculations is added in the appendix.

Figure 72: Completed frame and body

7. Chapter 7: Conclusions and recommendations

The objective of this work was the design of a lightweight chassis for the 2014 Sasol solar challenge. The frame had to comply with the regulations set out by the Sasol race officials and the FIA for alternative energy racing vehicles. It was decided to use composite materials for the body and frame of the vehicle and the use of a finite element modeller were required. The finite element modeller is used to define the frame material composition to assure sufficient strength for the maintained reliability of the frame.

The completed frame and body had a measured weight of 65kg; this is a 75kg improvement on the previous solar car built in 2012 saving 112.5W of power in weight. This is a significant improvement in the overall weight of the vehicle and can mainly be attributed to the analysis done on the frame and use of proper materials. This resulted in the fully assembled car having a weight of 207kg without the driver. This compares well with the leading teams in the world having vehicle weights of 200kg to 230kg. Therefore it can be concluded that the objective of weight reduction in this design has been met.

Officials from Motor Sport South Africa inspect the solar vehicles two days before the commencement of the 2014 Sasol solar challenge. These tests include both static and dynamic inspection of the competing solar cars to ensure they comply with the regulations.

North West University's solar car, the Sirius X25, passed both the static and dynamic inspection for the Olympia class without any penalties. The following year in 2015, the solar vehicle also passed the World Solar challenge's pre-race inspection for the Challenger class without any penalties. Therefore the objective of complying with the regulations of both the Sasol Solar challenge and the World solar challenge was met by this design.

The solar car completed the 2014 Sasol solar challenge with more than 2000km and another 3000km was travelled after completion of the 2015 World solar challenge in Australia. The car did not sustain any structural damage to the frame or the body during either of the competitions. The suspension and shock absorber mountings withstood all the loads imposed on them during the testing and the race without any damage or failure. Therefore the reliability of the frame was confirmed in practice and it can be concluded that the analysis method used on the frame was applied correctly for each of the load cases.

During the race thinner portions of the solar car's body exhibited visible vibrations. This creates excessive noise that can lead to faster fatigue of the driver during the long hours of an endurance race. Thus it is recommended that the frame and body is investigated to reduce the vibrations on the vehicle.

After the solar car was completed a difference in weight was found between the calculated weight and the measured weight of the frame and body. This can be attributed to both a calculation error and excessive material added during the manufacture stage of the car. For the future design team it is recommended that the weight calculations are refined using more and larger test samples. The manufacturing of the solar car can also be investigated to improve the current method or to find a new method of construction for the next generation of North West University solar car.

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Appendix

Material Properties

Material	**E11 (MPa)**	**E22 (MPa)**	**G12 (MPa)**	**v**	**S11T (MPa)**	**S22T (MPa)**	**S11C (MPa)**	**S22C (MPa)**	**S12 (MPa)**
Carbon UD	96000	8000	3000	0.2	890	50	500	170	48
Carbon BID2	48200	48200	2200	0.08	525	525	327.5	327.5	60
Carbon BID	55000	55000	4000	0.08	525	525	400	400	25
Carbon rovings	103000	7000	3000	0.2	900	40	750	170	40
Kevlar UD	60000	5000	1500	0.34	600	50	232	50	40
Kevlar BID	38000	38000	2200	0.15	400	40	120	120	50
Glass UD	32000	8000	3200	0.25	480	50	300	50	40
Glass BID	22500	22500	4200	0.28	223	223	180	180	60

Carbon fibre density: 1376.74 kg/m^3

Core material density: 80 kg/m^3

Rear suspension analysis (Torsion tube and swing arm)

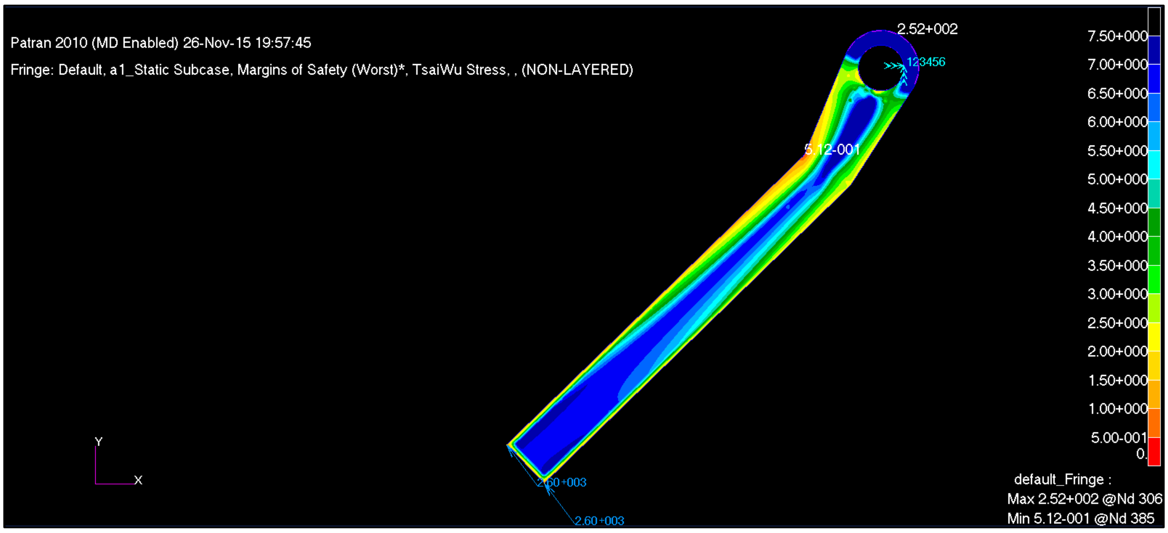

Figure 73: Rear suspension swing arm analysis safety factor 1.52 (80 layers of carbon bidirectional fibre no core)

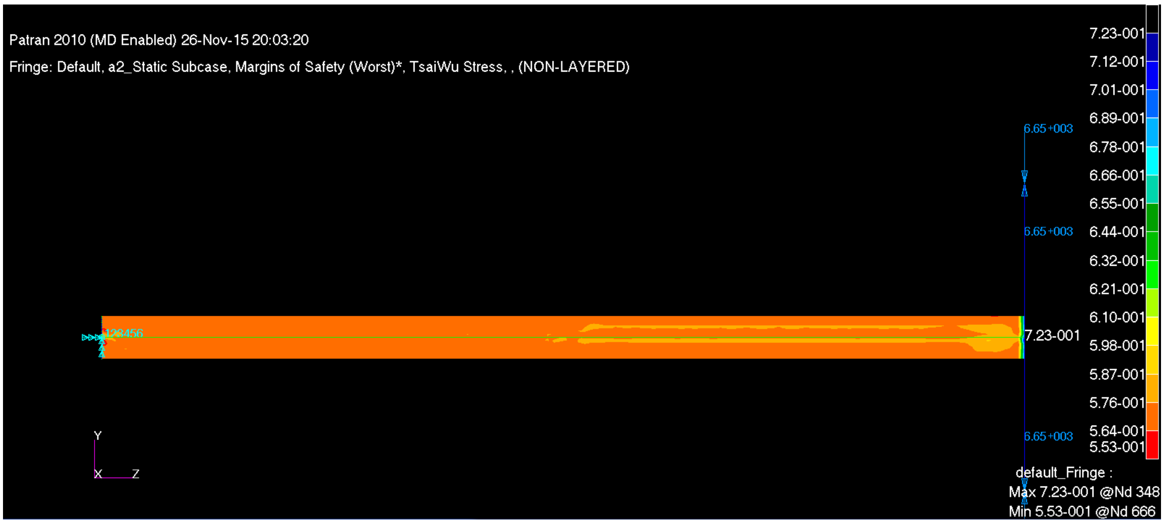

Figure 74: Rear suspension torsion excel analysis safety factor 1.55 (22 layers of bidirectional carbon fibre at 45°)

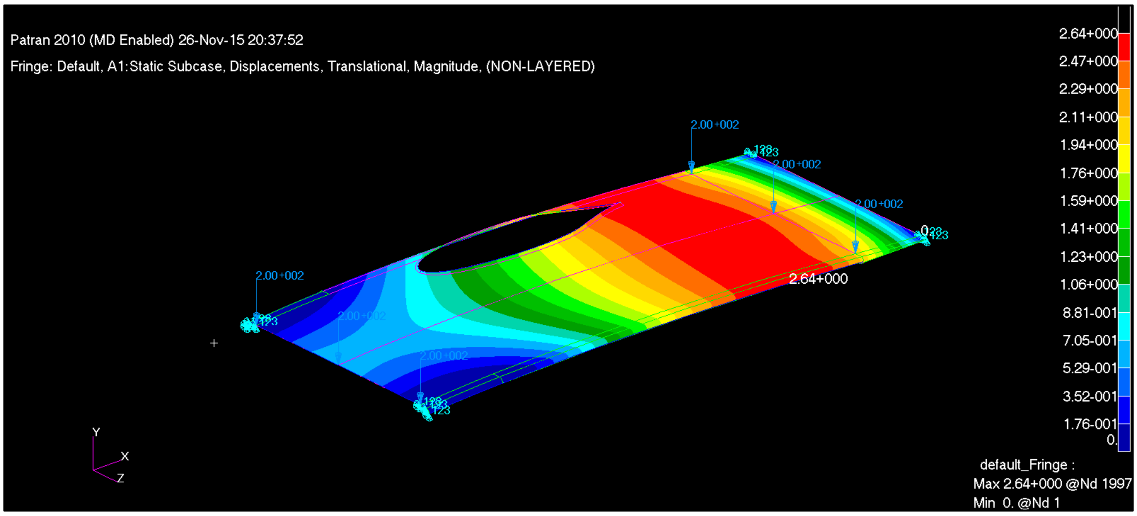

Figure 75: Solar panel deflection analysis maximum deflection 2.6mm (4 layers carbon fibre 10mm core)

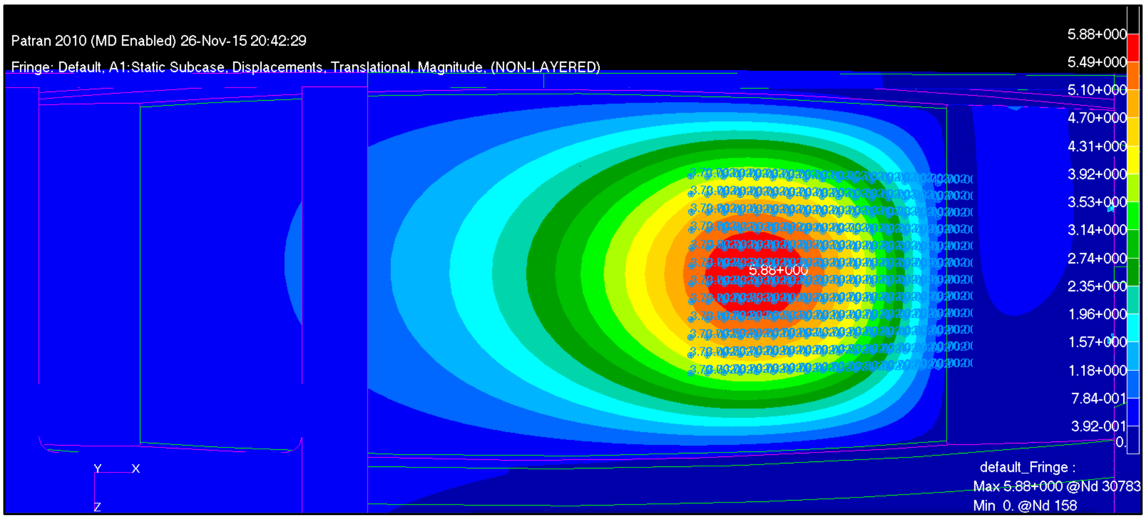

Figure 76: Driver bump load deflection analysis maximum deflection 5.9mm (4 layers 10mm core sides and front walls)

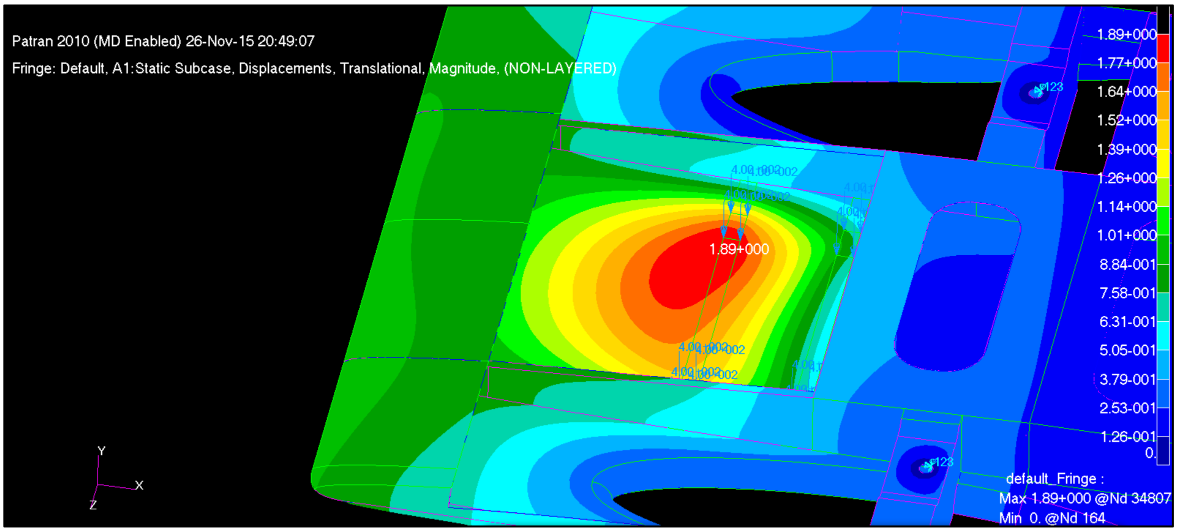

Figure 77: Battery weight deflection analysis maximum deflection 1.9mm (4 layers 3.5mm core)

Table 11: Composite material layup and weight calculations

Description	Layers	Core [mm]	Area [m^2]	Carbon Area [m^2]	Carbon Weight [kg]	Core Weight [kg]	Total Weight [kg]
BodyCenterFront Batery Strips	6	11.5	0.0214	0.1284	0.049496556	0.019688	**0.069184556**
BodyCenterFront Batery	4	3.5	0.7289	2.9156	1.12392648	0.204092	**1.32801848**
BodyCenterFront Batery Strips Center	4	5	0.0345	0.138	0.053197234	0.0138	**0.066997234**
BodyCenter	4	3.5	4.4017	17.6068	6.787196033	1.232476	**8.019672033**
BodyDopSupport	10	0	0.08	0.8	0.30838976	0	**0.30838976**
BodyFairings	5	0	1.1304	5.652	2.178773654	0	**2.178773654**
BodySides	4	3.5	1.005	4.02	1.549658544	0.2814	**1.831058544**
FrameCrossBeams	4	3.5	0.535	2.14	0.824942608	0.1498	**0.974742608**
FrameFrontStiffner	4	3.5	0.217	0.868	0.33460289	0.06076	**0.39536289**
FrameLeftStifner	4	0	0.0679	0.2716	0.104698324	0	**0.104698324**
FrameMainBeamFlange	10	3.5	1.072	10.72	4.132422784	0.30016	**4.432582784**
FrameMainBeam	6	3.5	0.656	3.936	1.517277619	0.18368	**1.700957619**
FrameRearSuspCross	4	3.5	0.113	0.452	0.174240214	0.03164	**0.205880214**
FrontSuspFrontBack	4	3.5	0.319	1.276	0.491881667	0.08932	**0.581201667**
FrontSuspTopBotom	4	3.5	0.19	0.76	0.292970272	0.0532	**0.346170272**
PotBackWall	4	10	0.183	0.732	0.28217663	0.1464	**0.42857663**
PotBotomWallFillet	4	0	0.015	0.06	0.023129232	0	**0.023129232**
PotBotomWall	4	10	0.42	1.68	0.647618496	0.336	**0.983618496**
PotCenterRibFlange	4	3.5	0.109	0.436	0.168072419	0.03052	**0.198592419**
PotCenterRib	6	10	0.104	0.624	0.240544013	0.0832	**0.323744013**
PotFrontWall	4	10	0.302	1.208	0.465668538	0.2416	**0.707268538**
PotInnerWall	4	10	0.5246	2.0984	0.80890634	0.41968	**1.22858634**
PotOuterWallBeam	12	40	0.096	1.152	0.444081254	0.3072	**0.751281254**
PotOuterwall	4	10	0.6919	2.7676	1.066874375	0.55352	**1.620394375**
RearSuspPotRib	8	23.5	0.1059	0.8472	0.326584756	0.199092	**0.525676756**
RearSuspRibFlens	10	0	0.0427	0.427	0.164603034	0	**0.164603034**
RearSuspRib	6	15	0.0754	0.4524	0.174394409	0.09048	**0.264874409**
RollBar	14	3.5	0.177	2.478	0.955237282	0.04956	**1.004797282**
RollBarRib	10	8	0.08	0.8	0.30838976	0.0512	**0.35958976**
RollBarRibBack	26	8	0.0648	1.6848	0.649468835	0.041472	**0.690940835**
FrameboxSides	4	3.5	0.053	0.212	0.081723286	0.01484	**0.096563286**
FrameboxFront	14	6	0.02	0.28	0.107936416	0.0768	**0.184736416**
Fairings Removable	4	0	4.095	16.38	6.314280336	0	**6.314280336**
TrailingEdge	4	0	0.008538	0.034152	0.013165159	0	**0.013165159**
TailFillets	4	0	0.0276	0.1104	0.042557787	0	**0.042557787**
SolarPanelDopSideRibsSides	4	10	0.3572	1.4288	0.550784111	0.28576	**0.836544111**
SolarPanelDopSideRibs	4	18	0.4102	1.6408	0.632507398	0.590688	**1.223195398**
SolarPanelDopTail	4	3.5	1.8568	7.4272	2.863090532	0.519904	**3.382994532**
SolarPanelDop	4	10	5.3114	21.2456	8.189906856	4.24912	**12.43902686**
Cannopy	4	3.5	0.0955	0.382	0.14725611	0.02674	**0.17399611**
			25.776938	**118.144352**	**45.54313545**	**10.914104**	**56.526424**