

2017-2018 Society of Automotive Engineers Baja Vehicle Design and Fabrication

A Major Qualifying Project

Submitted to the faculty of

Worcester Polytechnic Institute

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

Submitted By:

James Muller (ME)

Louis Muller (ME)

Approved By:

David Planchard, Advisor

John Hall, Advisor

Date: April 24th, 2018

This report represents work of WPI undergraduate students submitted to the faculty as evidence of a degree requirement. WPI routinely publishes these reports on its web site without editorial or peer review. For more information about the project program at WPI, see <http://www.wpi.edu/Academics/Projects>.

Abstract

Worcester Polytechnic Institute's (WPI) Society of Automotive Engineers (SAE) participates in two distinct competitions, Formula SAE (FSAE) and Baja SAE (SAE). The clubs mainly focus on FSAE as its flagship competition. In the past, WPI's SAE has participated in BSAE and has built some frames that have not competed. Our Major Qualifying Project (MQP) strives to create a rolling chassis that can be built upon by the club to create a competition ready vehicle. A rolling chassis includes a completed frame with attached suspension components and wheels. Our Project begins with research, design and computer simulations to create the chassis, and ends with the physical rolling chassis which will be given to the SAE club.

Contents

Abstract.....	1
List of Figures.....	3
List of Variables.....	4
List of Equations.....	5
Chapter 1: Introduction.....	6
Chapter 2: Background.....	7
Chapter 3: Design Methods and Procedures.....	11
Chapter 4: Design Analysis.....	12
Chapter 5: Design Iterations.....	32
Chapter 6: Subsystem Integration and Drivetrain Support.....	33
Chapter 7: Implementation.....	38
Chapter 8: Conclusion and Future Recommendations.....	39
References.....	40

List of Figures

Figure 1 Example Stress Visual with Yield Strength Failure.....	13
Figure 2 Front Impact 1 Stress Visual	15
Figure 3 Front Impact 2 Stress Visual	16
Figure 4 New Bracing to Account for Front Impact 2 Failure	17
Figure 5 Rear Impact Stress Visual	18
Figure 6 Roll Over Stress Visual.....	20
Figure 7 Drop Impact Stress Visual.....	22
Figure 8 Top Impact Stress Visual.....	23
Figure 9 Side Impact Stress Visual.....	25
Figure 10 New Bracing to Account for Side Impact Failure	26
Figure 11 Driver and Engine Drop Stress Visual.....	28
Figure 13 Highlighted fixture plates	35
Figure 14 Engine mounting plate bottom view	36
Figure 15 Fixture plates shown without transmission.....	37

List of Variables

Symbol	Name	Unit
M	Mass	Kg
K_b	Bending Stiffness	Nm^2
E	Modulus of Elasticity	GPa
I	Second Moment of Area	m^4
S_b	Bending Strength	Nm
S_y	Yield Strength	MPa
c	Distance from Neutral Axis to Extreme Fiber	M
F	Force	N
V	Velocity	m/s
t	Time	s
a	Acceleration	m/s^2
h	Height	m

List of Equations

Bending Stiffness: $k_b = E \times I$

Bending Strength: $S_b = S_y \times I / c$

Force of Collision: $F_{FI1} = \left(\frac{m_{FI1} \cdot v_{FI1}}{t_{FI1}} \right) * FOS$

Velocity from Free Fall: $v_{RHO}^2 = v_{RHO_0}^2 + 2 * a * h_{RHO}$

Moment of Roll Over: $m_{COM} * h_{COM} = m_{RHO} * h_{RHO}$

Chapter 1: Introduction

SAE International hosts a number of Collegiate Design Series (CDS) including the Baja SAE Series. The CDS is designed to help students apply classroom theory to real world problems through research, design, construction, testing, and intercollegiate competition. The Baja SAE Series challenges students to produce a prototype off-road vehicle capable of withstanding several different rough terrain conditions. In addition to physically testing the vehicle in competition, each team must present their prototype to a fictitious company. The teams must be able to defend any design decisions and expenses to the company. The fictitious company then decides which prototype is the best overall product.

Baja SAE Series are designed to be a comprehensive and challenging engineering competition. Local collegiate SAE clubs often spend several years working on a single Baja vehicle before they go to competition. Our MQP is the beginning of a new Baja vehicle for the WPI SAE club. The club will be able to use our work to continue preparing all the information and work to be able to bring a vehicle to competition and represent WPI. The goal of our project is to have a rolling chassis and the supporting research, design and data for the SAE club to work off of. A rolling chassis includes the frame, suspension and wheels. The supporting research, design, and data needs to explain each decision we have made and the information these decisions are based off of up to the completed chassis. Some of this information can help the club understand why we made each decision, know how we intended for other components to be fitted to the chassis, or be used in the documentation that the Baja SAE Series judges will use to score the Baja vehicle in competition.

For our MQP to be successful, we need to collaborate with several different groups of people and organizations. We are designing the chassis for the SAE club, therefore we need to keep them informed on the decisions we make on the design. The club can offer us advice and direction based off their experience working with the Formula SAE vehicle as well as general insight from competitions and vehicle design. Typically there is an MQP each year that helps the SAE club with the Baja SAE vehicle. The 2016-17 MQP group worked on designing a frame for the SAE club. They are another resource we can use to understand the methodology behind the frame design and how other components connect to the frame. We also need to work closely with our advisor so that we can verify that we are making forward progress with our design. Our advisor will also need to approve any components we purchase or send out to be fabricated. Our MQP advisor is also the advisor for the SAE Club and has additional understanding of the requirements the club has for the chassis. Finally, we will need to work with manufacturing companies, such as VR3 Engineering, to manufacture components of the vehicle that cannot be built on WPI's campus.

Chapter 2: Background

A Baja vehicle consists of several different subsystems. Those subsystems include the frame, suspension, steering, brakes, drivetrain, seating, electronic and safety. Each subsystem has a variety of components within them that need to be either purchased or designed and manufactured to work with the other components of that subsystem. Each subsystem must fit together with other subsystems that either work with or are close to each other.

The frame is the main subsystem that is designed to fit all other subsystems onto or around. It must also be designed to protect the driver of the vehicle from impacts or rollovers and it must comply with all the 2018 Baja SAE rules. Baja SAE specifies that the roll cage members must be constructed out of steel tubes. The roll cage is the part of the frame directed around the driver. Baja frames must be constructed as either a front braced frame, a rear braced frame, or a combination of the two. A front braced frame supports the roll cage from the front of the frame and a rear braced frame supports the roll cage from the back of the frame. As mentioned in the rules, a combination of both types of bracing yield a better designed frame. Different members of the frame are separated into two categories, primary members and secondary members. Each type of member serves a different purpose and have different dimensional requirements. Primary members are required to have a larger outside diameter and wall thickness as they provide the main shape and support for the vehicle. The secondary members provide triangulation for the primary members and additional points on the frame to mount other subsystems.

The suspension subsystem works most closely with the frame out of the other subsystems. It attaches to the frame at many different points, including suspension arm pick up point, and shock absorber pick up point. Pick up point are brackets welded to the frame that provide a location to mount components to the frame. The frame and suspension must be designed closely together. The type of suspension system will affect where certain members of the frame can be located. There are countless variations in suspension systems that can be categorized into a few different design styles.

One such system is the double a-arm or double wishbone suspension system. This system consists of two rigid members that attach to the frame at different locations and attach to the hubs at two other location. These members known as a-arms rotate about their own independent axes to help control the vertical motion of the wheel as it reacts to the uneven surfaces it may encounter. A shock absorber and spring can be attached in a variety of locations to control and absorb the energy of these uneven surfaces. Double a-arm suspensions offer the most control for suspension characteristics, but

have more parts than other suspension systems making them more difficult to design and more expensive to manufacture. In Baja vehicles, the benefits of controllability of double a-arm suspension outweighs the disadvantages of design complexity and manufacturing costs. This suspension style works for the front of Baja vehicles because it works well with the wheels that steer the car and react to the road surface first.

The rear end of the Baja vehicle does not steer the vehicle and react to the road surface after the front wheel. The rear wheels also provide power to drive the vehicle forward. With these ideas in mind, a trailing arm is a simpler suspension system that can perform well in a Baja competition. A trailing arm suspension consists of an arm that comes off the frame back and out from the frame. The shock and spring are mounted at some point along the length of the trailing arm and to a point higher up on the frame. This system has less parts than a double a-arm making it both simpler to design and less expensive to manufacture.

The steering system allows the driver to direct the front wheels in the desired direction. This system typically consists of a wheel the driver can turn that translate the motion to a rack and pinion that pushes each front wheel about an axis to change the direction of the vehicle. Steering systems need to be placed in a specific place so that the tie rods that connect the wheels to the rack and pinion follow a similar path as the two a-arms. Improper placement of the steering system causes the tie rods to push the tires in undesired directions as the suspension compresses and droops over rough terrain.

Brakes are used to slow down the Baja vehicle. They are important for the performance and safety of the vehicle. At the wheel, brakes consist of a spinning metal disc that is attached to the wheel hub and a stationary caliper that compresses a composite material against the metal disc. Brake convert the kinetic energy of the vehicle into heat, to slow it down. Brake are typically packaged within the wheel itself. The inside diameter of the wheel determines the maximum size of the brakes. Brakes should be designed as close to the inner diameter of the wheel as possible without interfering with the operation of the wheel. Larger brakes can dissipate heat faster which allows the brakes to work more efficiently. The brake pads, made out of the composite material, are compressed in the caliper by hydraulically driven pistons. These pistons are attached to a brake pedal by hydraulic tubes. The driver compresses the brake pedal which sends hydraulic fluid to the caliper pistons which compress the pads on the discs to slow down the vehicle.

The drivetrain is responsible for producing and transferring energy to the wheels to propel the vehicle. The main components of the drivetrain are the engine, transmission, and differential. The engine used in Baja vehicles is the model 19 Briggs and Stratton single cylinder engine. The engine outputs its energy through a shaft that connects to the transmission.

The transmission helps translate the power from the engine to the wheels for a variety of situations such as starting on a hill or reaching top speed. The transmission accomplishes this variability by changing the gear ratio between its input shaft and output shaft. There are several different methods this is achieved. One method is through a continuously variable transmission (CVT). A CVT consists of two tapered pulleys and a belt attached to both. As the vehicle speed increases, the pulleys open and close inversely to each other, changing the gear ratio between the engine and the wheels. CVTs are lighter than other transmissions but more difficult to adjust for optimal performance.

After the transmission is the final drive train component before the wheels. This is known as a differential. The differential serves two main purposes. The first is that it sets the final fixed gear ratio between the engine and the wheels. The second purpose is that it allows both drive wheels to spin at different speeds while still sending power to both. This feature is important when the vehicle turns. In a turn the wheel outside the turn travels a greater distance than the inner wheel. Without the differential, one of the wheels would lose traction to spin at the same rate as the other tire. This loss of traction translates to a loss in power and control for the vehicle. With a differential, each wheel can turn at the correct speed for the distance they travel while still translating power to the road surface.

The electronics in the Baja vehicles are all designed for safe operation and competitions with other Baja vehicles. The electronic systems consist of several kill switches that cut power to the engine. The switches are strategically located so that the driver and crew members can easily access one of them in the event of an emergency. The electronic system also includes a brake indicator to notify other drivers when the Baja vehicle is braking. The safety features on the Baja vehicles also include no electronic components such as the firewall, fire extinguisher, and spill pan. The firewall protects the driver if the engine catches fire. The fire extinguisher is mounted in an easily accessible location. The spill pan redirects any spilled gasoline away from hot engine components during refueling.

The seating system in the Baja vehicle is one of the simpler systems in the vehicle but arguably one of the most important. The seat is placed in the best spot to be able to comfortably reach the steering wheel and gas and brake pedal. The seat also includes a five-point harness. This harness

secures the driver at the shoulders and hipbone to keep the driver in a safe position during normal operation and in the event of a crash. The harness must be installed properly so that it does not break during an impact. It must also translate the inertia of the driver to the frame through the driver's skeleton rather than soft tissue.

Chapter 3: Design Methods and Procedures

To begin our MQP we looked at the Baja MQP from the 2016-17 academic year. The goal of this MQP was to design a frame and have it built. The frame from the previous MQP was designed but never built. We picked up the project with the SolidWorks model of the frame. When we compared the frame design from 2016-17 to the 2018 Baja SAE rules, we found that it was no longer compliant in several major design considerations. While comparing the frame model to the rules we also found that the frame had several redundant members built in that were not necessary to the function or safety of the frame. These members added weight, complexity, and cost to the frame. We decided that we would take the primary member design from this frame and redesign it so that it satisfied the 2018 Baja SAE rules. Once the primary members were redesigned, we added new secondary members to work with our suspension design. We designed the frame to have as few members as possible while still having the capabilities to perform in competition and protect the driver from crashes.

During this process, we conducted 3 iterations of design changes. The first iteration involved angling the front of the frame in order to better handle front impacts off jumps and achieve better maneuverability over obstacles such as logs. As we made these changes, we familiarized ourselves with the requirements explained in the Baja SAE Rules. After reviewing the altered frame from the 2016-2017 MQP we understood that major design changes were necessary to have a compliant frame.

After coming to this understanding, we decided to create a new SolidWorks model as opposed to editing the previous file. Through multiple edits and a misunderstanding of design logic from the previous MQP, the edited 2016-2017 model had many errors and artifacts from the edits. This new frame design, iteration 2, was created by referencing the iteration 1 file and a list of changes we wanted to make to optimize our frame design. Once this task was accomplished we conducted simulations on the second iteration model.

With our results from the iteration 2 simulations, we created a 3 iteration that both satisfied the requirement of the BAJA SAE rule book and withstood the forces in the simulation. This 3rd iteration is analyzed in detail under Chapter 4 of this report.

Chapter 4: Design Analysis

SolidWorks Simulations

Driver and vehicle safety are some of the key areas of concern for SAE and any engineer adhering to good engineering practices. It is essential to this project that the frame is designed in a safe way that can handle expected forces, especially those experienced in a crash of the vehicle. Physical testing on frame strength is costly, time consuming and impractical. SolidWorks simulations offer an effective solution to this problem because simulations can be conducted quickly and design integration can be created based on the results. SolidWorks features a large library of materials that can be used to simulate their performance in a model such as a BSAE frame. We used this technology to ensure the safety of our frame design and executed design changes based on any failed results.

To properly test our model's strength, we need to know what forces it would likely experience in extreme circumstances such as a full-speed impact with an immovable object. We tested our frame design under eight unique scenarios where various forces were applied in different ways to understand how the frame would perform in real life. The simulations we conducted included Front Impact 1, Front Impact 2, Rollover, Rear Impact, Top Impact, Drop Impact, Side Impact, and Driver/Engine Drop. Each simulation represented a different scenario that the frame could experience during competition and forces were calculated to represent the forces expected for each unique scenario.

In SolidWorks, simulations are set up using various steps to recreate a desired situation. First, the parts of the model that are being subjected to the simulation are selected and their material properties are also chosen using the SolidWorks materials library. Next, SolidWorks analyzes the model and places joint groups and connections in the appropriate locations. After verifying the proper execution of the previous step, fixture locations are selected on the model. These locations designate the parts of the frame that cannot move during the simulation and provide points for the reaction forces to originate. External loading points are then chosen, these points represent where a specified force is applied to the model. Finally, a meshing operation is conducted to divide the model components into smaller elements that will be individually analyzed during the simulation. A visualization of the results is then created to represent how each meshed element behaves during the simulation. These visualizations include stress and displacement of the individual elements. An example of the stress visualization is provided in *Figure 1* where the individual elements are color coded to represent the stress they experience with a scale for reference. The actual values can be accessed in the simulation

report for further analysis. If the model experiences a stress that is greater than the yield strength of the material, the yield strength will be represented as a red arrow along the scale as shown below.

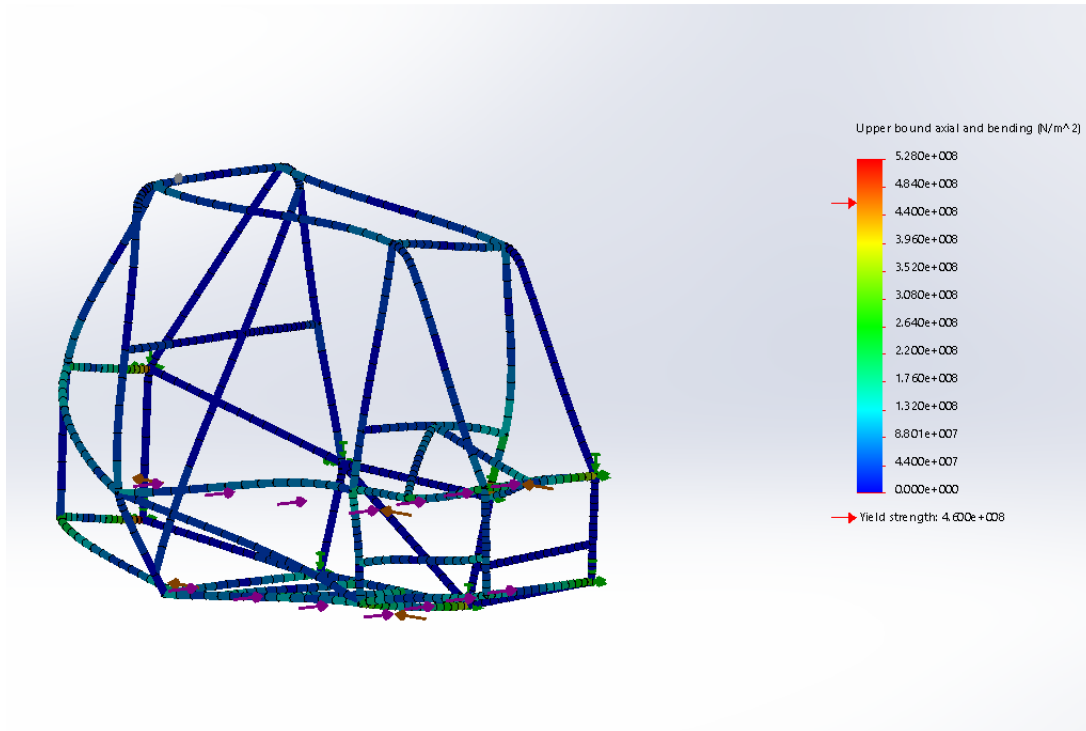


Figure 1 Example Stress Visual with Yield Strength Failure

A common metric for a product's ability to withstand forces is Factor of Safety (FoS). Incorporating FoS is essential for engineering reliable and safe products. It is not sufficient to design a product to handle no more than the performance loads expected because unexpected situations can occur where larger forces are experienced. If a product fails just beyond its expected loading, it is dangerous and the likelihood of failure during use is increased. A factor of safety for the BSAE frame of 2 was used to ensure the safety and reliability of the product we are designing. FoS is calculated by dividing the maximum stress we predicted our frame would experience by the yield strength of the material we used in the frame design. Yield strength values were provided by the SolidWorks materials Library. For our frame design, we used AISI 4130 Steel, normalized at 870 degrees Celsius, which has a yield strength value of $4.6 \times 10^8 \text{ N/m}^2$. This value was then compared to the forces each meshed element experienced in the simulation to ensure a FoS of 2 was achieved.

The force calculation for these simulations involved various assumptions such as the weight of a fully equipped BSAE vehicle with a 95th percentile male driving the vehicle. Other assumption included impact duration and FoS. The force calculation for this impact involved the vehicle mass (m_v), vehicle

speed (v_v), duration of the impact (t_v), and FoS (FoS_v). We found that the duration of an impact with a solid object is 0.1 seconds and a movable object is 0.3 seconds. The use of either duration was determined by the characteristics of the impact we were simulating. The average mass of a fully equipped BSAE vehicle is 204.1 kg and the mass of the 95th percentile male is 113.4 kg.

The simulations presented below were conducted on our third iteration of the frame design. When we tested the 2nd iteration, the Front Impact 2 and Side Impact simulations failed. We analyzed the resulting failures and reinforced the frame where necessary to achieve successful results. More details about the specific reinforcements will be discussed in their respective sections below.

Front Impact 1

The Front Impact 1 simulation was conducted to simulate the behavior of our BSAE frame in a front crash situation with a solid object, an object that would not move during the impact, with a duration (t_{FI1}) of 0.1 seconds. A velocity (v_{FI1}) of 15.65 m/s was determined to be a realistic top speed in a front crash situation. The total mass (m_{FI1}) of the Baja and driver was 317.5 kg the calculated force (F_{FI1}) is shown below.

$$F_{FI1} = \left(\frac{m_{FI1} * v_{FI1}}{t_{FI1}} \right) * FoS$$

$$F_{FI1} = \left(\frac{(204.1kgs + 113.4kgs) * 15.65 \frac{m}{s}}{0.1s} \right) * 2$$

$$F_{FI1} = 99377.5N$$

This value was rounded up to 100,000N for simplicity and an extra degree of safety. The next step in setting up the simulation was to distribute the load across the frame and fixture the frame properly so the force was distributed throughout the model in a realistic manner. We referenced the simulation set up from the previous Baja MQP report and used logic to confirm the placement of the forces and fixture (e.g. forces of a front impact are distributed across the front plane of the frame). A mesh was then applied and the simulation was executed. The stress visualization of Front Impact 1 is shown below in *Figure 2*.

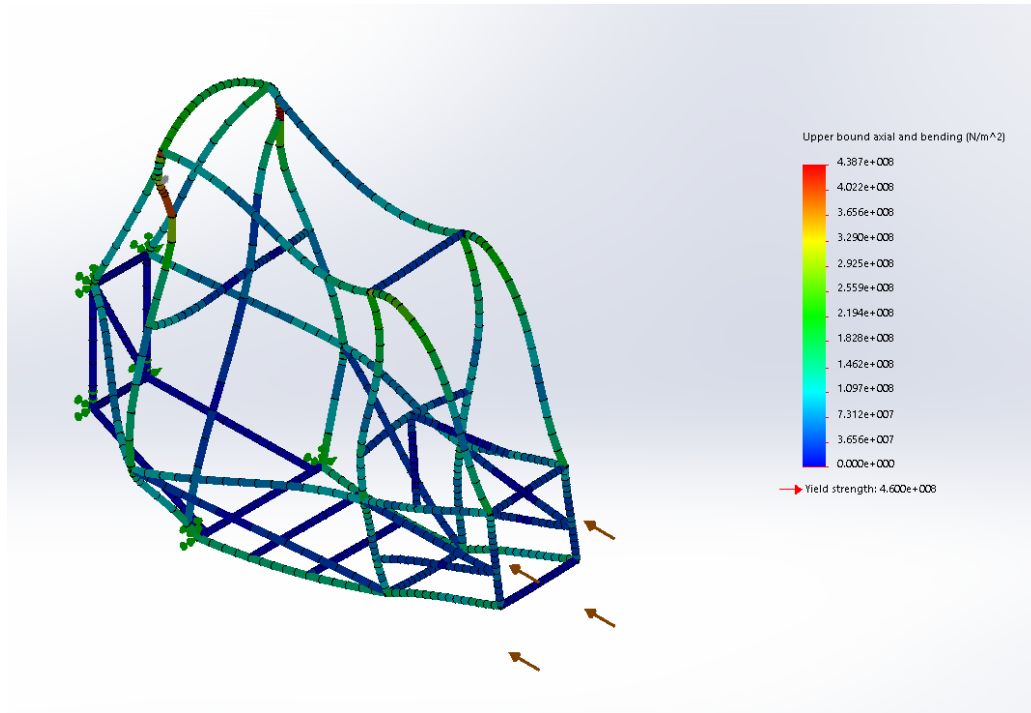


Figure 2 Front Impact 1 Stress Visual

We determined that 4 loading points on the front plane of the frame would accurately represent forces exerted on the frame during a front impact. Each individual force, represented in *Figure 2* by an orange vector, exerts 25,000N and represented a quarter of the total force, 100,000N. The fixture points, represented by green vectors, were placed on the rear plane of the frame and at the rear suspension connection points for a total of 6 fixture points. A meshing operation was conducted and the simulation was run. The results showed that the frame did not experience any forces beyond the yield strength of the material. The calculation for the force in this simulation accounted for a FoS of 2, thus the results proved that the frame could withstand forces of at least that magnitude. The frame experienced an upper bound bending stress of $4.387 \cdot 10^8 \text{N}$ compared to the yield strength of $4.600 \cdot 10^8 \text{N}$.

Front Impact 2

The Front Impact 2 simulation was similar to Front Impact 1 with an impact duration (t_{F12}) of 0.1 seconds and a velocity (v_{F12}) of 15.65m/s. The calculated force (F_{F12}) was the same, 100,000N.

$$F_{FI2} = \left(\frac{m_{FI2} * v_{FI2}}{t_{FI2}} \right) * FoS$$

$$F_{FI2} = \left(\frac{(204.1kgs + 113.4kgs) * 15.65 \frac{m}{s}}{0.1s} \right) * 2$$

$$F_{FI2} = 99377.5N$$

The difference between the simulations occurred in the force distribution, with Front Impact 2 consisting on only 2 force vectors located at the bottom front corners of the frame at points E. These two forces each exerted 50,000N on the frame to equal the total 100,000N of force. The mesh treatment in Front Impact 1 was used for Front Impact 2 as well. Front Impact 2 allowed for us to understand how the frame would behave if a front impact was concentrated on the lower front of the Baja, a situation especially important to consider with our inclined front end design.

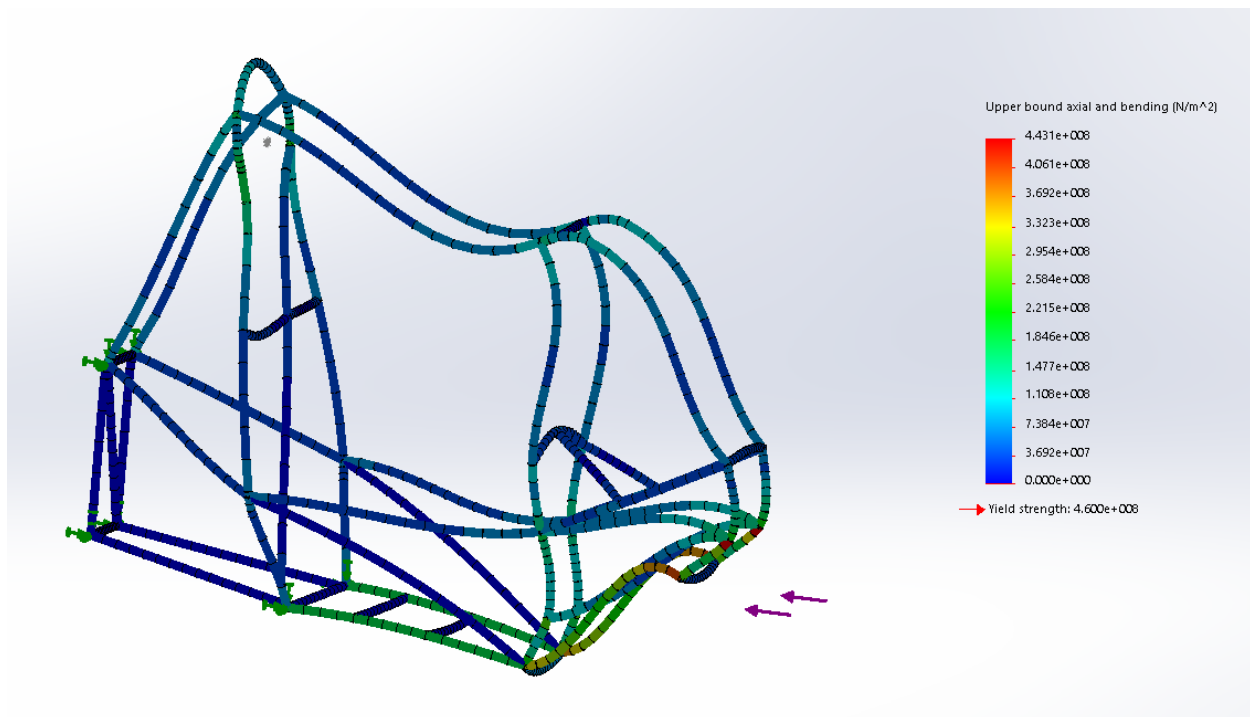


Figure 3 Front Impact 2 Stress Visual

This simulation was successful and our frame meet the required FoS of 2. As previously stated, the simulation of iteration 2 of our model failed. With the addition of the members highlighted in blue in Figure 4 we could achieve a successful test of Front Impact 2. The frame experienced an upper bound bending stress of $4.431 \times 10^8 N$ compared to the yield strength of $4.600 \times 10^8 N$.

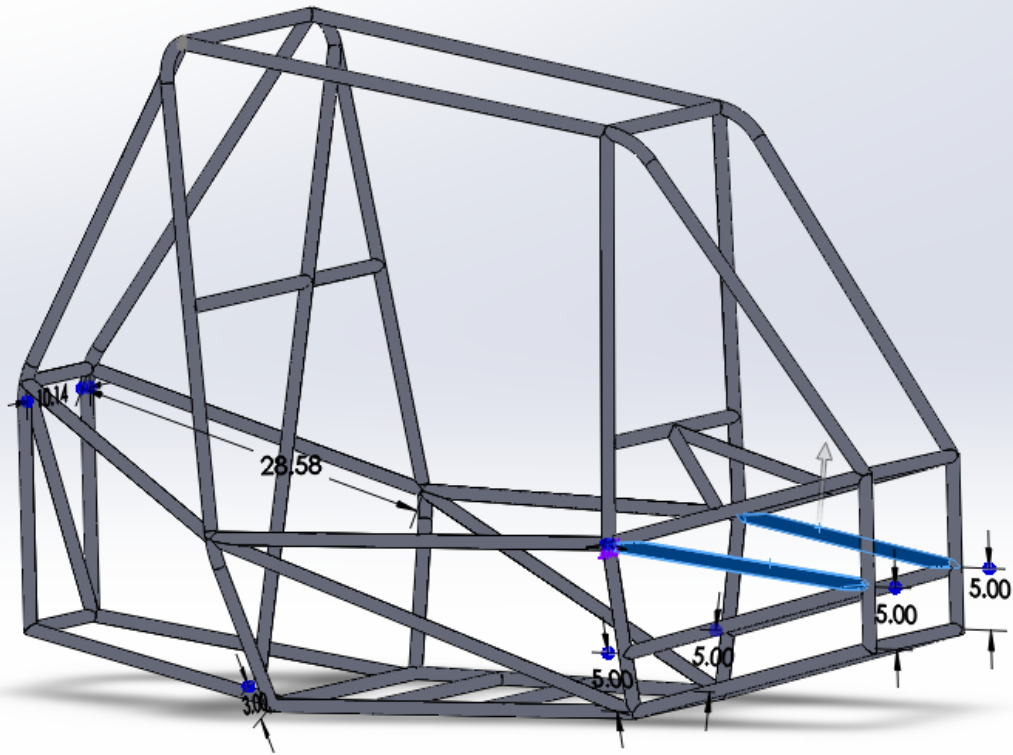


Figure 4 New Bracing to Account for Front Impact 2 Failure

Rear Impact

The Rear Impact simulation considered a situation in which another vehicle collides with our vehicle from the rear, an impact between two moveable objects, and thus an impact time (t_{RI}) of 0.3 seconds was used. A velocity (v_{RI}) of 15.65m/s was also used assuming that the vehicle striking our vehicle was traveling at top speed during the impact. The same mass (m_{RI}) as both Front Impact simulations was used in this calculation. The calculated force (F_{RI}) is shown below.

$$F_{RI} = \left(\frac{m_{RI} * v_{RI}}{t_{RI}} \right) * FoS$$

$$F_{RI} = \left(\frac{(204.1kgs + 113.4kgs) * 15.65 \frac{m}{s}}{0.3s} \right) * 2$$

$$F_{RI} = 33125.8N$$

This value was rounded to 33,000N for simplicity. The fixtures and loading of this simulation was opposite of the previous two. There were 8 loading points of 4125N each distributed across the rear of the frame. Their locations included 4 loading points on the rear plane of the frame at points R and either side of the lowest rear lateral cross member. There were 4 load points at the rear suspension pick up points and where the lower Fore – Aft Bracing members met the Rear Roll Hoop at points A. We selected 8 fixture points in the front of the frame around the driver’s legs at points G, E, F and D. This arrangement concentrated the forces of the impact the engine compartment and middle driver compartment as shown in *Figure 5* below.

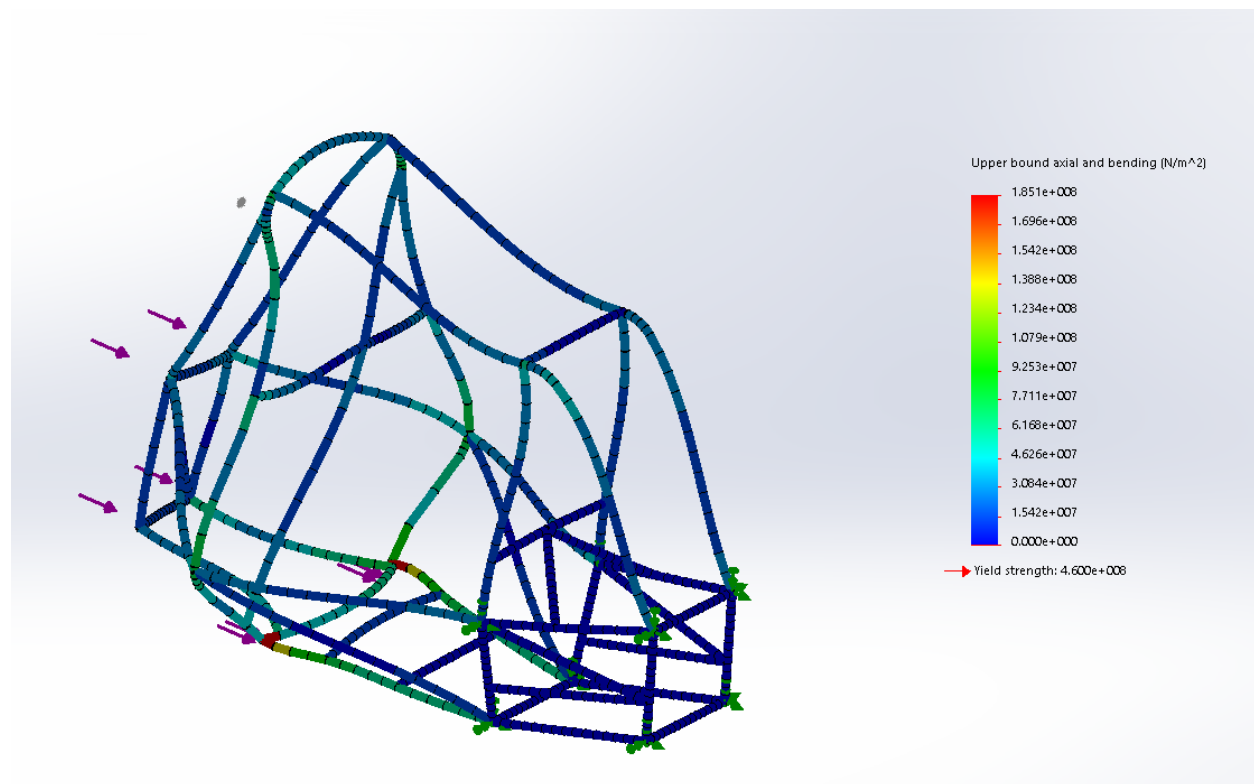


Figure 5 Rear Impact Stress Visual

This simulation was successful and our frame meet the required FoS of 2 with an upper bound bending stress of $1.851 \cdot 10^8 \text{N}$ compared to the yield strength of $4.600 \cdot 10^8 \text{N}$.

Roll Over

The Roll Over simulation considered a situation in which our vehicle rolls over and impacts the ground, an immovable object, along one side of the frame. An impact time (t_{RHO}) of 0.1 seconds was used. A velocity (v_{RHO}) of 5.14m/s was determined by calculating the free-fall speed of the RHO from its ride height of 1.346m (h_{RHO}).

$$v_{RHO}^2 = v_{RHO_0}^2 + 2 * a * h_{RHO}$$

$$v_{RHO} = \sqrt{2 * a * d}, (v_{RHO_0} = 0)$$

$$v_{RHO} = \sqrt{2 * 9.8m/s^2 * 1.346m}$$

$$v_{RHO} = 5.14m/s$$

The mass equivalent (m_{RHO}) of the RHO was determined by comparing the moment experienced about the center of mass (COM) of the fully equipped frame with a driver. The moment experience about the COM was calculated by multiplying the mass (m_{COM}) by the ride height (h_{COM}) of the COM. The mass at the COM was determined to be 320kg, which is a rounded value of the total mass of the Baja and driver, 317.5kg, used in previous calculations. The calculated mass is shown below.

$$m_{COM} * h_{COM} = m_{RHO} * h_{RHO}$$

$$320kg * 0.673m = m_{RHO} * 1.346m$$

$$m_{RHO} = 160kg$$

These two calculated values, v_{RHO} and m_{RHO} , were then used to determine the force (F_{RHO}).

$$F_{RHO} = \left(\frac{m_{RHO} * v_{RHO}}{t_{RHO}} \right) * FOS$$

$$F_{RHO} = \left(\frac{160kg * 5.14 \frac{m}{s}}{0.1s} \right) * 2$$

$$F_{RHO} = 16448N$$

This value was rounded to 16500N for simplicity. The fixtures for this simulation involved 8 points along the lower side of the frame opposite of the loading points at points G, E, F, D, A, S, R, and the lowest rear lateral cross member point along the same plane. The loading points were located at 5 points and 1 beam, the RHO. The loading points were at points located at 5 locations along the same side as the loaded RHO member. Each load point experienced 12500N of force and the RHO member experienced 4000N of force.

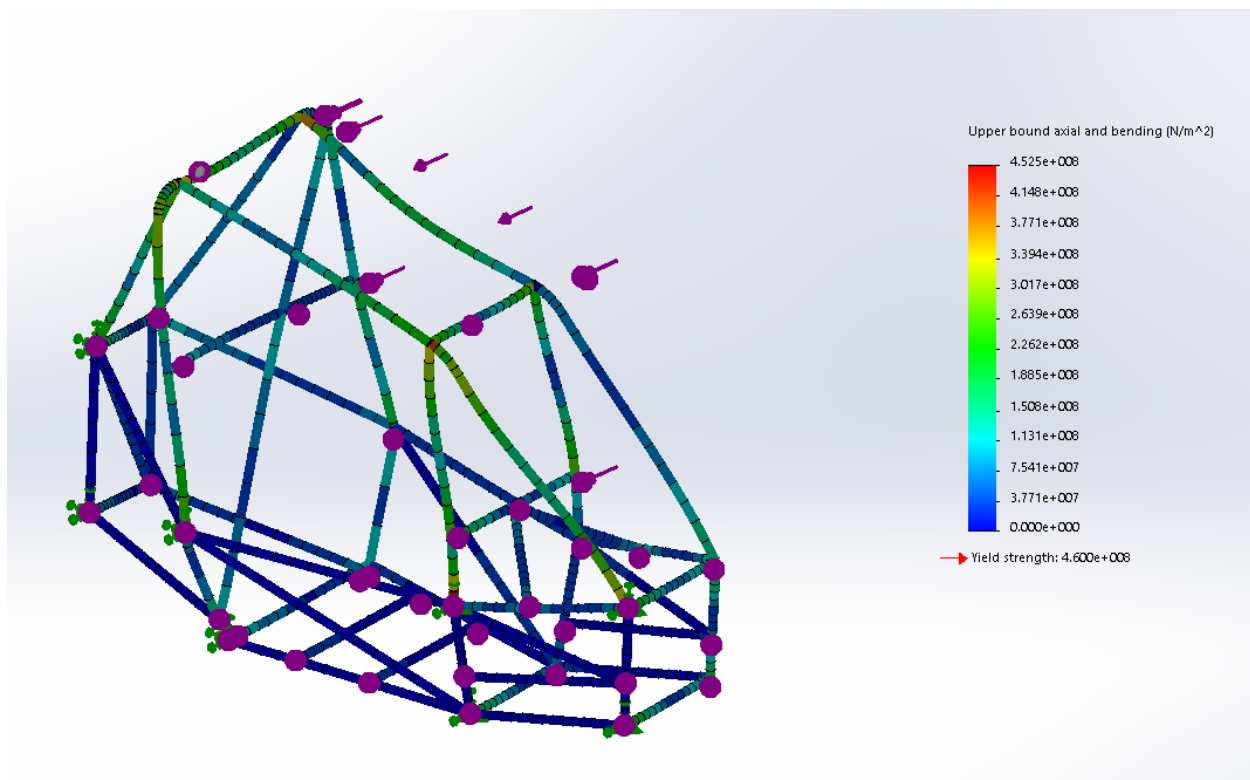


Figure 6 Roll Over Stress Visual

This simulation was successful and our frame meet the required FoS of 2 with an upper bound bending stress of $4.525 \cdot 10^8 \text{N}$ compared to the yield strength of $4.600 \cdot 10^8 \text{N}$.

Drop Impact

The Drop Impact simulation considered a situation in which our vehicle falls from 6.096m (h_{DI}) with an impact time (t_{DI}) of 0.3 seconds, considering the suspension exists below the frame's lower plane and will absorb part of the impact. A velocity (v_{DI}) of 10.9m/s was determined by calculating the free-fall speed of the frame from h_{DI} .

$$v_{DI}^2 = v_{DI_0}^2 + 2 * a * h_{DI}$$

$$v_{DI} = \sqrt{2 * a * d}, (v_{DI_0} = 0)$$

$$v_{DI} = \sqrt{2 * 9.8 \frac{m^2}{s} * 6.096m}$$

$$v_{DI} = 10.9m/s$$

This velocity was then used to determine the force (F_{DI}).

$$F_{DI} = \left(\frac{m_{DI} * v_{DI}}{t_{DI}} \right) * FOS$$

$$F_{DI} = \left(\frac{317.5kg * 10.9 \frac{m}{s}}{0.3s} \right) * 2$$

$$F_{DI} = 23071.7N$$

This value was rounded to 24000N for simplicity. The fixture in this simulation was located at the 4 upper corners of the RHO at points C and B. The load points were located along the bottom plane of the frame at E, F, A, either side of the lowest rear lateral cross member, at either side of the two Under Seat Members (USM), and at the rear suspension pickup points located next to points A. Each point experienced a load of 1715N.

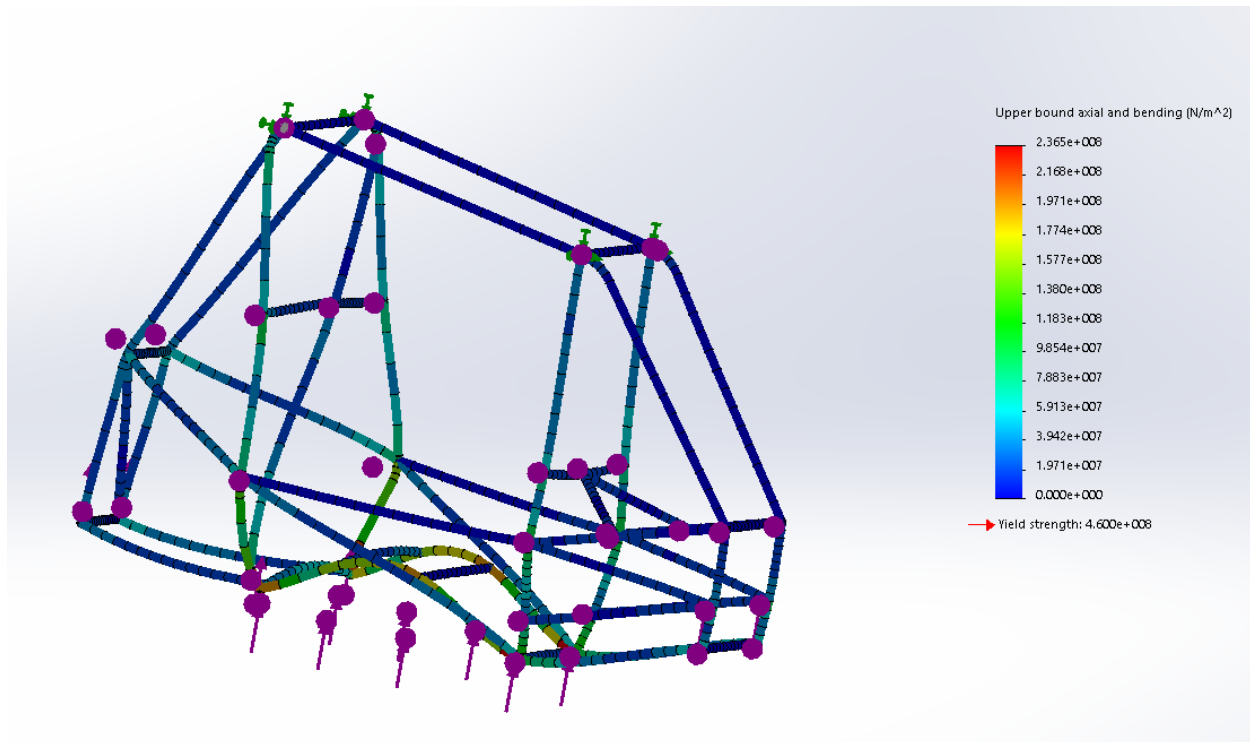


Figure 7 Drop Impact Stress Visual

This simulation was successful and our frame meet the required FoS of 2 with an upper bound bending stress of $2.365 \cdot 10^8 \text{N}$ compared to the yield strength of $4.600 \cdot 10^8 \text{N}$.

Top Impact

The Top Impact simulation considered a situation in which another vehicle lands on top of our frame from 6.096m (h_{TI}) with an impact time (t_{TI}) of 0.3 seconds. Both vehicles are moveable objects which is the reasoning behind the impact time. A velocity (v_{TI}) of 10.9m/s was determined by calculating the free-fall speed of the frame from h_{TI} .

$$v_{TI}^2 = v_{TI_0}^2 + 2 * a * h_{TI}$$

$$v_{TI} = \sqrt{2 * a * d}, (v_{TI_0} = 0)$$

$$v_{TI} = \sqrt{2 * 9.8 \frac{m^2}{s} * 6.096m}$$

$$v_{TI} = 10.9m/s$$

This velocity was then used to determine the force (F_{TI}).

$$F_{TI} = \left(\frac{m_{TI} * v_{TI}}{t_{TI}} \right) * FoS$$

$$F_{TI} = \left(\frac{317.5kg * 10.9 \frac{m}{s}}{0.3s} \right) * 2$$

$$F_{TI} = 23071.7N$$

This value was rounded to 24000N for simplicity. The fixture and load points of this test were the opposite of those in the drop test. The fixture points were located along the bottom plane of the frame at E, F, A, either side of the lowest rear lateral cross member, at either side of the two Under Seat Members (USM), and at the rear suspension pickup points located next to points A. The load points in this simulation was located at the 4 upper corners of the RHO at points C and B. Each point experienced a load of 6000N.

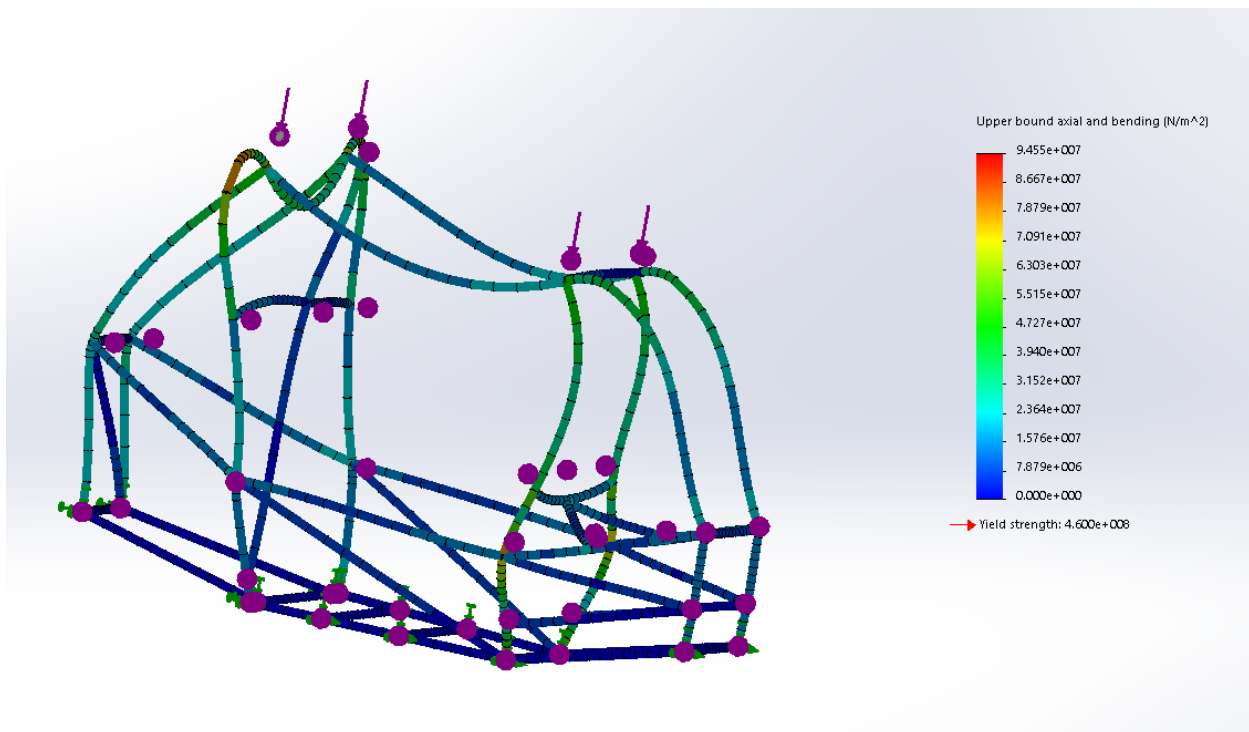


Figure 8 Top Impact Stress Visual

This simulation was successful and our frame meet the required FoS of 2 with an upper bound bending stress of $9.455 \times 10^7 \text{N}$ compared to the yield strength of $4.600 \times 10^8 \text{N}$.

Side Impact

The Side Impact simulation considered a situation in which another vehicle collides at top speed with the side of our vehicle, an impact between two moveable objects. This was considered an impact between moveable object with a duration (t_{SI}) of 0.3 seconds. A velocity (v_{SI}) of 15.65m/s was also used assuming that the vehicle striking our vehicle was traveling at top speed during the impact. The same mass (m_{SI}) as previously calculated was used. The calculated force (F_{SI}) is shown below.

$$F_{SI} = \left(\frac{m_{SI} * v_{SI}}{t_{SI}} \right) * FOS$$

$$F_{SI} = \left(\frac{(204.1 \text{ kgs} + 113.4 \text{ kgs}) * 15.65 \frac{\text{m}}{\text{s}}}{0.3 \text{ s}} \right) * 2$$

$$F_{SI} = 33125.8 \text{ N}$$

This value was rounded to 33,000N. For this simulation, a combination of beam loading and point loading was used, as per the recommendations of the previous Baja MQP. There were 4 beams loaded each with of 2358N and 5 joints loaded with 4715N distributed across the rear of the frame. The Lower Frame Side Members (LFS) and Side Impact Members (SIM) on one side of the frame were the loaded beams. Meanwhile 5 points along the same side of the frame were selected.

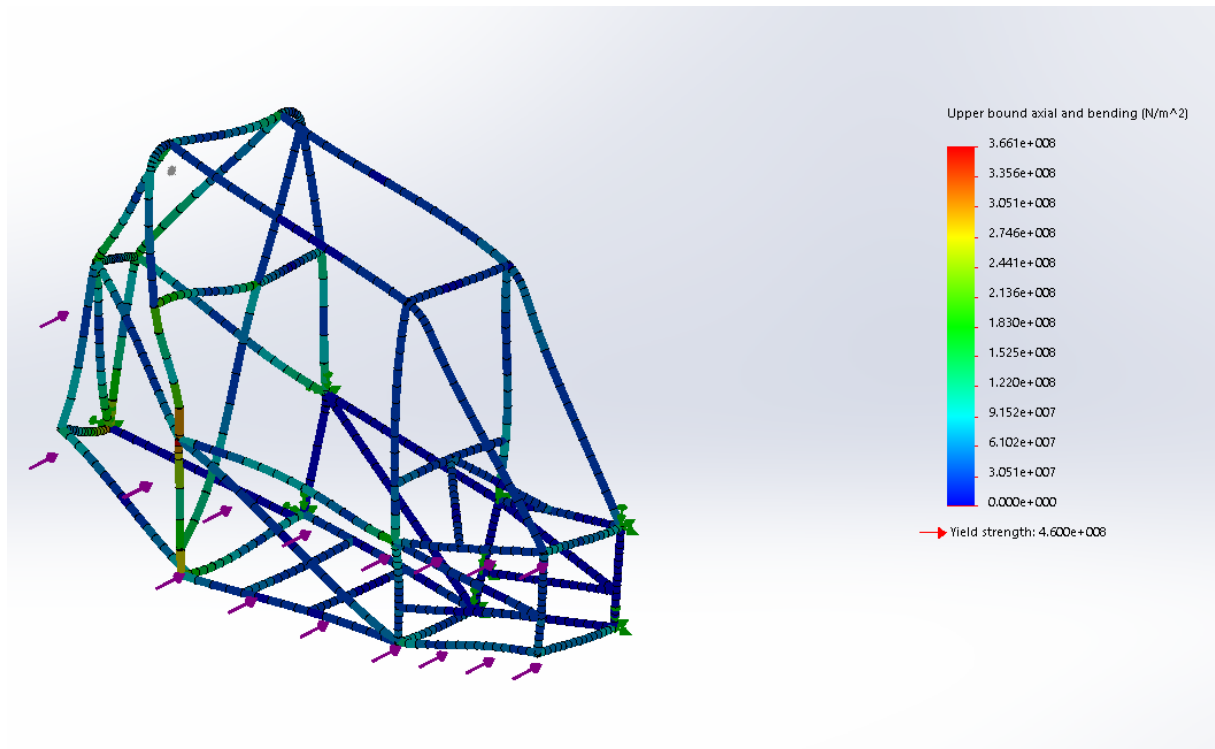


Figure 9 Side Impact Stress Visual

This simulation was successful and our frame meet the required FoS of 2. As previously stated, the simulation of iteration 2 of our model failed the side impact test at both rear Lateral Cross Members. With the addition of the bracing member highlighted in blue in *Figure 10* we could achieve a successful test of the Side Impact study. The frame experienced an upper bound bending stress of $3.661 \cdot 10^8 \text{N}$ compared to the yield strength of $4.600 \cdot 10^8 \text{N}$.

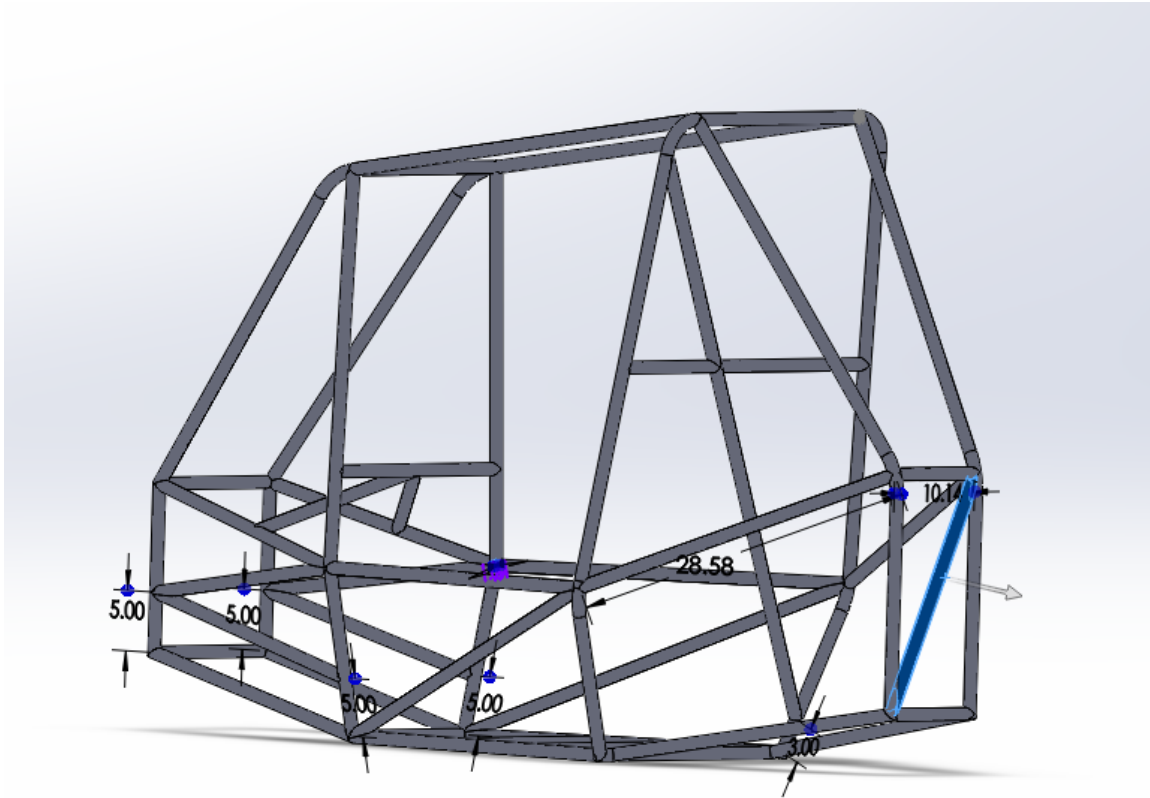


Figure 10 New Bracing to Account for Side Impact Failure

Driver and Engine Drop

The Driver and Engine Drop simulation considered a situation in which our vehicle falls from 6.096m (h_{DDE}) with an impact time (t_{DDE}) of 0.3 seconds, considering the suspension exists below the frame's lower plane and will absorb part of the impact. The study looked to see how well the supporting structure below the engine and drive could perform in a drop situation. A velocity (v_{DDE}) of 10.9m/s was determined by calculating the free-fall speed of the frame from h_{DDE} .

$$v_{DDE}^2 = v_{DDE_0}^2 + 2 * a * h_{DDE}$$

$$v_{DDE} = \sqrt{2 * a * d}, (v_{DDE_0} = 0)$$

$$v_{DDE} = \sqrt{2 * 9.8 \frac{m}{s} * 6.096m}$$

$$v_{DDE} = 10.9m/s$$

This velocity was then used to determine the force (F_{DD}) exerted by a driver weighing 113kg (m_{DD}).

$$F_{DD} = \left(\frac{m_{DD} * v_{DDE}}{t_{DDE}} \right) * FOS$$

$$F_{DD} = \left(\frac{113kg * 10.9 \frac{m}{s}}{0.3s} \right) * 2$$

$$F_{DD} = 8211N$$

This velocity was also used to determine the force (F_{DE}) exerted by a engine weighing 49kg (m_{DE}).

$$F_{DE} = \left(\frac{m_{DE} * v_{DDE}}{t_{DDE}} \right) * FOS$$

$$F_{DE} = \left(\frac{49kg * 10.9 \frac{m}{s}}{0.3s} \right) * 2$$

$$F_{DE} = 3561N$$

The fixtures for the driver was located at the 4 points of the Under Seat Member (USM) that connect to the Lower Frame Side Members (LFS). Each point experienced a load of 2053N. Four load beams were used for the engine force location because selecting the same load points and fixture points for the engine simulation would interfere with each other. The beams selected make up the bottom X-Y plane behind the Rear Roll Hoop (RRH) and each beam was loaded with 891N.

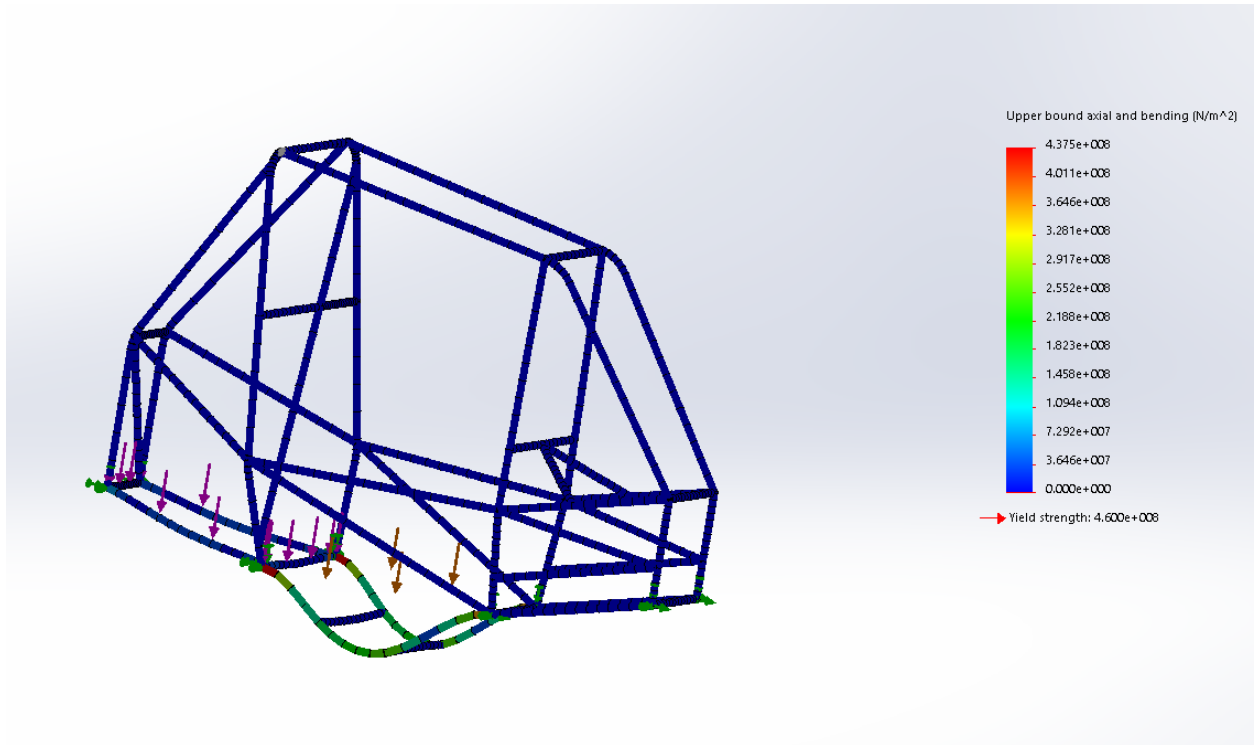


Figure 11 Driver and Engine Drop Stress Visual

Frame Material Selection

Baja SAE uses a standard pipe material of 1018 Steel for the rules and specifications for frame construction. Primary members of the frame must meet one of two requirements for dimensions and carbon content. The first requirement is that the primary members must be circular steel tubing with at least 25mm in outside diameter (OD) with a minimum wall thickness (WT) of 3mm, with a carbon content of at least 0.18%. The second requirement is that the primary members must be a steel shape that meets or exceeds the bending strength and bending stiffness of 1018 steel with an outside diameter of 25mm and a wall thickness of 3mm. The steel shape must have at least 1.57mm in wall thickness, with a carbon content of at least 0.18%. These bending strength and stiffness are to be calculated from the neutral axis to give minimum values. The rules give equations to determine the bending criteria. Based off the information on our manufacturer, VR3 Engineering's website and our research into alternative materials, we decided to choose 4130 circular steel tubing with an outside diameter of 31.75mm and a wall thickness of 1.65mm as the material for our primary members. These values meet the dimensional requirements for primary members. 4130 steel also meets the requirement for carbon content with its carbon content from between 0.28% and 0.30%. We also calculated the bending strength and stiffness of 4130 steel at 25mm OD and 3mm WT. The rules provided the modulus of elasticity for all types of steel as 205GPa and the yield strength of 1018 steel as 365MPa. The bending criteria was calculated using the following equations.

k_b : Bending Stiffness

E: Modulus of elasticity

I: Second Moment of Area

S_b : Bending Strength

S_y : Yield Strength

c: Distance from Neutral Axis to Extreme Fiber

For 1018 Steel OD: 25mm WT: 3mm

$$k_b = E \times I$$

$$k_b = 2.05 \times 10^{11} \text{Pa} \times 1.2778 \times 10^{-8} \text{m}^4$$

$$k_b = 2620 \text{Nm}^2$$

$$S_b = S_y \times I / c$$

$$S_b = 3.65 \times 10^8 \text{Pa} \times 1.2778 \times 10^{-8} \text{m}^4 / 0.0125 \text{m}$$

$$S_b = 373 \text{Nm}$$

For 4130 Steel OD: 25mm WT: 3mm

$$k_b = E \times I$$

$$k_b = 2.05 \times 10^{11} \text{Pa} \times 1.2778 \times 10^{-8} \text{m}^4$$

$$k_b = 2620 \text{Nm}^2$$

$$S_b = S_y \times I / c$$

$$S_b = 4.35 \times 10^8 \text{Pa} \times 1.2778 \times 10^{-8} \text{m}^4 / 0.0125 \text{m}$$

$$S_b = 444 \text{Nm}$$

For 4130 Steel OD: 31.75mm WT: 1.65mm

$$k_b = E \times I$$

$$k_b = 2.05 \times 10^{11} \text{Pa} \times 1.2778 \times 10^{-8} \text{m}^4$$

$$k_b = 2620 \text{Nm}^2$$

$$S_b = S_y \times I / c$$

$$S_b = 4.35 \times 10^8 \text{Pa} \times 1.7723 \times 10^{-8} \text{m}^4 / 0.0177 \text{m}$$

$$S_b = 436 \text{Nm}$$

Initially we looked at 4130 steel with 25mm OD and WT 3mm and calculated the values for bending stiffness and strength. These values surpassed the requirements for the primary members. After discussing the frame design with MQP members from the 2016-17 Baja SAE MQP. We decided to research 4130 steel with 31.75mm OD, 1.65mm WT as alternative dimensions for the primary members.

These dimensions have a better weight to stiffness ratio according to VR3 Engineering. We calculated that the bending stiffness of 4130 steel is equal to the bending stiffness of 1018 steel at any wall thickness and diameter. The bending strength of 4130 steel is greater than the bending strength of 1018 steel at either of the calculated dimension. Since both values are greater than or equal to the values of 1018 steel, we can use 4130 steel with an outside diameter of 31.75mm and a wall thickness of 1.65mm as the primary members of our frame. 4130 steel with 25mm OD has a greater strength than 4130 steel with 31.75mm OD, but the 25mm OD 4130 steel is heavier per unit length than 31.75mm OD 4130 steel. Both 4130 steels meet the Baja SAE rules, therefore we chose the lighter weight 4130 steel with 31.75mm OD and 1.65mm WT for the primary members.

Chapter 5: Design Iterations

Throughout the project, we created multiple iterations of our frame design, 5 in total. The initial iteration involved taking the design from the previous year's Baja MQP and selecting the aspects that we found fit for our design. The previous design was heavy compared to other Baja frames in the competition. We also needed our frame to adhere to the new rules SAE Baja published for the 2018 competition. We reduced the number of members in the frame and began testing our new model to make sure that our design was strong enough to handle the expected loads.

The second iteration was adapted to match our suspension design. The Suspension pick-up points needed to be at specific locations on the frame. Members also needed to be present at those locations and strong enough to handle loads transferred through the suspension systems. During this iteration we began using FEA studies in SolidWorks to test the strength of the frame. The testing method is explained in our Design Analysis section of the report. The initial design failed some of the studies and we made changes to the frame so it would pass all the studies. The design that passed all the studies became our third frame iteration.

The third iteration also featured our final tube profile sizes. We had found that using a stronger type of tube steel, AISI 4130, allowed us to use smaller wall thicknesses and save weight. We conducted more FEA testing on the model and adjusted the design further to make sure that it passed all the studies again.

The fourth iteration explored design optimization such as weight reduction and increased strength. We analyzed ways to alter the design to achieve these goals. Some changes were alterations in the use of primary material, the larger heavier profile, with secondary material to reduce the overall weight of the frame. The design was also reviewed by WPI's SAE club to ensure that our design met all the requirements in the SAE Baja regulations. We address the club's concerns and made alteration where deemed necessary.

Our fifth iteration featured the addition of the drive train support members and mounting fixtures for the components. This arrangement is explained further in our Subsystems section of the report. This model was the final iteration of our project. We ensured that our design met all the requirements in the SAE BAJA rules. Furthermore, it was designed to fit a specific suspension design and fit a 95th percentile male within specific clearance requirements. It passed all our FEA impact studies and could house the drivetrain we planned to use in our completed vehicle.

Chapter 6: Subsystem Integration and Drivetrain Support

An integral part of the design of any vehicle frame is the consideration for packaging the various subsystems that operate in the vehicle. The most important of these is suspension compatibility. The characteristics and function of the suspension system depend on where it connects to the frame. Different suspension designs require different pick-up points on the frame and will influence the geometry of the frame at those points. Before completely designing the frame, we researched and chose suspension system designs for the front and rear of the vehicle. We decided to use a double A-arm suspension for the front and a 3-link, semi-trailing arm suspension for the rear as explained previously in our research section.

The suspension choices influenced the shape of the frame at the front and the back. We had accounted for specific spacing of the pick-up points on the frame to preserve the performance characteristics of the suspension design. This design sequence illustrates how we planned for all subsystems while creating the frame. Another system that required consideration was the drivetrain mounts. This feature consisted of two tube members running parallel from the bottom of the rear roll hoop to the bottom of the bottom lateral cross member as shown in Figure 12. The engine, mounted just behind the plane of the rear roll hoop, is supported on a steel plate that is supported by 4 vertical members connected to the drive train support members.

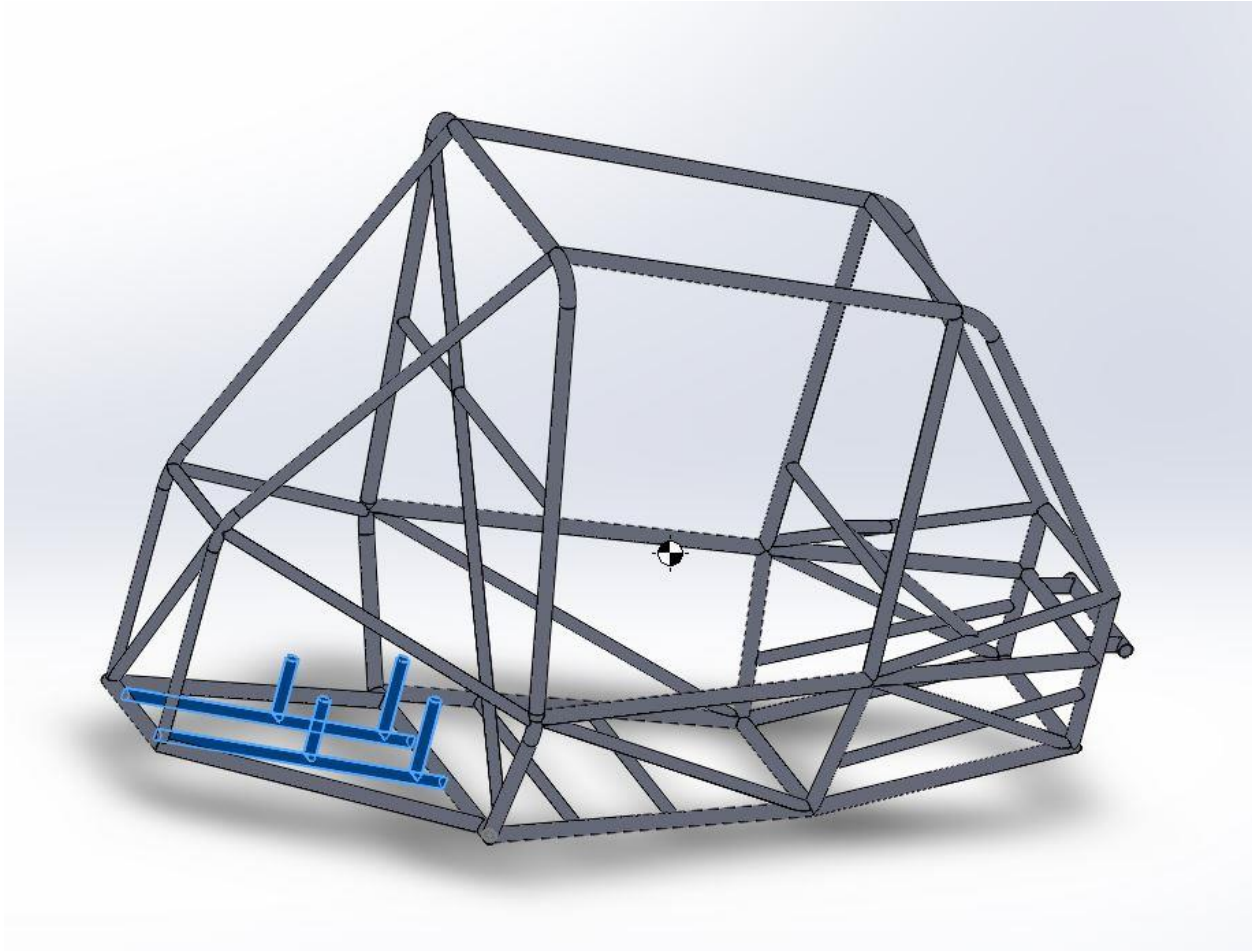


Figure 12 Highlighter drivetrain support members

The connection points between the four vertical members and the steel plate were at fixed locations. The connection between the engine and mounting plate were made with slots, rather than holes, where the mounting fasteners pass through. These fasteners are secured by grooved nuts beneath the plate and the engine allowed the engine to move longitudinally in respect to the frame and mounting plate. The purpose of this feature is to allow easy adjustment of the tension on the CVT pulley belt that transmits power between the engine and transmission. The transmission is in a fixed location and moving the engine closer to the front of the vehicle increases tension in the belt. These features can be seen in Figure 13.

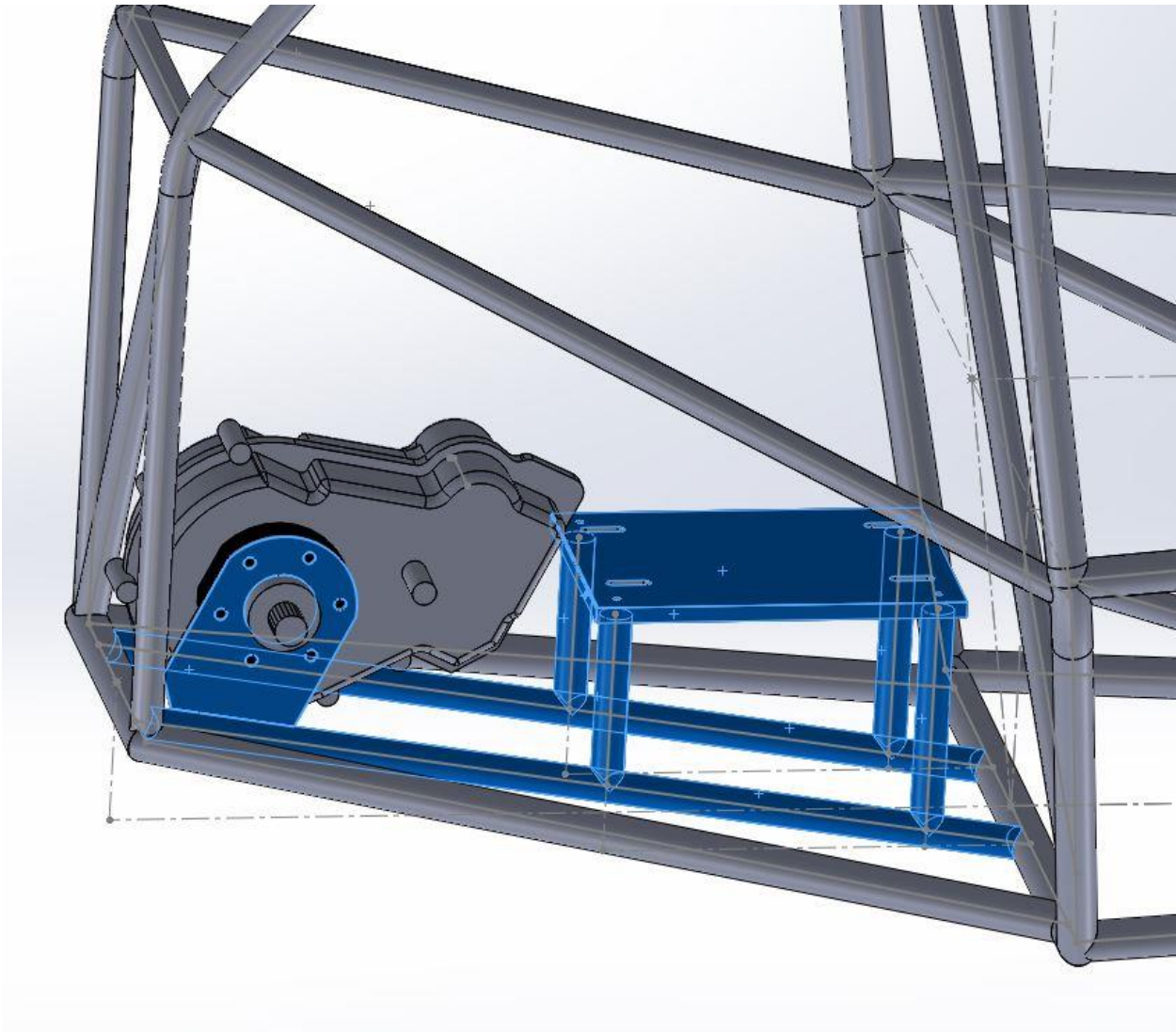


Figure 123 Highlighted fixture plates

One of the two advantages of this method are that the CVT can be installed with little tension in the belt and can then be adjusted to its operational tension. Another advantage is apparent when considering that CVT belts have a tendency to stretch over time. We can easily compensate for this stretching by moving the engine position further from the transmission. The locking mechanism for the slide feature involves grooves on the steel support plate by the 4 slots and the fastener nuts have a complementary geometry to secure the engine position. The steel plate is shown in Figure 14 with the grooved features roughly represented around the slots.

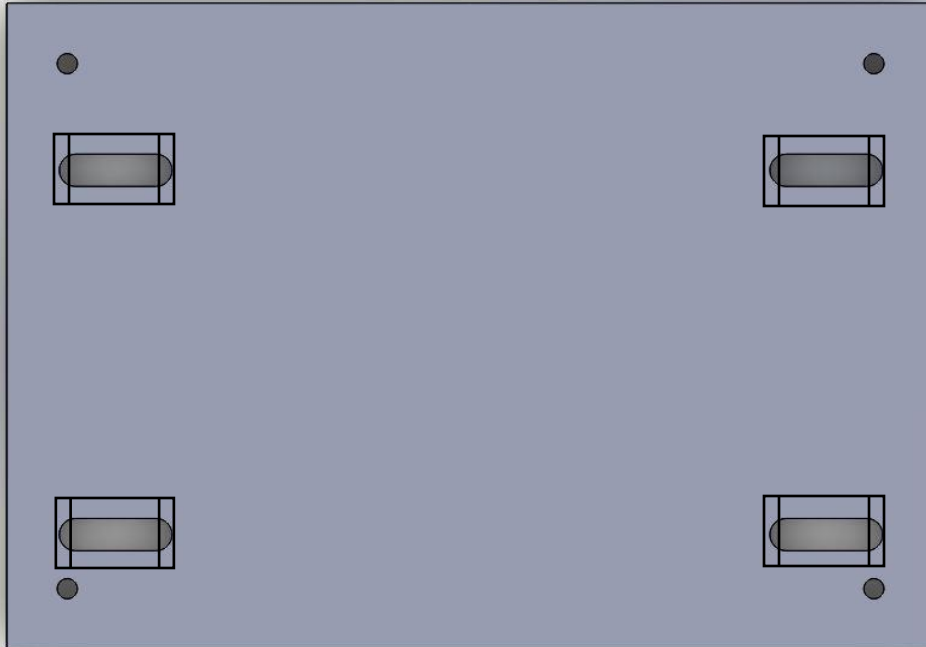


Figure 134 Engine mounting plate bottom view

The transmission is secured in a permanent position by two pieces of plate steel welded to the top of the drive train support members. The transmission has a specific bolt pattern, as shown in Figure 12. The support plates have the same pattern with unthreaded holes. The transmission bolts are removed and the transmission is placed between the plates and then secured using those bolts. Figure 15 shows the mating point between the transmission and fixture plates.

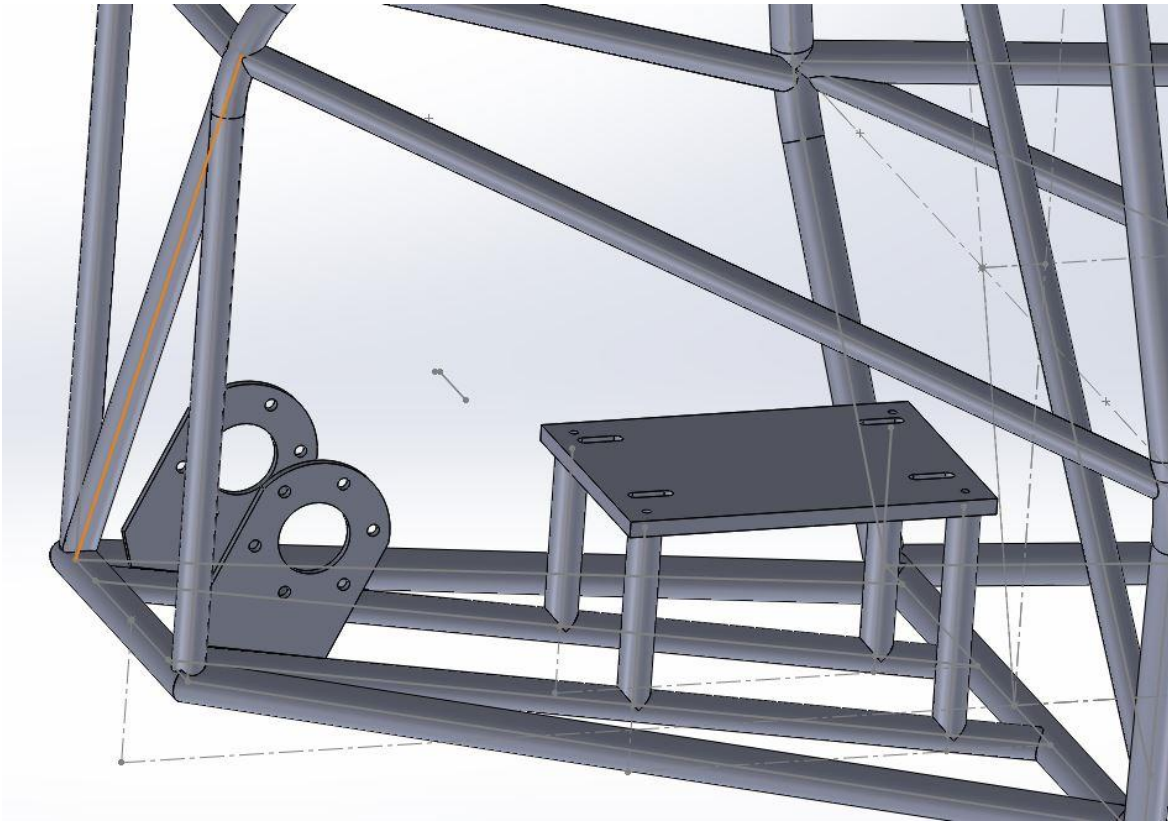


Figure 145 Fixture plates shown without transmission

We had to design the rear section of the frame to fit all the components within the frame and allow for movement of the engine. The engine is placed higher than the transmission to reduce the horizontal space between the two components and still achieve the proper distance for the CVT to function. The transmission is placed lower in the frame to align the output shafts with the half shafts that extend towards the rear wheel. We had to design the rear suspension and place the transmission in such a way that they performed together without any interference.

Other subsystems that we accounted for included the driver's seat, the steering system and the brake and throttle pedals. The SAE Baja rules include clearance specifications for driver in the seat which allowed us to properly size the frame around the seat of the driver. Head, shoulder, and hip clearance are represented by the respective spheres of space shown in the figure. The values were based on the size of a 95th percentile male and the clearance spacing specified by the SAE rules. For pedal placement, we made sure that the distance from the front of the car to the back of the driver's seat accounted for enough space for both the driver's legs and the pedal sizes. The steering location was considered during the front suspension design and can be decided under future recommendations for this project.

Chapter 7: Implementation

The frame of the Baja vehicle is the main building block on which every other system is mounted. Therefore; it is critical that the frame be precisely manufactured to our SolidWorks model. VR3 Engineering is a company based in Canada that uses Computer Numerical Control (CNC) machines to precisely profile tube steel to match a CAD model. Their machines and methods can profile tube to a tolerance of 0.005". This level of precision exceeds the requirements of our frame. VR3 Engineering has experience in several different fields, including SAE and student projects. WPI has worked with them in the past and they have a developed procedure for student groups. Using these procedures, we can ensure that VR3 Engineering builds the frame to our exact specifications.

The dialogue with VR3 Engineering begins with the quote process. We send VR3 Engineering a 3D .sldprt file containing the tube structure of our frame, a PDF file of the assembly drawing, and a .xls file containing the bill of materials. The assembly drawing must contain bubble labels for each individual tube. The bubble labels contain a number that corresponds to the list of tubes in the .xls file. The .xls file indicates the type and dimensions of the material for each individual tube. With the above information, VR3 Engineering sends back a quote estimating the cost to cut the profiles in the tubes and the cost to assemble and weld the frame if requested.

Once we review the quote we can approve the model for manufacturing. VR3 Engineering only requires an email confirmation to begin manufacturing the frame. Once the frame is manufactured it is shipped to the address provided by us. After we receive the frame, VR3 Engineering will send us an invoice for the frame payable by wire transfer, check, or credit card.

Chapter 8: Conclusion and Future Recommendations

The goal of this project was to design a frame for an off road capable vehicle under specific guidelines from SAE Baja. The frame was required to withstand certain impact forces and was designed with specific subsystem integration in mind. We could accomplish these goals through our research and design process. Our design is sustainable for future work to be done and can be used to create a competition ready vehicle by a future project team. We were aware that a future MQP team may continue our project and documented important information for the future team to easily work with our design.

Our recommendations for furthering this project include use of specific suspension designs, use of the engine and transmission we researched for the vehicle, and more detailed research into vehicle components such as shock absorbers. The suspension design we suggest is a double A-arm for the front and a 3-point semi-trailing suspension for the rear. The engine used is the Briggs and Stratton model 19 engine as specified by SAE. Further research into suspension components and the other subsystems such as steering, braking, and throttle control must be conducted for the next portion of this project. With these tasks completed, the frame and further work will produce a vehicle that can compete and represent WPI at the next SAE Baja competition.

References

Engineers, Society of Automive. (2017). 2017 Collegiate Design Series Baja SAE Rules. History of Mini Baja East.). Retrieved Novemeber, 2017, 2017, from

<http://bajasae.net/content/2018-BAJA-RULES-FINAL-2017-08-30.pdf>

Selmer, Heather; Shweiki, Sabbrin; Tencati, Paige. (2017). 2016-2017 Design and Optimization of a SAE Baja Chassis (M. Engineering, Trans.): Worcester Polytechnic Institute.

Reimpell, J., Stoll, H., & Betzler, J. W. (2000). The automotive chassis: Engineering principles. Oxford: Butterworth-Heinemann.

Gillespie, T. D. (1992). Fundamentals of vehicle dynamics. Warrendale, PA: Society of Automotive Engineers.

Jazar, R. N. (2017). Vehicle dynamics: Theory and application. Cham: Springer.