MEMORANDUM

to: DR. JOHN TESTER
from: TEAM 01
subject: SAE MINI BAJA FRAME
date: MAY 2, 2014

This is the final report for the SAE Baja Frame Team. The team designed and manufactured an entire frame for a Baja off-road vehicle. We compared different sizes and material of tubing and decided to build the frame out of AISI 4130 steel with a 1.250 inch diameter and a 0.650 inch wall thickness. Simulations performed in Solidworks showed that the frame would not fail even in the most extreme cases. The frame was manufactured at the NAU Fabrication Shop located in building 98C. All the tubes were cut to size and manually bent and notched to the correct specifications. The frame was welded using gas metal arc welding also known as MIG welding. The team also designed tabs for the vehicle. This included seatbelt harness tabs, suspension tabs and body panel tabs. These were manufactured using the CNC capabilities at the fabrication shop. The frame team also made body panels for the vehicle. These were made from high density polyethylene. The vehicle was completed the second week of April. It was tested in Phoenix. It was painted and prepped for completion. The 2014 SAE Baja Collegiate completion was held at the University of Texas El Paso campus. There the vehicle competed in a set of dynamic challenges and a four hour endurance event. The dynamic events included an acceleration, hill-climb, maneuverability, and suspension and traction events. The vehicle placed 64th in the acceleration, 56th in the hill-climb, 27th in the maneuverability, and 56th in the suspension and traction challenge. The team placed 46th in the endurance event. The vehicle would have performed better, but the team encountered a critical engine mount failure forcing an early retirement from the race. The team scored well on the sales presentation and placed 18th out of 96 teams. The team finished 51st overall.

SAE Mini Baja Frame

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Team 01

Final Report

Document

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Mechanical Engineering Design II – Spring 2014

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Contents

1 NOMENCLATURE

F = Force [lbf]

m = Mass [slug]

V_0 = Initial Velocity [ft/s]

t = Impulse Time [s]

E = Young's modulus [ksi]

I = second moment of area [in^4]

S_y = yield strength [ksi]

c = distance from neutral axis to extreme fiber [in]

g = Acceleration of Gravity [ft/s^2]

h = Drop Height [ft]

2 LIST OF FIGURES

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4 ABSTRACT

The frame of the SAE Baja vehicle needs to be lightweight and structurally sound to be competitive but still protect the driver. The vehicle needs to traverse all types of off-road conditions including large rocks, downed logs, mud holes, steep inclines, jumps and off camber turns. During the competition events there is significant risk of rollovers, falling from steep ledges, collisions with stationary objects, or impacts from other vehicles. There are certain needs and constraints that will be defined to create a frame that can be resilient to these conditions. Before starting the frame tubing has to be compared to determine a uniform material for the frame. Several frames will be compared against each other to decide which one would fit best to satisfy the needs. Types of welding will be compared to determine the mode of assembling of the frame. The frame design has been analyzed in a variety of different simulations to predict whether it will survive the impact scenarios that may exists at the competition. The results from these simulations indicate that the frame is indeed safe enough in the variety of worst-case scenarios tested. There is a projected cost for building the frame for the competition as well as buying safety equipment. There is a theoretical budget for a general manufacturing of the frame and attaching the safety equipment. There is a schedule for next spring to complete the frame, attach the drivetrain and suspension to the frame, test the vehicle, and compete in the SAE competition 2014.

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5 INTRODUCTION

The Society of Automotive Engineers International (SAE) has contracted the team to design a Mini Baja vehicle. The stakeholders for the project include Dr. John Tester and the Northern Arizona University student chapter of SAE. SAE is a United States based organization that provides international standards for the automotive, aerospace, and commercial vehicle industries. They sponsor a variety of collegiate competitions that simulate the real-world engineering process and challenge students in their area of study. The SAE Mini Baja competition is designed to challenge each team in the design, planning, and manufacturing process as applied to a small off-road vehicle that could be turned into a consumer product. The competition consists of a variety of different events to test speed and maneuverability, and culminates in a final endurance race. Our sub-team has been assigned the task of designing the frame of the vehicle and ensuring the overall vehicle compliance with the safety regulations.

6 PROJECT NEED STATEMENT

NAU has not won an event at the SAE Mini Baja competition in many years. During the competition, there will be several events that will test the limits of the vehicle. They include the Presentation, Hill Climb, Endurance, and Acceleration tests. The team must make a sales presentation to a panel of judges on the viability of the design as a consumer product. The maneuverability test consists of a variety of tough obstacles and tight turns, and the hill climb event tests the vehicle’s low-speed power. The endurance race is a three hour driving test to prove the long-term reliability and average speed of the vehicle. The acceleration event tests the maximum speed of the vehicle. It has been many years since NAU has won an event, and a single event win would satisfy our stakeholders. Therefore, the solution to our need is a single event win at the 2014 SAE Mini Baja competition.

7 PROJECT GOALS

The specific goal for our sub-team is to design the lightest possible frame that satisfies all the criteria specified in the 2014 SAE Mini Baja rulebook. To achieve this goal, the team must use lightweight materials and minimize the size of the frame. At the same time, the frame must be designed to meet all the safety requirements. After the frame is completed, our goal shifts to the overall safety of the vehicle. We will make sure all the sub-teams adhere to the strict safety guidelines throughout the design process, and we will do a final safety inspection before the competition.

8 OBJECTIVES

The most important objective for the frame design is safety. The Mini Baja competition focuses heavily on creating a safe environment for the competitors and has very strict safety rules. After safety, our next most important objective is to minimize the frame weight. After consulting with

Dr. Tester and thoroughly reading the rulebook, our main objectives were generated and are listed below:

- The frame must be safe.
- The frame weight should be minimized.
- The frame should be easy to manufacture.
- The frame should be inexpensive.
- No damage to the safety cell after an impact.
- No significant damage to the overall chassis after an impact.

9 OPERATING ENVIRONMENT

The vehicle will need to traverse rocks, sand jumps, logs, steep inclines, mud, and shallow water. The frame must be able to withstand large impacts and provide a safe environment for the operator. The vehicle may encounter collisions from other vehicles while competing, and there is significant roll-over risk in the maneuverability events. It will also experience various magnitudes of vibrations over different types of terrain and must maintain the safety of the operator at all times.

10 CONSTRAINTS

All of the constraints for this project come directly from the SAE Mini Baja rulebook. While we are limited by the school manufacturing facilities, everything in this project is within the capabilities of the NAU machine shop. The primary design constraints are:

- Must be constructed from steel tubing.
- Tubing must have a bending strength of at least 395 N-m.
- Tubing must have a bending stiffness of at least 2790 N-m^2.
- Tubing must have a minimum wall thickness of 0.062 inches.
- Frame length must be below 108 inches.
- Frame width must be below 40 inches.
- Height must be at least 41 inches above the seat bottom.
- Frame geometry must conform to the specifications.
- Vehicle must satisfy all the safety regulations in the rulebook.

11 DESIGN PROBLEM

The purpose of the frame is to protect the driver in the event of a collision or rollover, and to provide a chassis to mount the other subsystems. A minimum spacing between the driver and the frame must be maintained to ensure driver safety, and minimum strength requirements must be met. There are also specific requirements for the geometry of the frame as shown in Figure 21. There must be a gap of at least 6 inches in all directions between the driver's head and the frame, and there must be a 3 inch gap for the driver's body. [1] The frame must be constructed of an SAE standardized tubing size or an equivalent size of similar strength. A 64 inch tall driver weighing 250 pounds must be able to sit comfortably in the vehicle with all the proper safety devices. The frame must be no wider than 64 inches and no longer than 108 inches.

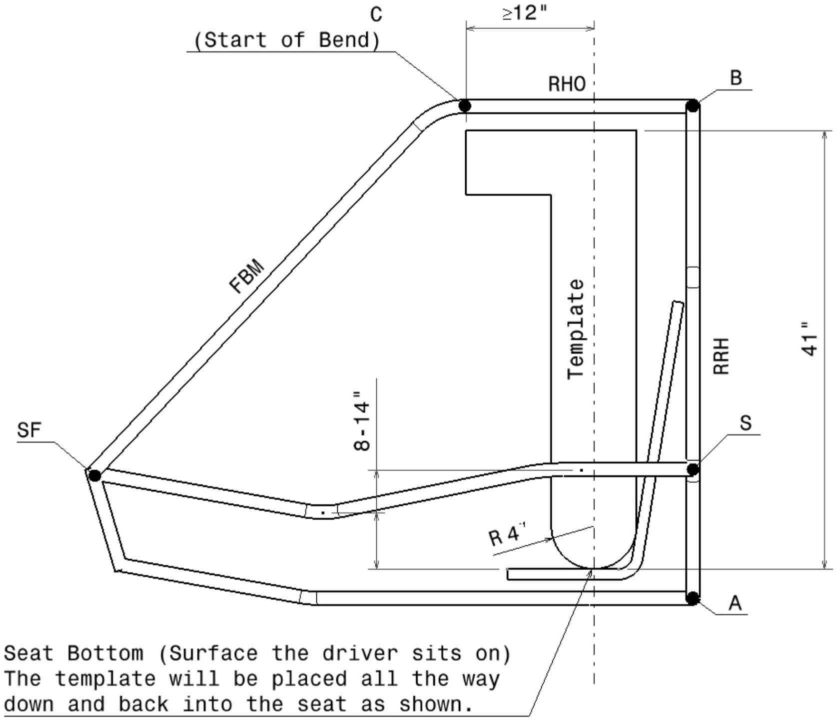
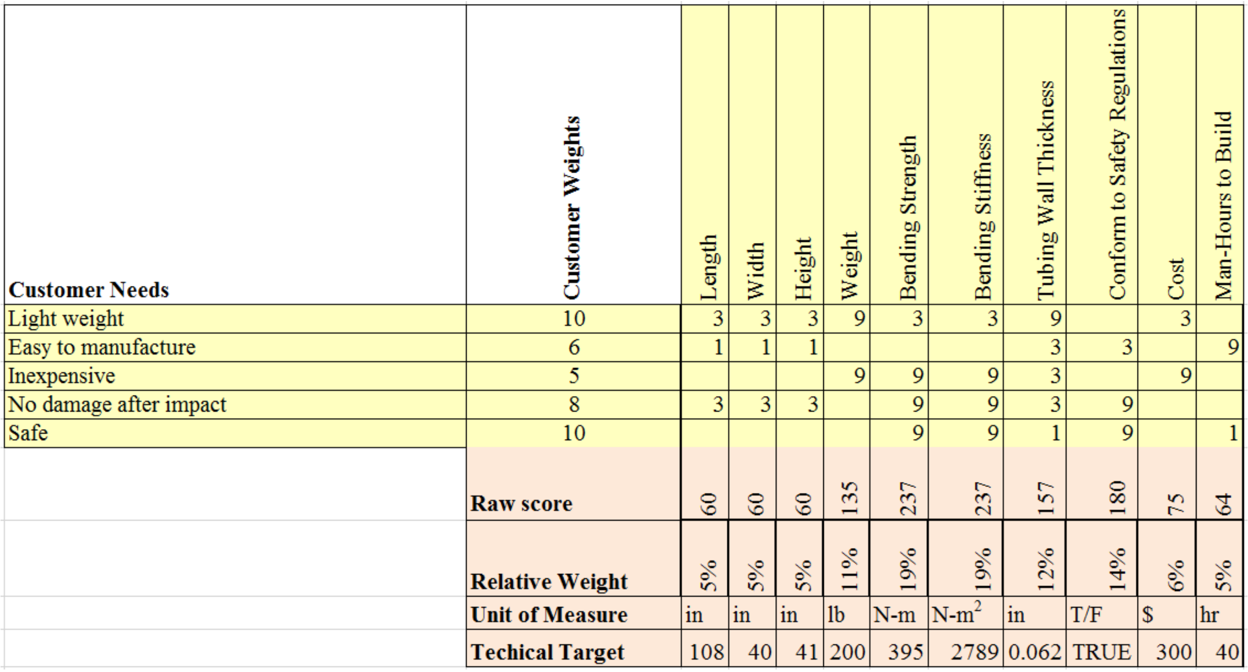


Figure 21: Clearance for the driver [1]

12 QUALITY FUNCTION DEPLOYMENT

The objectives and constraints have been compiled into the QFD chart below. Each customer need has been given a correlation score of 1, 3, or 9 with the corresponding engineering requirement. The relative weight indicates how important a specific requirements is compared to the others. The most important requirements are related to the safety and overall weight of the frame.



Customer Needs	Customer Weights	Length	Width	Height	Weight	Bending Strength	Bending Stiffness	Tubing Wall Thickness	Conform to Safety Regulations	Cost	Man-Hours to Build
Light weight	10	3	3	3	9	3	3	9		3	
Easy to manufacture	6	1	1	1				3	3		9
Inexpensive	5				9	9	9	3		9	
No damage after impact	8	3	3	3		9	9	3	9		
Safe	10					9	9	1	9		1
	Raw score	60	60	60	135	237	237	157	180	75	64
	Relative Weight	5%	5%	5%	11%	19%	19%	12%	14%	6%	5%
	Unit of Measure	in	in	in	lb	N-m	$N\text{-}m^2$	in	T/F	$	hr
	Techical Target	108	40	41	200	395	2789	0.062	TRUE	300	40

Figure 22: Quality Function Deployment

13 TUBING SELECTION

The 2014 SAE Baja rulebook specifies a standard tubing selection of AISI 1018 steel, with 1-inch outside diameter and a wall thickness of 0.120-inch. However, SAE does allow alternate selections as long as the team uses steel tubing and can prove that their selection has equivalent bending strength and stiffness. The tubing must have a minimum diameter of 0.5-inch and a minimum wall thickness of 0.065-inch. The tubing selection is independent of the frame geometry and thus was a completely separate decision process.

The most common alternate steel choice in the Baja competition is AISI 4130, because it has significantly higher ultimate tensile strength and yield strength than AISI 1018. [2] Both 4130 and 1018 have the same density, but 4130 produces a much stronger frame for the same weight. The equations defining bending stiffness and bending strength are shown below:

$$Stiffness = E \cdot I \tag{1}$$

$$Strength = \frac{S_y \cdot I}{c} \quad (2)$$

Where:

E = Young's modulus

I = second moment of area

S_y = yield strength

c = distance from neutral axis to extreme fiber

[3] Young's modulus is 29,700 ksi for all steels, and the yield strength for AISI 4130 is 63.1 ksi. AISI 1018 has a yield strength of 53.7 ksi. Calculated values for the bending stiffness and strength for the SAE specified tubing as shown in Table 8.

Table 8: Properties of SAE specified AISI 1018 tubing

Diameter [in]	Wall Thickness [in]	Stiffness [in-lb]	Strength [in^2-lb]
1.000	0.120	971.5	3.513

[4] Calculated properties for a variety of available AISI 4130 tubing sizes and comparisons with the standard tubing's relative stiffness, strength, and weight are shown in Table 9. The relative measures are simply the property of the 4130 tube as a percentage of the property of the SAE specified AISI 1018 tube.

Table 9: Properties of AISI 4130 tubing of various sizes

Diameter [in]	Wall Thickness [in]	Stiffness [%]	Strength [%]	Weight [%]
1.000	0.120	100	118	100
1.125	0.083	113	119	81.9
1.125	0.095	126	131	92.7
1.250	0.065	130	122	72.9
1.375	0.065	176	150	80.6
1.500	0.065	231	181	88.3

The lightest tubing size that exceeds the SAE minimum requirements is AISI 4130 steel, 1.250-inch outside diameter tubing with 0.065-inch wall thickness. This is the tubing we have selected to use regardless of the frame design. AISI 1018 tubing of the same size is less expensive and still meets the SAE minimum requirements, but is not as safe. If sufficient funds are not available for the AISI 4130 steel, the AISI 1018 of the same size will be used as a backup selection.

14 CONCEPT GENERATION

The team came up with four different designs for the overall frame geometry. Each design considered conforms to the 2014 SAE Mini Baja Rules. Below, the advantages and disadvantages for each design are discussed.

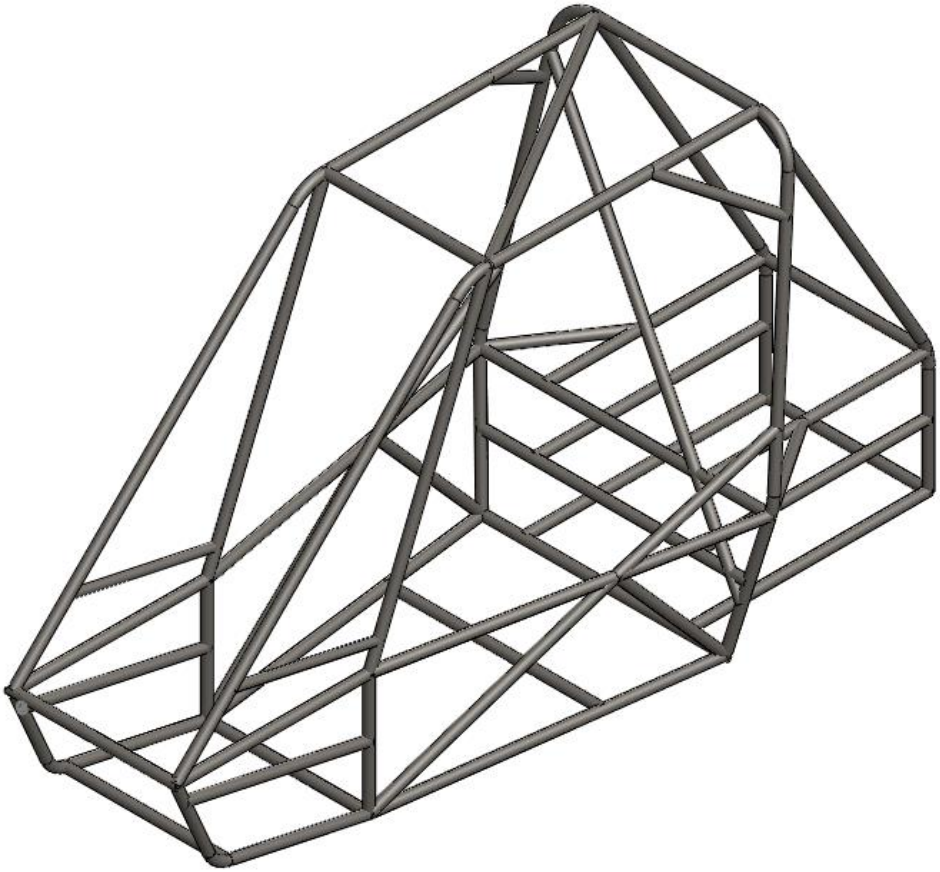


Figure 23: Design 1

Advantages of Design 1:

- Rear roll hoop and cage will provide increased rigidity in frame. There is cross bracing to increase the strength of the roll hoop.
- Wider frame will allow driver to exit vehicle in case of emergency
- Shorter frame length will allow for better handling throughout course

Disadvantages of Design 1:

- Highest amount of tubing will make this the heaviest frame.
- The height of the frame affects the center of gravity potentially causing the vehicle to be less stable.
- Highest number of individual tubes will decrease ease of manufacturability. More tubes will need to be cut and welded together to complete the frame.

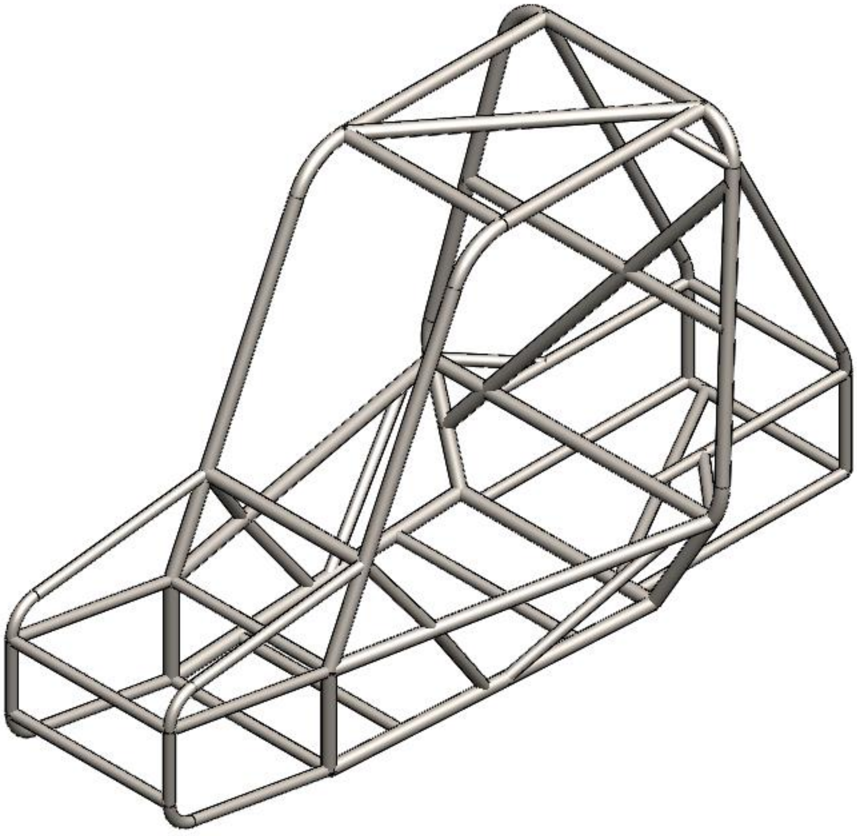


Figure 24: Design 2

Advantages of Design 2:

- Least amount of material used will make for the lightest frame
- Shortest wheelbase will make this the most maneuverable frame because the turning radius will decrease.
- Least number of individual tubes will make this the easiest frame to manufacture as it will require the least cutting and welding of individual tubes.

Disadvantages of Design 2:

- The lack of tubing could affect frame rigidity as there are less members to transfer the loads.
- The height of the frame affects the center of gravity potentially causing the vehicle to be less stable.

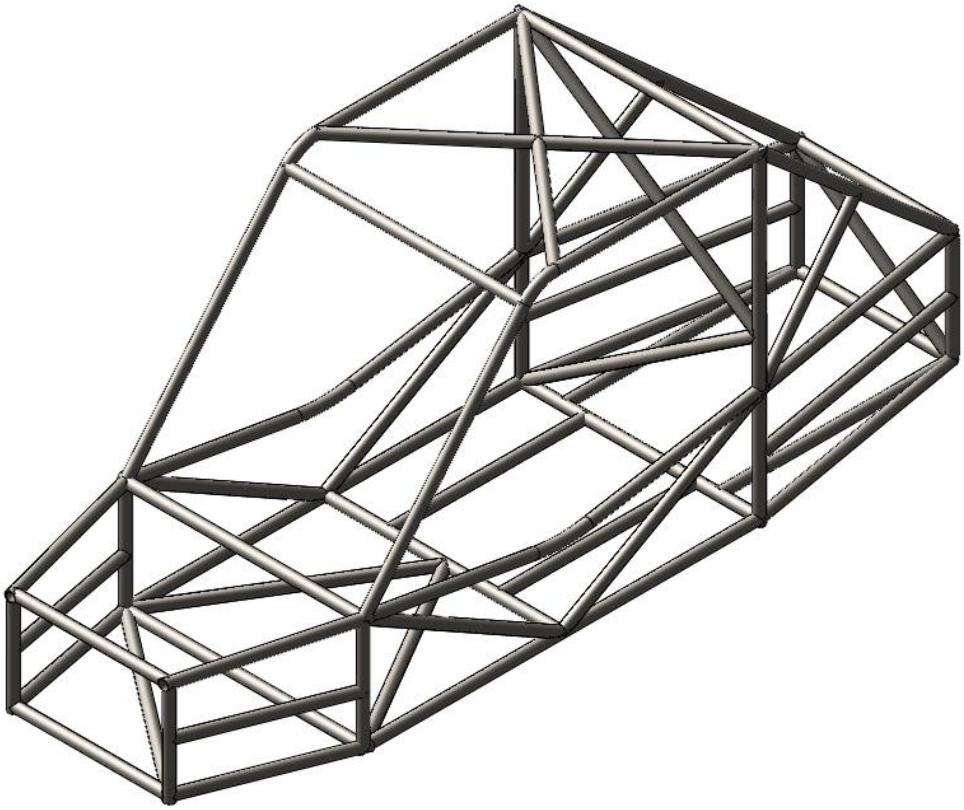


Figure 25: Design 3

Advantages of Design 3:

- Longer frame allows for a longer wheel base increasing the overall stability of the vehicle
- Higher number of individual tubes allows for frame stiffening at specific points increasing the overall rigidity of the frame.
- Low number of bends allows for easier manufacturing because less operations will have to be performed to the pipes saving time.

Disadvantages of Design 3:

- Longer frame decreases maneuverability. The long frame will increase the turning radius
- Large amount of material results in heavy frame which will hinder performance.
- High number of individual tubes will decrease ease of manufacturability. More tubes will need to be cut and welded together to construct the frame taking up more time and resources.

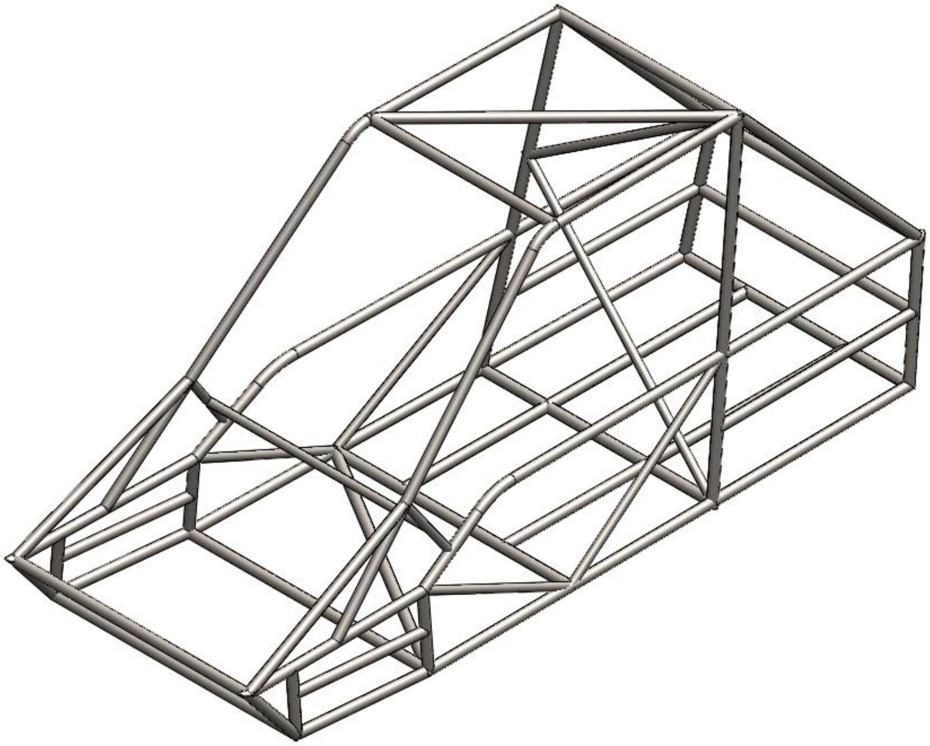


Figure 26: Design 4

Advantages of Design 4:

- Longer frame allows for a longer wheel base increasing the overall stability of the vehicle
- Relatively large interior space will allow taller drivers to operate the vehicle.
- Low number of bends allows for easier construction of the frame.

Disadvantages of Design 4:

- Longer frame increases the turning radius thus decreasing vehicle maneuverability.
- A tall frame will raise the center of gravity. A high center of gravity could cause a vehicle rollover.

- High number of individual tubes will decrease ease of manufacturability. More tubes will need to be cut and welded together to construct the frame taking up more time and resources.

15 DECISION MATRIX

The team reviewed the four designs and created a decision matrix shown in Table 10. The relative weight of each criterion indicates its importance in the decision process. The weights were restricted to a nine, five, or one because we cannot determine subtle differences at this point in the design process. Raw data was used to populate the design columns for simplicity. The goal was to minimize each of the criteria, thus the lowest overall score is the winner.

Table 10: Decision Matrix

	Weight	Design 1	Design 2	Design 3	Design 4
Amount of Material (ft)	9	109	94	105	107
Length (in)	5	83	78	100	100
Width(in)	1	32	33	30	31
Height (in)	5	45	44	39	44
Number of Bends	1	10	10	4	4
Number of individual tubes	1	65	43	50	55
Total		1728	1542	1724	1773

The team selected a relative weight of nine for the amount of material needed to build the frame because this directly correlates to the final weight of the frame. Because the tubing selection is independent of the frame design, only the length of tubing required was considered.

The team selected a relative weight of five for the length and height of the frame. The length of the frame affects the maneuverability of the vehicle as well as high speed stability, and the height affects the center of gravity. Although a long length increases the stability, the maneuverability of the vehicle is much more important. The length needs to be minimized to decrease the turning radius and reduce the chance of high-centering on obstacles. A shorter length frame will also make the vehicle easier to transport when not in use. The height also needs to be minimized to reduce rollover risk.

A relative weight of one was assigned to the width, number of bends, and number of tubes. The width of the frame is not the outside width of the vehicle, and does not directly affect clearance or stability. The number of bends and the number of tubes were used to quantify the manufacturability of the frame. The more bends and individual tubes required, the more operations there are to construct the frame. All of these criteria also need to be minimized.

The decision matrix indicates that design 2, shown in Figure 24, is the best fit for our objectives. This design has the least amount of material needed and has smaller overall dimensions than the others. It requires more bends than other designs given, but the light weight and small dimensions make up for this minor disadvantage.

16 WELDING TYPE SELECTION

The NAU Machine Shop has three types of welding equipment availbe to use: Gas Metal Arc Welding (GMAW), Shielded Metal Arc Welding (SMAW), and Gas Tungsten Arc Welding (GTAW).

SMAW (commonly known as stick welding) requires an electrode, an electrode holder and a ground to the metal to be able to weld the tubing together as shown in Figure 27. [5] Stick welding requires no prep-work whatsoever and the workpiece can be very dirty without any loss in weld strength. However, this process would be very difficult for welding the frame because it is difficult in tight spaces and requires a special type of electrode for AISI 4130. This type of welding also creates a lot of spatter and left over welding material which must be removed afterward. SMAW requires no prep-work but is time consuming and difficult at awkward angles and in tight spaces.

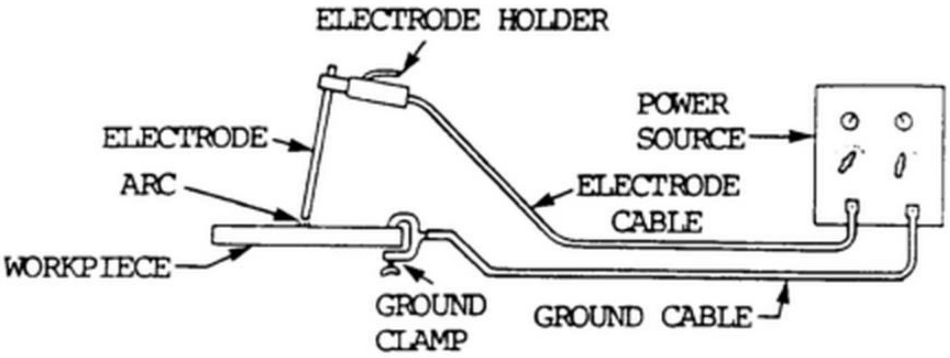


Figure 27: Shielded Metal Arc Welding [5]

GTAW (also known as tungsten inert gas, or TIG) would be the most time consuming type of welding process. This type of process uses an electrode, a torch, a ground and a foot pedal for controling the amperage of the torch current while welding [Figure 28]. [6] The welder must simultaneously control the torch and the foot pedal while manually feeding filler rod into the weld. This process will create no spatter or slag and is the cleanest type of welding process because it requires no clean up. However, it requires a lot of pre-weld prepping and meticulous cleaning of the material, or a weak weld will result. When there are tight or hard to reach spots this welding process becomes very difficult because of the coordination it requires to perform correctly.

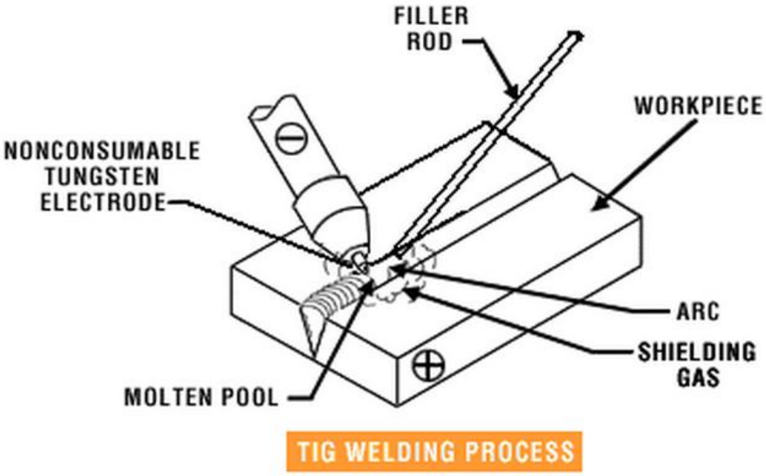


Figure 28: Gas Tungsten Arc Welding

GMAW (also known as metal intert gas, or MIG) welding is process that uses an electrode holder and a ground with a constant wire fed through the electrode holder, as shown in Figure 29. [7] A wire continously feeds through the electrode holder, eliminating the need for the welder to add filler by hand. The electrode holder itself is also small and easy to fit in tight spaces. This type of welding requires little or no prep-work, only produces minimal spatter, and requires very little cleaning after welding. This is the easiest process to use in joining the different parts of the frame together because no special rod is needed and it is easy to weld at odd angles and in tight spaces. The process we choose to weld this frame is the GMAW or MIG process because it will be easier than the other processes and one process does not produce a stronger weld than the other. This is the process the team chose for the construction of the frame because of its simplicity and user-friendliness

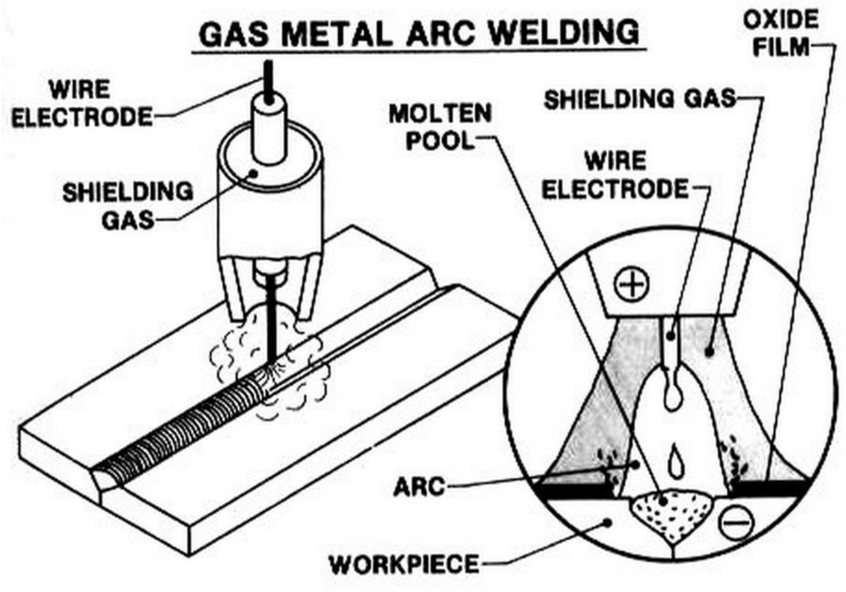


Figure 29: Gas Metal Arc Welding [8]

17 ENGINEERING ANALYSIS

In order to determine a frame design which satisfies the engineering design targets, each of the frame iterations was put through SolidWorks simulations. Because the frame consists of both hollow tubing and solid metal tabs, two separate types of analyses were conducted. Beam elements were used in the frame simulations as shown in Figure 30: Frame *Analysis* For the analysis of the solid frame components, tetrahedral elements were used, as shown in Figure 31: Tab *Analysis* All of the simulations are static stress analyses. For the dynamic impact simulations, a static analysis at the moment of maximum acceleration was performed.

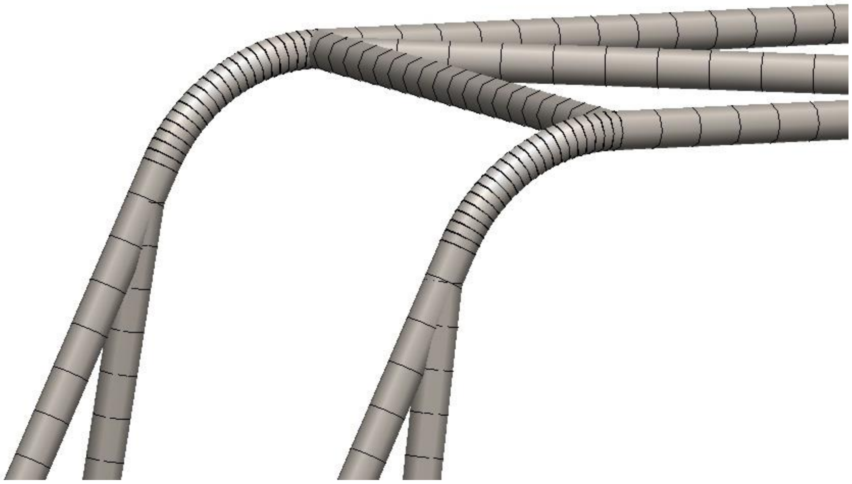


Figure 30: Frame Analysis

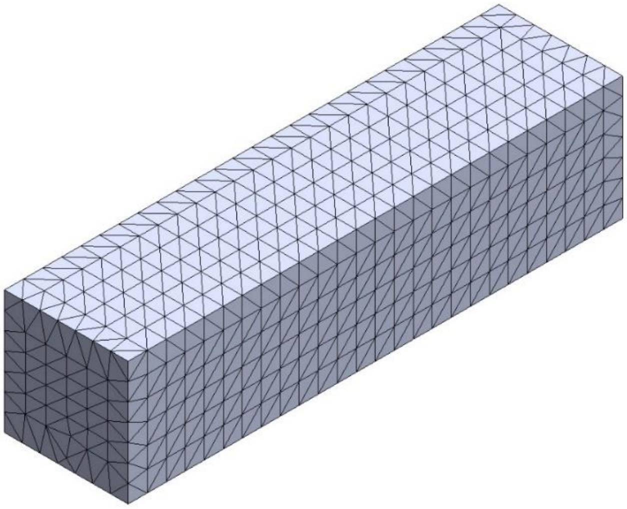


Figure 31: Tab Analysis

18 REFINED FRAME DESIGNS

The four versions of the frame analyzed in this report are shown below. Design 6 retained the majority of the platform from design 5, with the exception of additional bracing in the roll hoop and the rotation of the front roll bar supports from a 45° angle to a 90° angle to increase the rigidity of the roof structure.

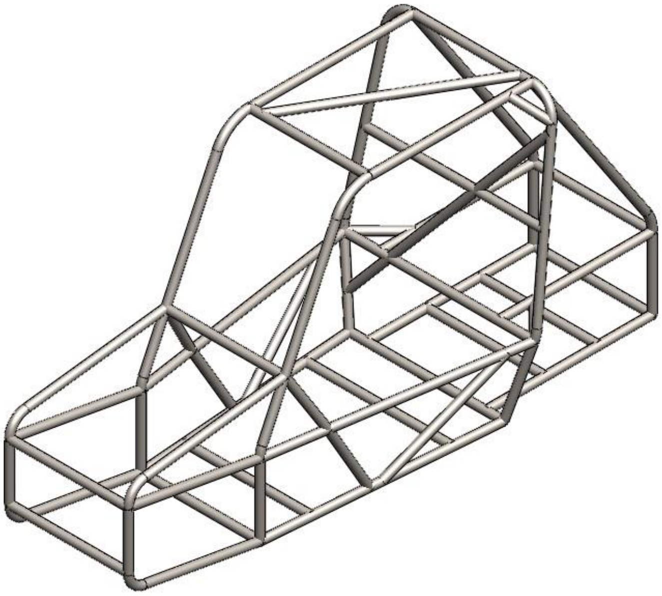


Figure 32: Design 5

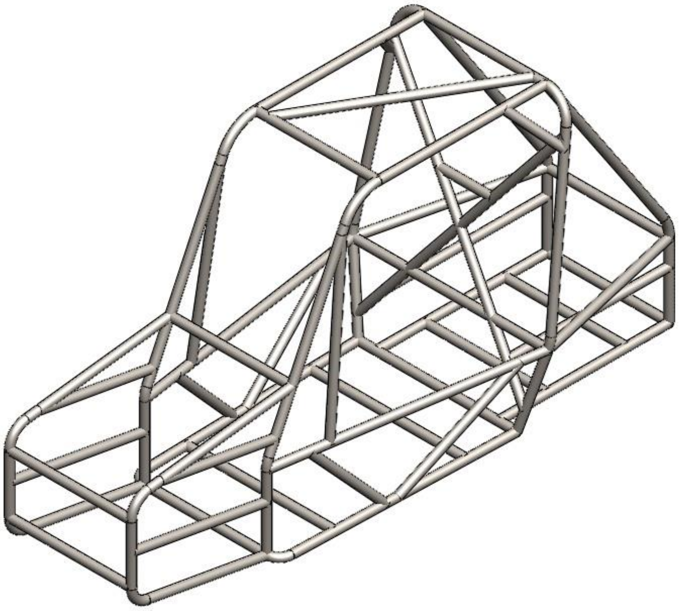


Figure 33: Design 6

Design 7 is an updated version of design 6, but with a focus on manufacturability. Because the Baja vehicle is intended to be a production off-road vehicle, the ease of manufacturability is important and must be taken into consideration. Alterations were made to the rear roll hoop and roll cage to lower the number of bends needed. The current frame, design 8, took the manufacturability of design 7 a bit further by altering the tubing geometry in the base of the frame, at suspension mounting points, and in the drivetrain compartment.

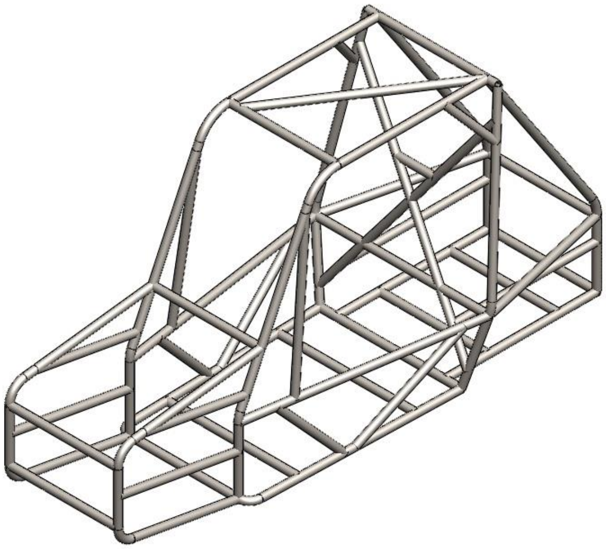


Figure 34: Design 7

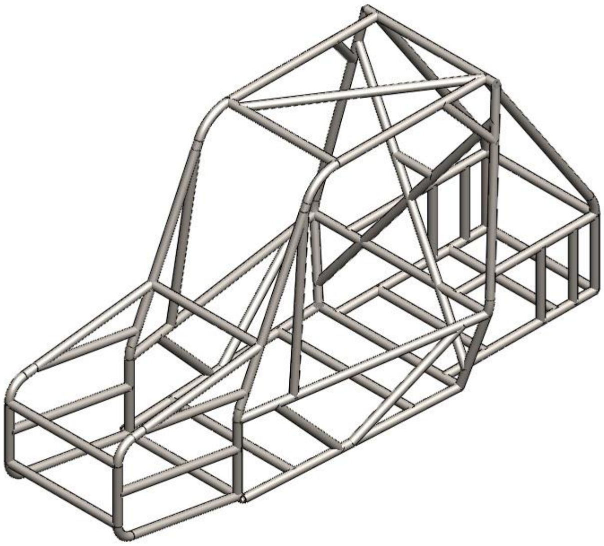


Figure 35: Design 8

To validate that design 8 is indeed stronger than the previous versions, a simple test was simulated to show the stress distribution and yield safety factor of each of the four frames. An arbitrary load of 6000 pounds was evenly applied to the top bars of the roll cage and a static stress simulation was performed in SolidWorks. The frame with the lowest maximum stress has

the most even stress distribution, and the highest minimum safety factor. The results of these tests are shown in
Table 11.

Table 11: Simple Loading Results

Design	Max Stress (ksi)	Max Deflection (in)	Yield Safety Factor
5	61.61	0.256	1.08
6	61.20	0.210	1.09
7	60.16	0.202	1.11
8	56.89	0.206	1.17

Based upon these results, Design 8 is the optimal design and the alterations did improve the frame. The removal of the bends from the base of the frame increased manufacturability and allow for better distribution of stresses throughout the frame. The alterations made to the suspension mounting points improved rigidity and allow for easy adjustment of the design based upon changes in the suspension geometry. Design 8 was chosen for all of the more advanced simulations.

19 FRAME IMPACT TESTS

Each impact test is a worst case scenario that could potentially occur at the competition. There are four tests: a drop test, front collision test, rear impact test, and side impact test. The drop test consists of the vehicle being dropped upside down onto its roof from a height of 10 feet. The three collision tests simulate different 35 mph impacts with stationary objects or other vehicles.

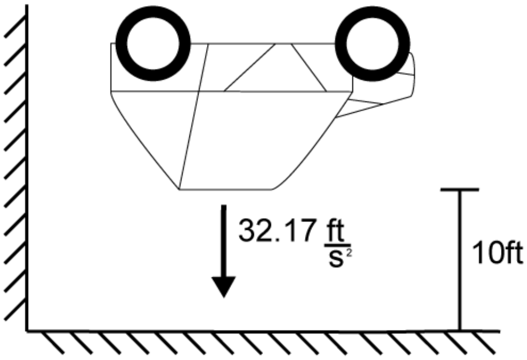


Figure 36: Drop Test

The team selected 10 feet for the drop height because it is sufficiently greater than anything expected at the competition. Equation 1 shows the calculation for the force on the vehicle during the impact. An impulse time of 0.1 seconds was used for the drop test.

$$F = m \cdot \frac{\sqrt{gh}}{t} \tag{1}$$

Where:
F = Force
m = Mass
g = Acceleration of Gravity
h = Drop Height
t = Impulse Time

The front collision test simulates the vehicle hitting a solid, immovable object at a speed of 35 mph as shown in Figure 37. This is the maximum top speed the vehicle is expected to reach. The rear impact test simulates the vehicle being rear-ended by another 500 lb Baja vehicle, again at a speed of 35 mph (Figure 38). To make this test as hard as possible, the front of the vehicle is resting against a solid wall. The side impact test is identical to the rear impact, but the vehicle is oriented sideways relative to the motion of the incoming 500 lb vehicle (Figure 39). In reality the wheels and suspension of the vehicle would absorb some of the energy in the side impact test, but these were removed from the simulation to make it an absolute worst-case scenario.

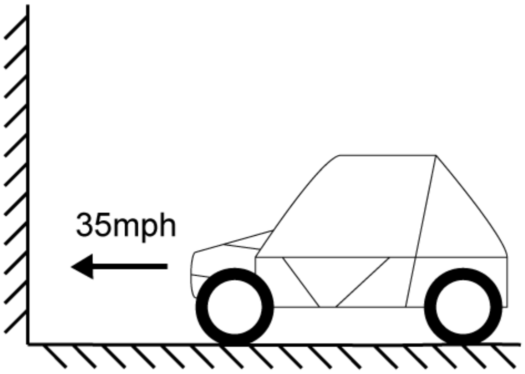


Figure 37: Front collision Test

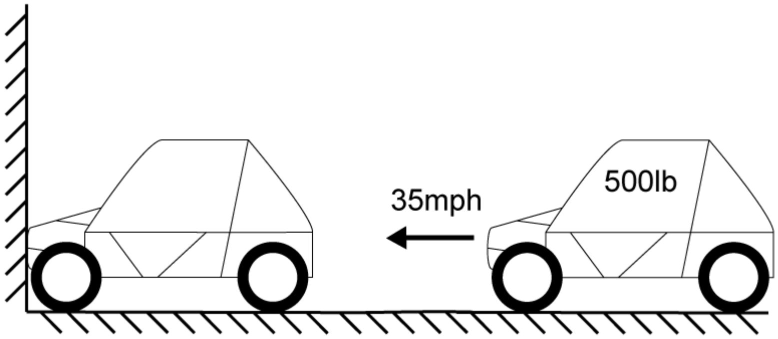


Figure 38: Rear Collision Test

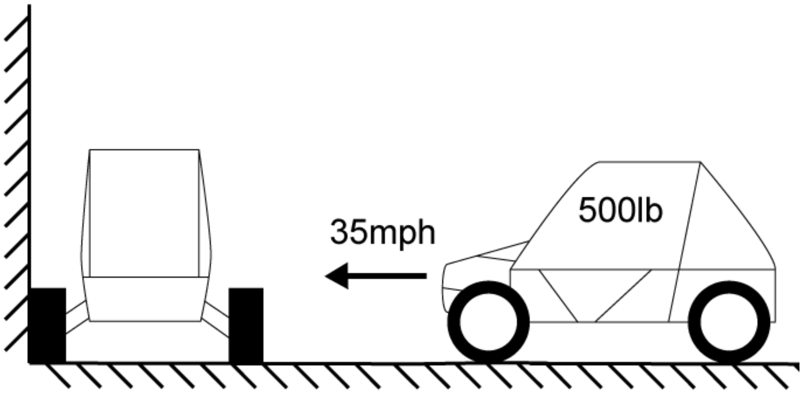


Figure 39: Side Collision Test

For the impact tests, Equation 2 is used to calculate the force on the vehicle. An impulse time of 0.2 seconds was used.

$$F = m \cdot \frac{V_0}{t} \tag{2}$$

Where:
F = Force
m = Mass
V_0 = Initial Velocity
t = Impulse Time

20 ANALYSIS ASSUMPTIONS

For the simulations a few simple assumptions were made. The drivetrain was assumed to be a total weight of 120 pounds, including the engine, transmission, sprockets, and chains. The suspension load was assumed to be a total weight of 50 pounds per corner which includes the A-arms, shocks, and tires. The driver weight was assumed to be 250 pounds because the SAE Baja rules requires a minimum design driver weight of 250 pounds. The frame weight was evaluated to be 100.29 pounds using the SolidWorks model. The tubing used in the simulation was AISI 4130 steel with a 1.25 inch diameter and 0.065 wall thickness. The force equations stated in the test descriptions were applied to each load to simulate the acceleration experienced during the impact.

All the loads were applied at appropriately corresponding to their actual mounting locations in the frame. The suspension evenly on the correct members in each corner. The driver weight was distributed evenly between the 3 pieces of tubing used to secure the safety harness. The drivetrain load is applied on the two tubes in the bottom of the engine compartment that will be used to secure the drivetrain components. Figure 40 shows an example loading condition with the various loads applied in the correct locations.

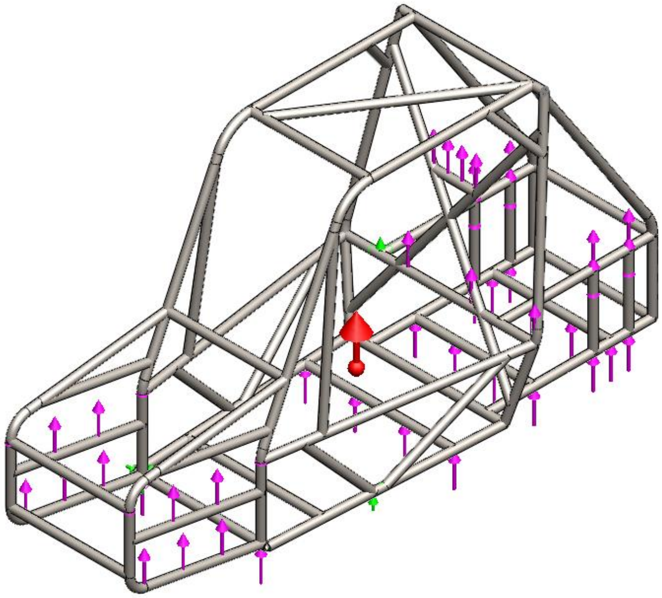


Figure 40: Example Frame Loading

21 SIMULATION RESULTS

The results for the four advanced frame tests are discussed below, but for formatting's sake the images generated in SolidWorks are shown in Appendix A at the end of the document. Table 12 shows the maximum displacements and the minimum factor of safety for each test.

Table 12: Impact Results Summary

Test	Max Deflection [in]	Yield Safety Factor
Drop	0.089	5.32
Front Collision	0.135	2.90
Rear Impact	0.263	1.45
Side Impact	0.363	1.01

Keep in mind that the maximum displacement is not necessarily the location of maximum stress. The colors in the deflected shape figures simply indicate the displacement of the element relative to its original position, not bending deflection. In the case of the drop test, the maximum stresses are in the vertical members supporting the roof, but the maximum displacement occurs in the front suspension area of the frame. As the roof crushes, the deformation pulls the front with it. Even though some of the lowest stresses are in the front members, the maximum displacement occurs there because of the effect of the members they're attached to.

In our tests the maximum stresses are expected at the location of impact, which is often the location restrained by the boundary conditions. In SolidWorks these restraints effectively make the point of impact the origin of the displacement measurements. This can make the displacement figures misleading if care is not taken to correctly interpret the results. It may be wise to ignore the color gradients of the deflected shapes and simply examine the geometry alone. For all of the impact analysis, the deflected shapes agree with the results one would expect in a real world scenario.

For each individual test, the figures for the stress distribution and the safety factors produced by SolidWorks are identical. The safety factor figure is simply the stress distribution divided by the yield stress, so the color gradients are the same. SolidWorks simply changes the units and the magnitude of the scale. Because these figures are identical, only the safety factor is included, but the results are equally valid for the stress distribution.

In the drop test, the roof structure begins to crush, and the members supporting the driver and the drivetrain show significant stresses. In the front collision test, the momentum from the driver produces high stresses on the shoulder harness mounts, and the momentum of the drivetrain makes the rear end deflect towards the front of the vehicle. The front of the frame has the smallest indicated displacements because it is pushed against the wall, but careful examination of the deflected shape shows significant deformation relative to the rest of the frame. The rear impact test is very similar to the front collision test, but the momentum effects of the driver, drivetrain, and suspension are removed because the vehicle is at rest and pinned against a wall. The frame has sufficiently high safety factors in all three of these tests.

The side impact test is the toughest frame test, and our vehicle barely passes with a 1.01 safety factor. This seems low at first, but it must be noted that the safety factor is for yield stress, not ultimate tensile stress. AISI 4130 steel has a very high ultimate tensile strength, and there is a large plastic deformation region present before the deflection of the frame begins to endanger the driver. Our current frame design passes all of the impact tests within the yield limits of the material, thus there will be no permanent damage from the scenarios analyzed here.

22 TAB SHEAR TESTS

While analyzing the frame we spoke with our client and he informed us that most frames do not fail while at the competition. Rather, the most common structural failure is of the mounting tabs welded onto the frame. These tabs are used to attach almost everything, including the drivetrain, suspension elements, and the driver restraints. To reduce the risk of such a failure in our design, the mounting tabs were intentionally overdesigned using extreme loading cases. Such excess is acceptable because increasing the strength of the tabs adds very little material to the overall frame design and does not greatly affect the weight. Two cases were analyzed: the tabs for the safety harness mounts and the tabs for the suspension mounts. These two were selected because they are the most significant and experience the highest stresses. The force values used in the analysis correspond to the maximum forces calculated for the frame impact tests. 322 pounds was applied to each safety harness tab, and 250 pounds was applied to each of the suspension tabs.

Table 13: Tab Shear Results

Test	Max Deflection [in]	Yield Safety Factor
Driver Harness	0.001	4.70
Frame Tab	0.024	1.50

The SolidWorks figures for the tab shear tests are shown in Appendix C at the end of the document. The maximum deflections are extremely small and the factor of safety for the driver harness is very high. The safety factor for the frame tabs is lower at 1.5, but 250 pounds per tab is an absolutely ridiculous load. As stated earlier, overdesigning these two components is perfectly acceptable and minimizes the risk for the most common structural failure at the competition.

23 ENGINEERING DESIGN TARGETS

The following table lists our engineering design targets from the QFD matrix and compares them to the actual values of our current frame design. All of the targets have been met with the exception of the frame height. The original requirement was unrealistic because of the required empty space between the driver's helmet and the top of the frame. This consideration was overlooked or miscalculated in the original target generation. The current design is as short as possible while still satisfying the safety regulations.

Table 14: Engineering Design Targets

Requirement	Target	Actual
Length [in]	108	88.175
Width [in]	40	32
Height [in]	41	44.679
Bending Strength [N-m]	395	486
Bending Stiffness [N-m^2]	2789	3631
Wall Thickness [in]	0.062	0.065
Pass Safety Rules	TRUE	TRUE

24 PROTOTYPE FABRICATION

Once all designs passed FEA analysis and complied with all regulations set forth by the Society of Automotive Engineers for the 2014 Mini Baja competition, construction of the frame commenced.

Before any member was cut, bent or created, build sheets were created through the use of Solidworks to help map the number, size, and cuts of all frame members.

Tubing was cut to length with the help of a horizontal band saw and chop saw equipped with zirconia grain design, double-reinforced, angle iron chop saw blade. After tubing sections were cut, any tubes which needed to be bent were done so through the use of a mechanical tube bender.

Figure 21: Tube Bending

To insure proper fitment while maximizing weldable area all intersecting tubing within the frame were notched to their respective diameters with a hole saw and notching jig pictured below.

Figure 22: Notching

With all of the necessary tubing members cut and notched to size, a wooden jig was fabricated with matching dimension and angles to the frame to provide a solid foundation for the frame to be affixed to while all members were welded together.

Figure 23: Frame Jig

Figure 24: Frame Welding

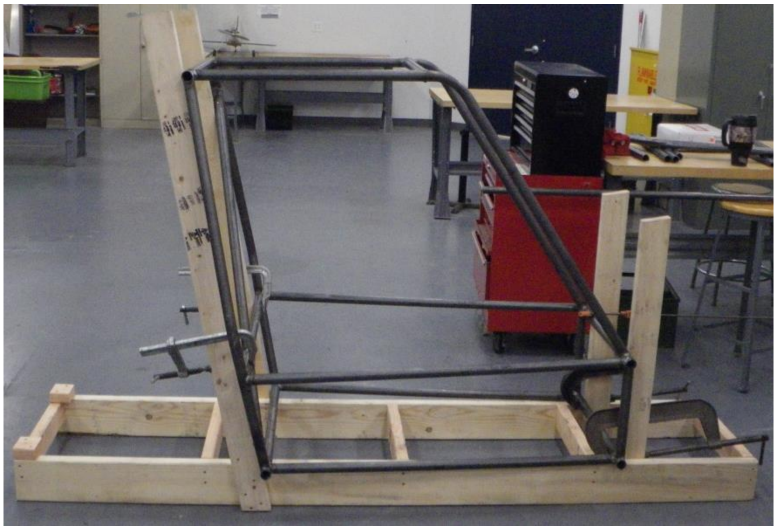


Figure 25: Completed Center Section

The main roll cage was constructed first while final dimensions and calculations were being completed by the drivetrain and suspension teams. Once all dimensions agreed upon, progress began on the front and rear sections of the frame.

Figure 26: Engine Mount

Figure 27: Completed Frame

The frame was welded together using GMAW (gas metal arc welding) by a single team member to ensure continuity and to minimize complexity during technical inspection while at competition. Per SAE Mini Baja rules and regulations, whoever welded structural members on the roll cage must provide weld coupons to be inspected at competition. Two welding coupons must be created from the same tubing used in the roll cage; one coupon welded at a 90^o angle and the other welded at a 45^o angle. These coupons are created solely for destructive testing. The 90^o coupon was tested past its yielding point to ensure the tubing would fail before the welded joint. The 45^o coupon was cut in half to inspect the penetration of the weld and check if the penetration depth is sufficient.

Once suspension geometry and mounting locations were finalized, fabrication began on suspension mounting tabs. Through the use of CNC controlled machines such as the HAAS and the TORMACH, tab could be reproduced with very high accuracy and very low tolerances. Tabs were MIG welded to plate steel to guarantee proper clearances while the tabs were welded to the frame. These clearances were critical because custom spacers would be created for each of the mounting points for all suspension components.

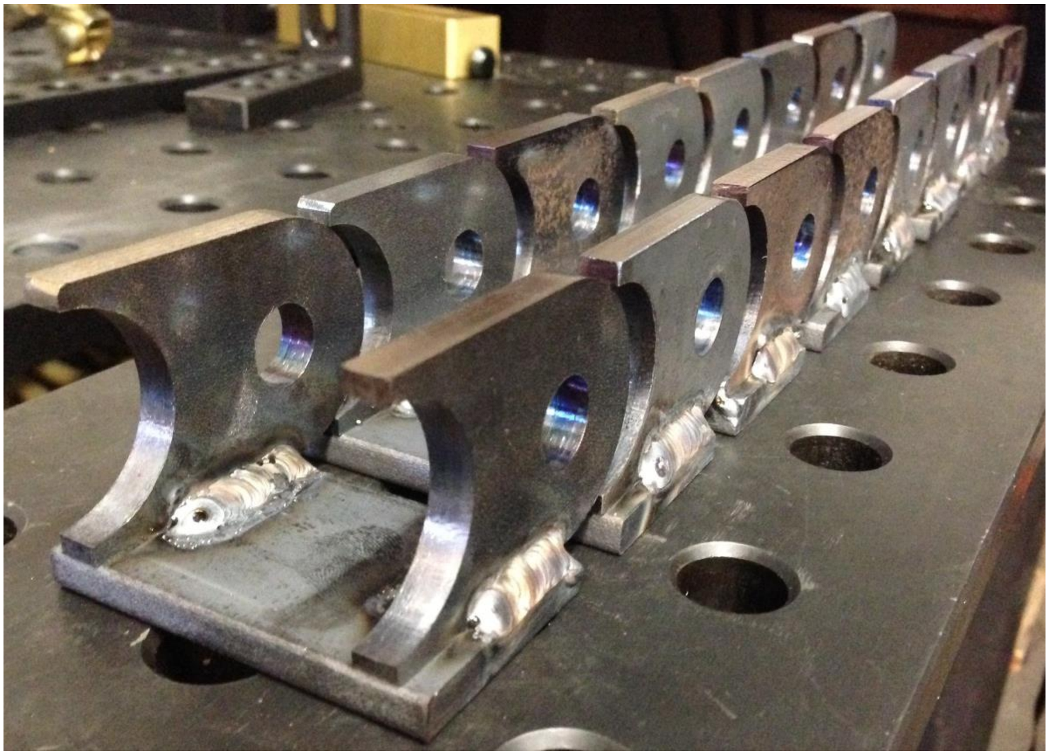


Figure 28: Suspension Tabs

Firewall tabs were fabricated and MIG welded onto the rear roll hoop of the roll cage to provide a mounting surface for the firewall. The firewall was then created from 20 gauge steel to provide a barrier between the drive and the drivetrain. Should any gas from the fuel tank ignite, the firewall would keep the driver free from harm while they safely exit the vehicle. Because the shoulder harnesses were attached to one of the cross beams in the rear roll hoop, sections of the firewall were cut out to provide a pathway for the harnesses to pass through. According to SAE Mini Baja rules, no part of the safety harnesses are allowed to be exposed to the drivetrain area. In compliance with SAE rules and regulations, a safety harness retention box was created to cover the safety harness and seal up any gaps in the firewall which resulted in the mounting of the safety harnesses

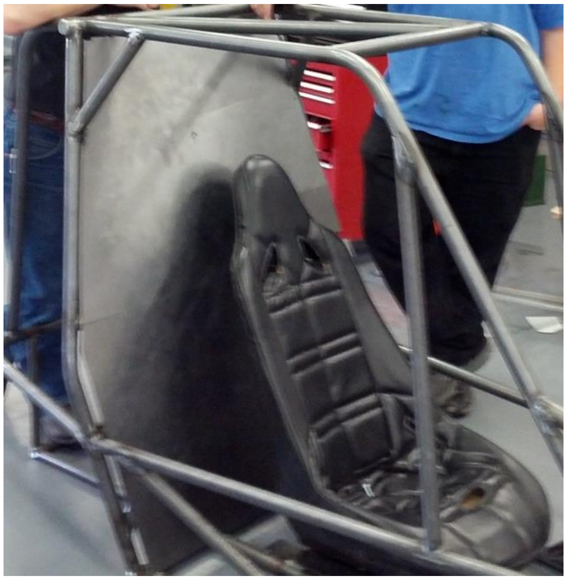


Figure 29: Completed Firewall

During competition the driver is susceptible to flying rocks, debris, engines, drive shafts, wheels and other Baja vehicles. To keep the driver safe, body panels were created out high density polyethylene sheets and mounted to the frame with metal body tabs. These tabs were fabricated and MIG welded to the frame in various locations to prove maximum rigidity while minimizing the amount of material used on the vehicle.

Figure 30: Body Tabs

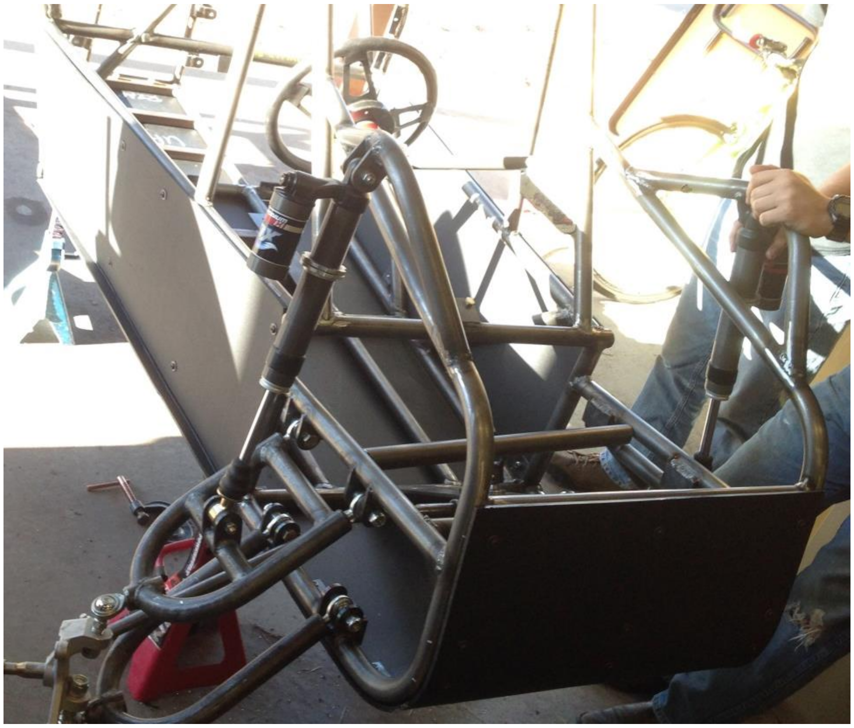


Figure 31: Body Panels

Once all parts were test fitted and the vehicle was test driven to insure all issues were alleviated, final cosmetic touches were given to the frame. The entire buggy was stripped down to the bare frame and all bare metal components got a fresh coat of either black or NAU blue to represent the school with pride at competition.

Figure 32: Painted Frame

Throughout the fabrication process minimal difficulties were faced and even less were needed to be overcome thanks to the capabilities of Solidworks.

25 TESTING AND RESULTS

The vehicle was tested both in the desert of Phoenix, AZ and in the forest located behind Northern Arizona University in Flagstaff, AZ. It was during the testing session in Phoenix, AZ that the tie rod extension broke and a new design was quickly adapted after consulting with a local off road shop, Geiser Bros. Design & Development. After the new tie rod extension was implemented, no other issues arose during the testing in Flagstaff, AZ. Although steering components broke during testing, the frame performed flawlessly and required no alterations. Because no alterations were needed, all of the objectives and constraints were either met or satisfied.

26 COST ANALYSIS

The cost analysis for this project was broken up into two different budgets; the total cost for the team to build and go to competition and a theoretical production cost for a run of 4000 units annually.

The team budget was broken into main categories: raw materials, safety, and miscellaneous. The Raw Materials category contained all the materials needed to construct the bare frame. A total of 120 feet of 1.25” x 0.065” AISI 4130 chromoly tubing will be purchased to construct the main structural supports of the frame. A total of 60 feet of 1.00” x 0.095” AISI 4130 chromoly tubing will be purchased for all of the secondary supports in the frame. A 0.375” x 6” x 6’ section of AISI 4130 chromoly plate will be ordered to create all mounting tabs for suspension, drivetrain, safety components, ect. The next main category is Safety, in which, all components are outlined and required under the SAE Baja rulebook. A 5-point safety harness, fire extinguisher, and one Ski-Doo kill switch are already provided by previous year’s teams. A Corbeau Baja RS seat, one Ski-Doo kill switch, and a SAE certified brake light still need to be purchased to qualify under the safety guidelines. The last category in the team budget is Miscellaneous which contains all costs needed to go to competition. The entry fee of $1,100.00 will be evenly divided between the three Baja teams. Food costs are budgeted for $20.00 per person per day for the four days of competition. The team will split up into two hotel rooms for four nights through the competition. The total cost of the frame, all safety components, and the cost to go to competition total up to $1,994.50.

Table 8: Material Cost

Category	Item	Quantity	Price
Raw Materials	1.25” x 0.065” AISI 4130	120’ x ($1.67 per foot)	200.00
	1.00” x 0.095” AISI 4130	60’ x ($1.67 per foot)	100.00
	0.375” x 6” AISI 1018	1 x (6’ Sections @ $111.86)	111.86
Safety:	Corbeau Baja RS Seat	1 x ($249.99)	249.99
	5-point Safety Harness	1 x ($73.99)	0.00
	Ski-Doo Kill Switch	2 x ($19.99) – 1 x (Provided)	19.99
	Fire Extinguisher/Mount	1 x ($25.46) – 1 x (Provided)	0.00

	Brake Light	1 x ($33.99)	33.99
Miscellaneous:	Entry Fee	1/3 x ($1100.00)	366.67
	Food	5 x (4 Days) x ($20.00 per day)	400.00
	Hotel	2 x (4 Days) x ($64.00 per night)	512.00
Total			1994.50

The theoretical production cost is a projected budget analysis for a manufacturing company to produce 4,000 units per year. This budget is broken down even further into the categories of Raw Materials, Marginal Costs, Labor, and Fixed Costs. The first table contains the Raw Materials category, where the raw materials and the safety categories of the team budget are combined. Because this is modeled to be an efficient manufacturing process, there will be significantly less waste material and a total of only 80 feet of 1.25” x 0.065” tubing and 45 feet of 1.00” x 0.095” tubing will be needed for this process. Due to the high volume of material this production will go through, it is calculated that all raw materials will be purchased for half the of the retail price resulting in the total cost of raw materials being $317.79 per frame.

Table 9: Raw Materials

Category	Item	Quantity	Price
Raw Materials:	1.25” x 0.065” AISI 4130	80’ x ($0.83 per foot)	66.67
	1.00” x 0.095” AISI 4130	45’ x ($0.83 per foot)	37.50
	0.375” x 6” AISI 4130	1 x (6’ Sections @ $55.93)	55.93
	Corbeau Baja RS Seat	1 x ($124.99)	124.99
	5-point Safety Harness	1 x ($36.99)	36.99
	Ski-Doo Kill Switch	2 x ($9.99)	19.99
	Fire Extinguisher/Mount	1 x ($12.73)	12.73
	Brake Light	1 x ($16.99)	16.99
Total			$371.79

The next table within the Production Cost contains both Marginal Costs and Labor categories. Marginal Costs consists of the raw materials costs spread over the 4,000 units projected to be produced. Because an average of 16 frames will need to be produced per day, labor for the frame will be spread between fabricators, welders, and installers. With four working fabricators, each fabricator will have two hours per frame to produce all the necessary cuts, bends, and notches. Eight working welders will each have four hours to assemble and weld each frame. Two installers each will have one hour each to install the necessary safety components once the completely welded. Four fabricators at $10.00/hour, eight welders at $15.00/hour, and two installers at $10.00/hour brings the total annual labor cost to $360,000.

Table 10: Marginal Costs

Category	Item	Quantity	Price
Marginal Costs:	Raw Materials	4000 units x (371.79)	1,487,146.67
Labor:	Fabricators	4 x (2000 hours x $10.00 per hour)	80,000.00
	Welders	8 x (2000 hours x $15.00 per hour)	240,000.00
	Installers	2 x (2000 hours x $10.00 per hour)	40,000.00
Total			$1,847,146.67

The last table in the Production Costs is the Fixed Costs category which includes rent, utilities, and overhead. Rent is calculated with 10,000 square feet at $1.26 per square foot totaling to $150,000 annually. Utilities are calculated at 50% of rent which totals to $75,000 per year. Overhead includes all tooling, insurance, and any unforeseen costs and is calculated at 50% of total Labor costs. The total Production Costs including raw materials, marginal costs, labor, and fixed costs totals to $2,252,146.67, which breaks down to $563.04 per frame.

Table 11: Fixed Costs

Category	Item	Quantity	Price
Fixed Costs:	Marginal Costs		1,847,146.67
	Rent/Utilities	$150,000 + $75,000	225,000
	Overhead	Labor Cost x (0.5)	180,000
Total			$2,252,146.67

27 PROJECT PLAN

The team accomplished everything that was planned for the fall semester of 2013, shown in appendix B. The frame design has been finalized and analyzed. The raw material for the frame has been ordered and should arrive soon. The construction for the frame will be started during winter break. Building 98C will be open during the first weeks of January. In order to finish the vehicle before competition, the team needs to have the frame constructed by the end of January and all the components such the suspension and drivetrain attached to the vehicle by the end of February. This ensure that there will be enough time to test the vehicle before the competition to allow the team to make any necessary modifications. The SAE Mini Baja Competition is April 24 – 27 in El Paso Texas. The project schedule for spring semester of 2014 can be found in Appendix B.

28 CONCLUSION

The team was contracted to build a Mini Baja that can compete in a various competitions and win. We defined the many constraints and needs the Baja must meet to compete. We compared different sizes and material of tubing and decided to build the frame out of AISI 4130 steel with a 1.250 inch diameter and a 0.650 inch wall thickness. A variety of frames were compared using a decision matrix and design 2 was the better choice due to the lightweight and simplicity of the frame. The analysis of the frame was designed to confirm that the frame can withstand several tests while keeping the driver safe. The drop test analysis determined that after a 10 foot drop it will hold with a yield factor of safety of 5.32 and a max deflection of 0.089 inches. The front collision analysis resulted in a 2.90 factor of safety and a 0.135 inch deflection. The rear impact analysis showed a yield safety factor of 1.45 and a deflection of 0.263 inches. The side impact analysis showed a yield safety factor of 1.01 and a deflection of 0.363. A tab shear test was used to determine if the tabs that hold various parts of the vehicle will fail under certain tests which confirmed that they will not fail under a large amount of force. The team was within the design targets for the constraints and needs of the frame and safety. The projected total cost for the frame and safety equipment for the frame used in competition was 1994.50 $. The theoretical total cost for the frame and safety equipment to be manufactured was $2,252,146.67.

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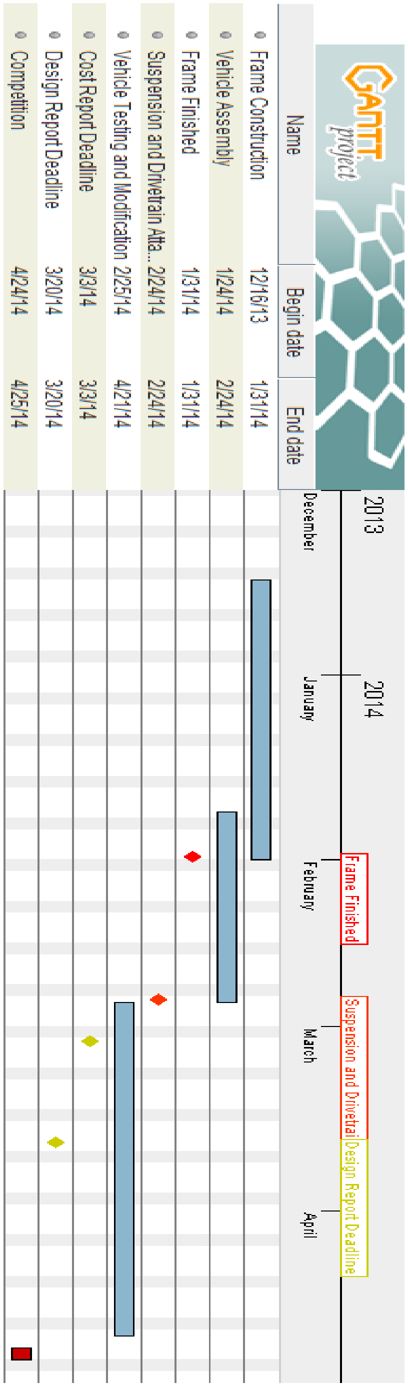
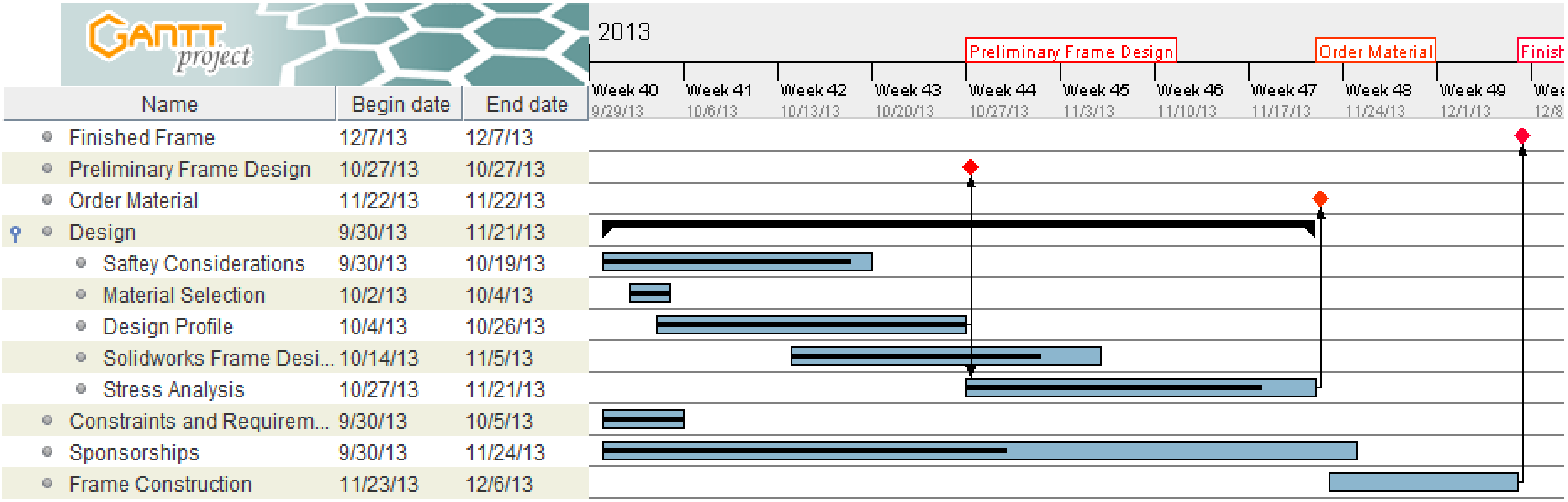
30 APPENDIX B: PROJECT PLANNING



Name	Begin date	End date
Frame Construction	12/16/13	1/31/14
Vehicle Assembly	1/24/14	2/24/14
Frame Finished	1/31/14	1/31/14
Suspension and Drivetrain Atta...	2/24/14	2/24/14
Vehicle Testing and Modification	2/25/14	4/21/14
Cost Report Deadline	3/3/14	3/3/14
Design Report Deadline	3/20/14	3/20/14
Competition	4/24/14	4/25/14

Figure 41: Project Plan fall 2013



Name	Begin date	End date
Finished Frame	12/7/13	12/7/13
Preliminary Frame Design	10/27/13	10/27/13
Order Material	11/22/13	11/22/13
Design	9/30/13	11/21/13
Saftey Considerations	9/30/13	10/19/13
Material Selection	10/2/13	10/4/13
Design Profile	10/4/13	10/26/13
Solidworks Frame Desi...	10/14/13	11/5/13
Stress Analysis	10/27/13	11/21/13
Constraints and Requirem...	9/30/13	10/5/13
Sponsorships	9/30/13	11/24/13
Frame Construction	11/23/13	12/6/13

Figure 42. Project Plan fall 2013

APPENDIX C: ADDITIONAL MATERIAL

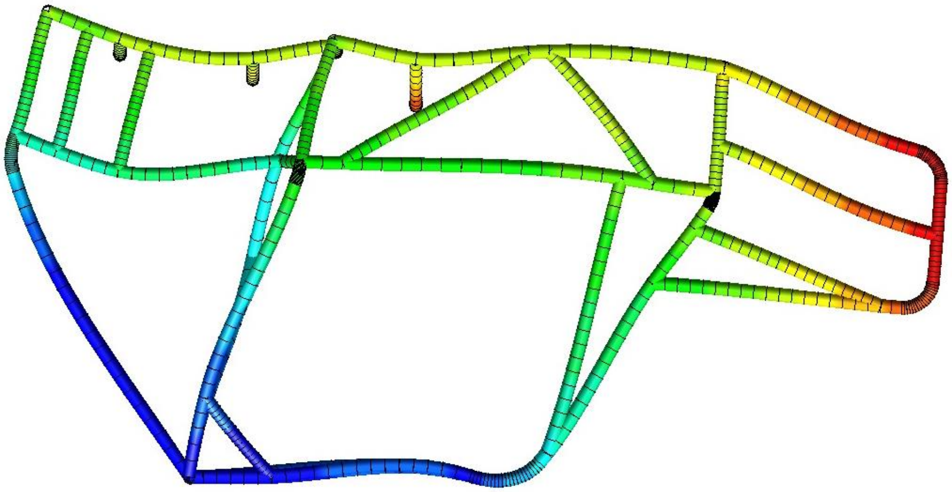


Figure 43. Drop Test Deflected Shape

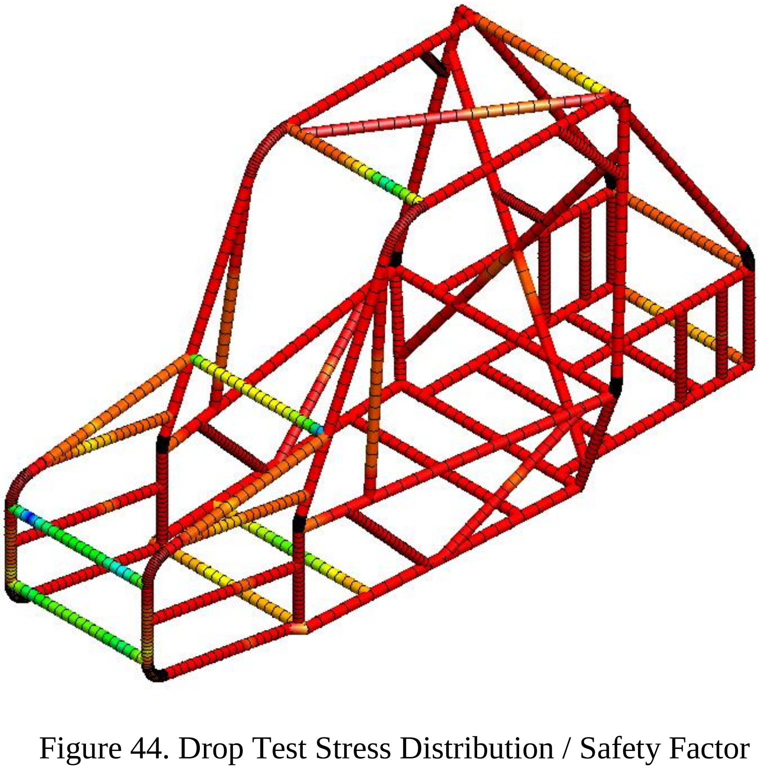


Figure 44. Drop Test Stress Distribution / Safety Factor

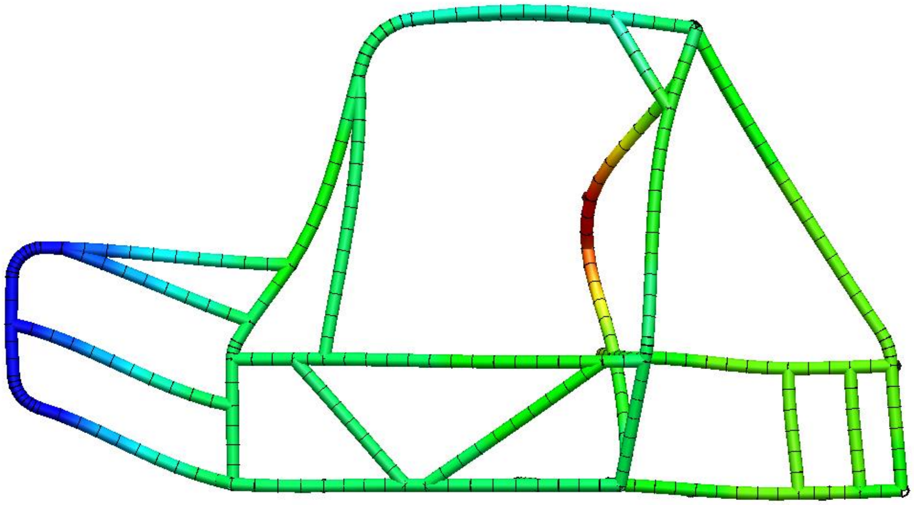


Figure 45. Front Collision Deflected Shape

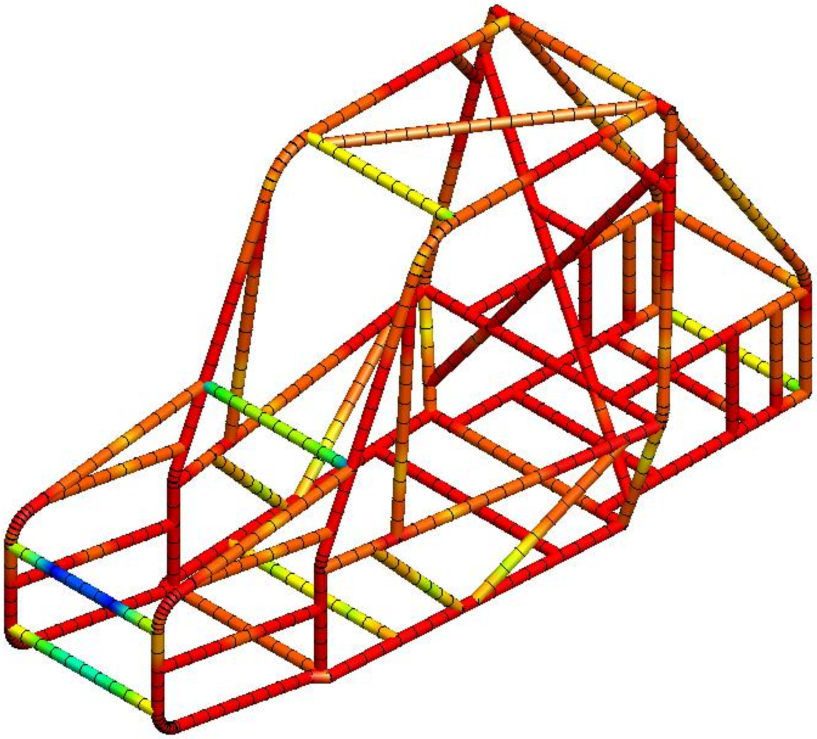


Figure 46. Front Collision Stress Distribution / Safety Factor

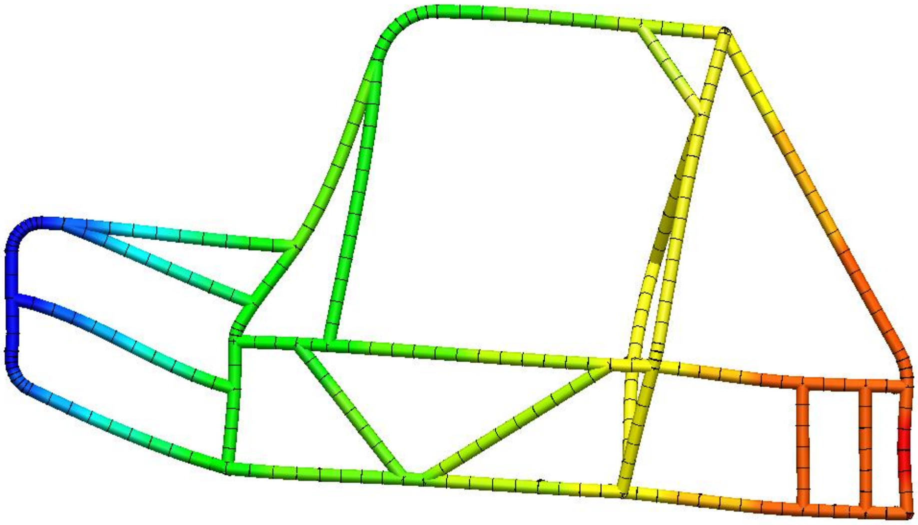


Figure 47. Rear Impact Deflected Shape

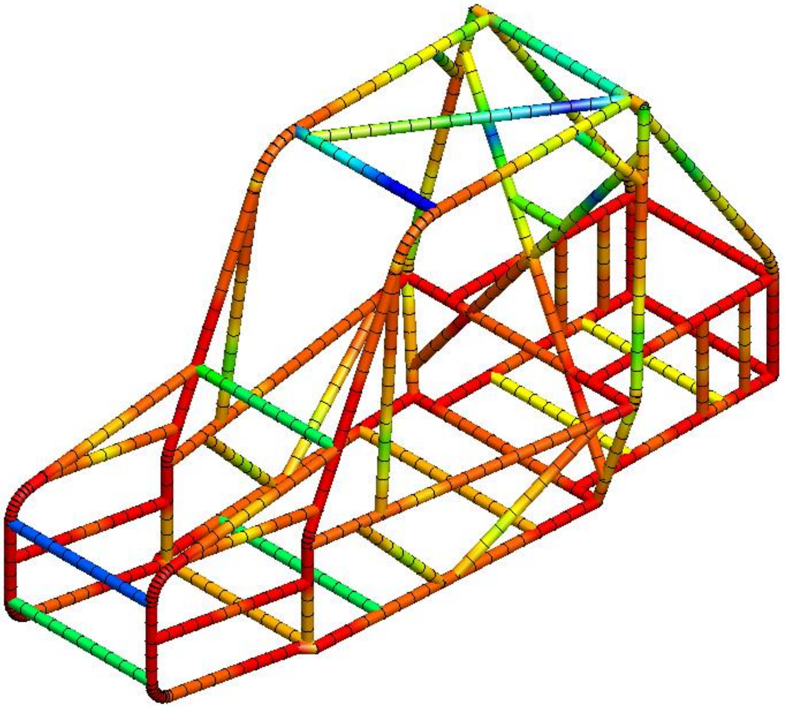


Figure 48. Rear Impact Stress Distribution / Safety Factor

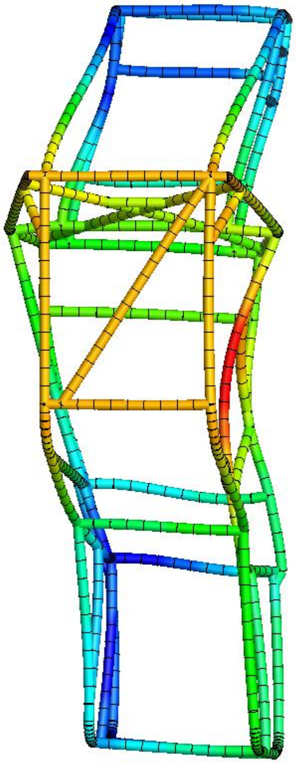


Figure 49. Side Impact Deflected Shape

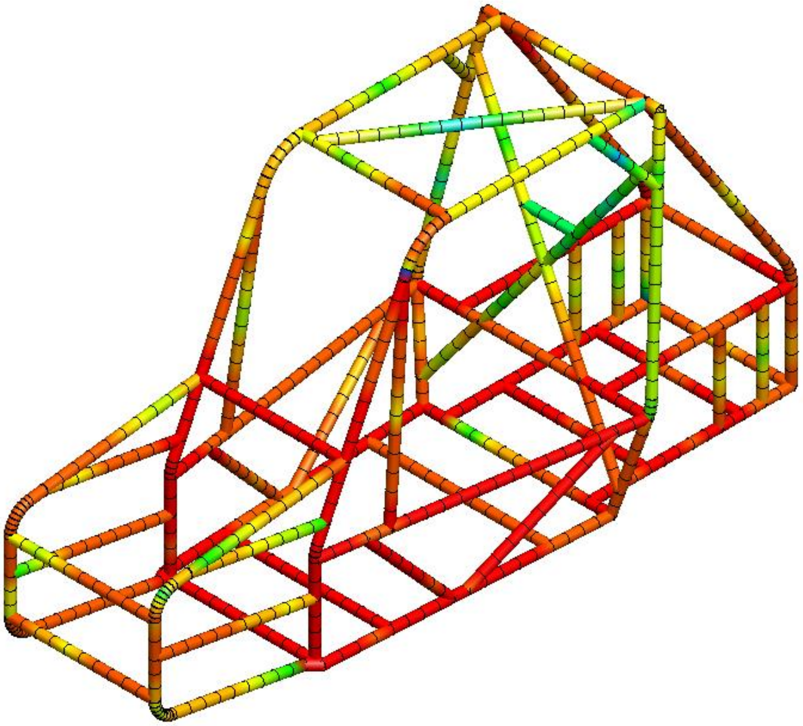


Figure 50. Side Impact Stress Distribution / Safety Factor

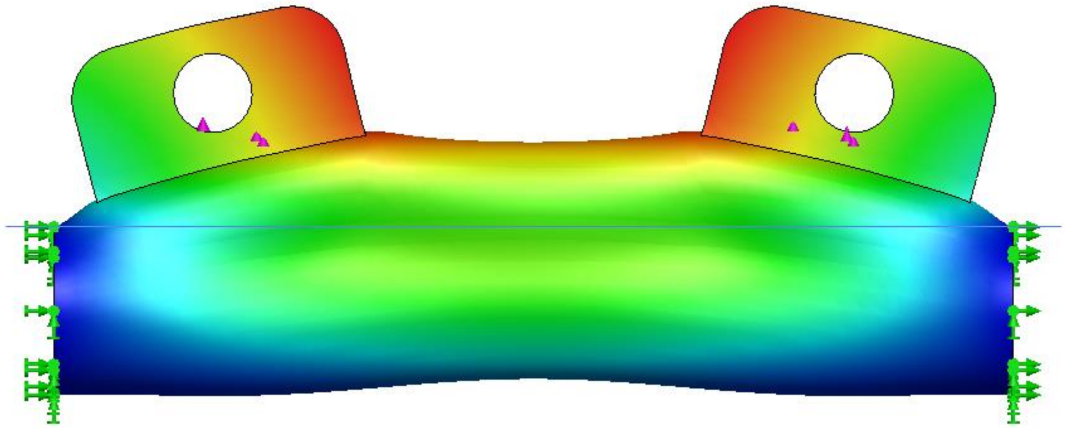


Figure 51. Seatbelt harness tab deflection

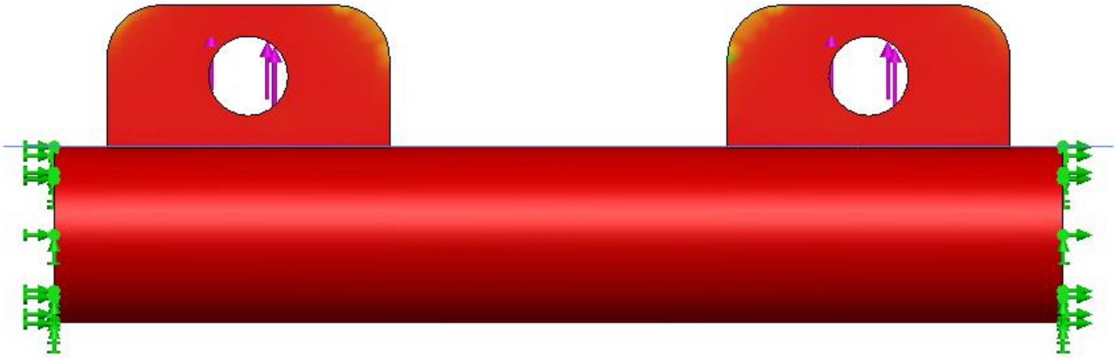


Figure 52. Seatbelt harness tabs factor of saftey

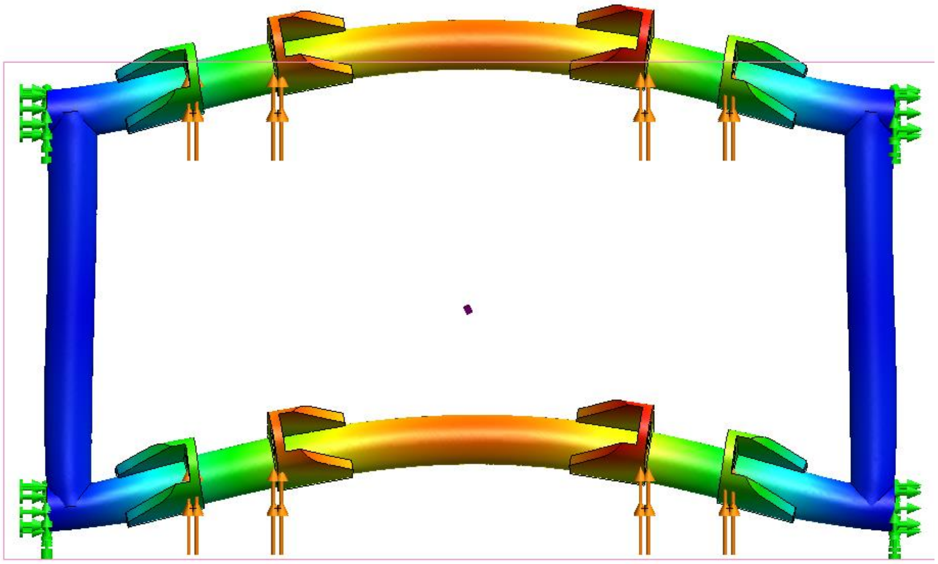


Figure 53: Tab deflection

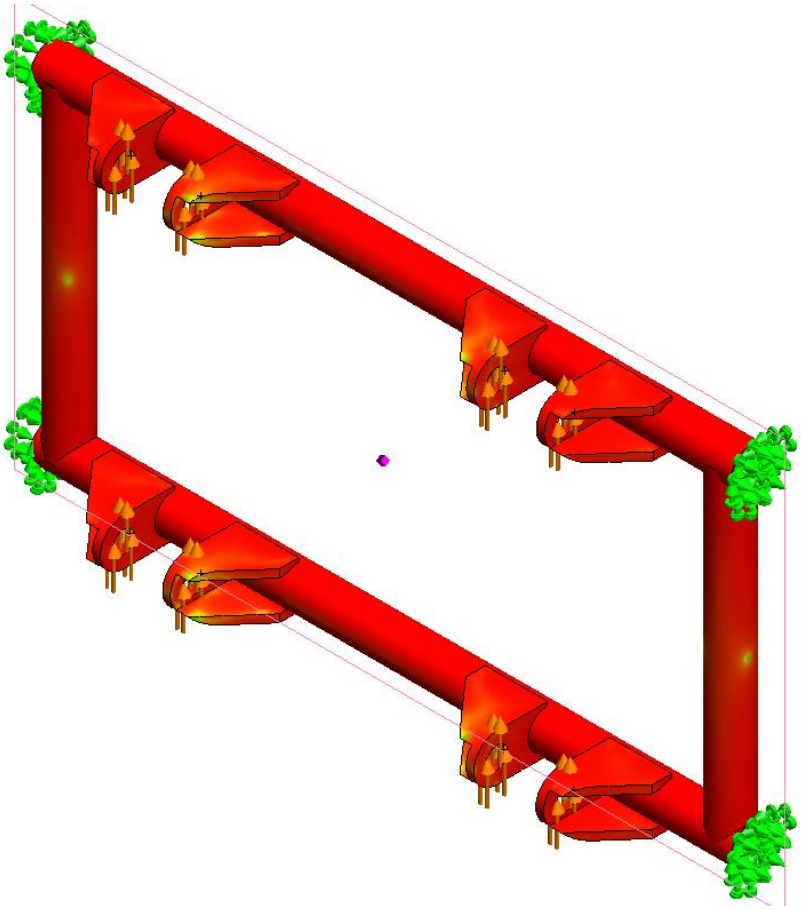


Figure 54. Tab factor of safety