

2019 University of Cincinnati SAE Baja® Frame

A Baccalaureate thesis submitted to the
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College of Engineering and Applied Science
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requirements for the degree of

Bachelor of Science

in Mechanical Engineering Technology

by

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ABSTRACT

Each year there are three competitions held across the United States by the Society of Automotive Engineers (SAE) Baja. Each school that competes is required to design, build, and then compete against other schools to determine the best team. Some big areas that may be judged would be the cars weight, cost, and overall design. The cars will be tested with many challenging events in towing, hill climbing, and a rock course. To keep the challenges fair and competitive all teams are required to run the same Briggs and Stratton 10 horse power motor that is specifically called out in the Baja SAE rule book.

PROBLEM DEFINITION AND RESEARCH

PROBLEM STATEMENT

The main purpose of the Baja SAE project is to build a competitive car that meets all necessary rules and regulations. The Baja car has a large rulebook to follow which will require extensive research to make sure our car passes all specifications. Many teams compete in the competition each year so making our car stand out from the rest and be good in all race sections is going to be a key factor of this build.

My portion of the build is going to focus mainly around the roll cage design of the new Baja car. For the roll cage, I will be required to follow very strict guidelines on the degree of each bend and placement of connection joints to ensure a safe car. Being that the roll cage is the main frame of the car and all else will be built from this, I'm going to be required to work closely with all members of the team to be able to have every piece of the car come together with ease. Ensuring all the suspension components, pedal assembly, powertrain, and all other roll cage connection points have mounting in the correct location is going to require a great amount of group effort.

BACKGROUND

Previously cages have been built and designed in many different ways (Figures 1 & 2). As goes with all things in life, there are rights and wrongs on how to build a safe cage. Understanding how to create a strong connection point and eliminating any weak points requires many factors to be accounted for. The most important factor relies on having the proper thickness tubing along with tightly coped tube ends for welding. Any place where tubes are joined for welding should be tight all the way around and not require gaps to be filled with weld.

Two styles of cages are found during the Baja SAE challenge (See Figures 3 & 4). The pictures below give a good representation of each style. The Rochester Institute of Technology 2017 Baja car (Figure 1) shows a rear braced frame cage and the Lamar University 2016 Baja car (Figure 2) shows a front braced frame. Both are acceptable to the rules and regulations and figure 3 and 4 show the main support braces for each style. Having the primary members properly bent and safely welded into place is crucial for a safe roll cage around the driver.



Figure 1: Rochester Institute 2017 Baja Car [3]



Figure 2: Lamar University 2016 Baja Car [2]

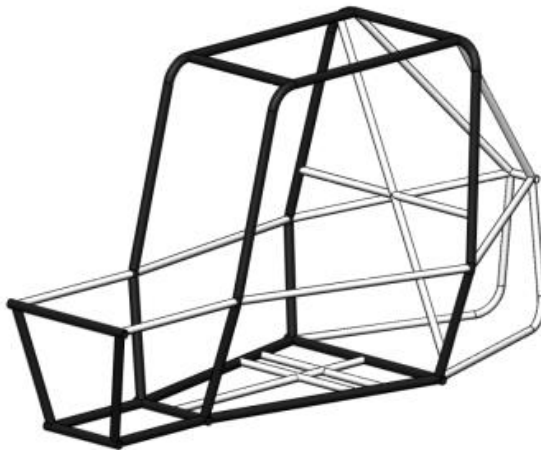


Figure 3: Baja SAE Rear Braced Roll Cage [1]

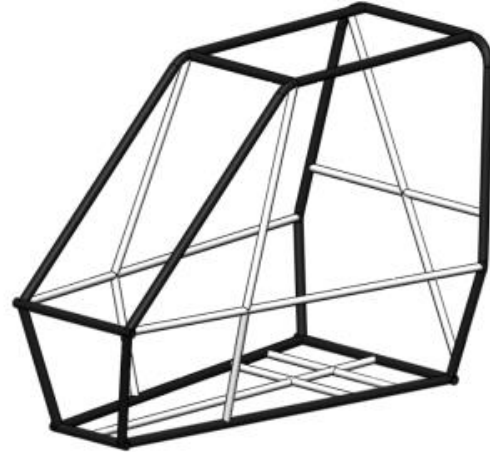


Figure 4: Baja SAE Front Braced Roll Cage [1]

RESEARCH

SCOPE OF THE PROBLEM

The purpose of the roll cage is to maintain a minimum space surrounding the driver. The cage must be designed and fabricated to prevent any failure of the cage's integrity during normal operation or during a collision or roll over. Roll cages have been one of the most crucial safety features in competitive vehicles for years. Not only does the roll cage keep the driver safe but it also has to be light weight and incorporate all the mounting areas for suspension components, pedal assemblies, seat base, and drive train components.

My main goal is going to be designing and building a safe roll cage that meets all standards and specifications set by the Baja Rules Committee [1]. This needs to be addressed appropriately to ensure any one of my team members who may drive the car is safe. Following the rule book closely is going to be key for not only passing spec but to also ensure the cage is built to withstand the hardest impact if a rollover may occur.

List of Specifications:

- Frame: The entire tubular structure including all non-cantilevered tubes.
- Roll Cage: Primary and Secondary Members used to protect the driver.
- Member: A Primary or Secondary required element beginning and ending at Named Points.

CURRENT STATE OF THE ART

Many Baja SAE roll cages have been designed and built in the past. This being said, there has been many different designs created and some better than others. The biggest issue with building a roll cage is following the SAE rules and specifications that have been set by the BAJA SAE Rules Committee [1]. Rules give you a base guideline to follow and only allow modification in certain areas so a safe roll cage is built for the driver.

Cons of previous roll cages would mainly focus on the build quality. The 2018 UC Baja car (Figure 5) sent out their bars to be CNC bent and then assembled them in the shop. The welds on the roll cage were very poor and most had minimal penetration. This is where safety becomes an issue with many teams not having students that know much about welding. Weld penetration and quality is critical to ensure a safe cage. Weld examples below show visual quality and penetration. (Figure 6)



Figure 5: 2018 UC Baja Car Roll Cage [5]

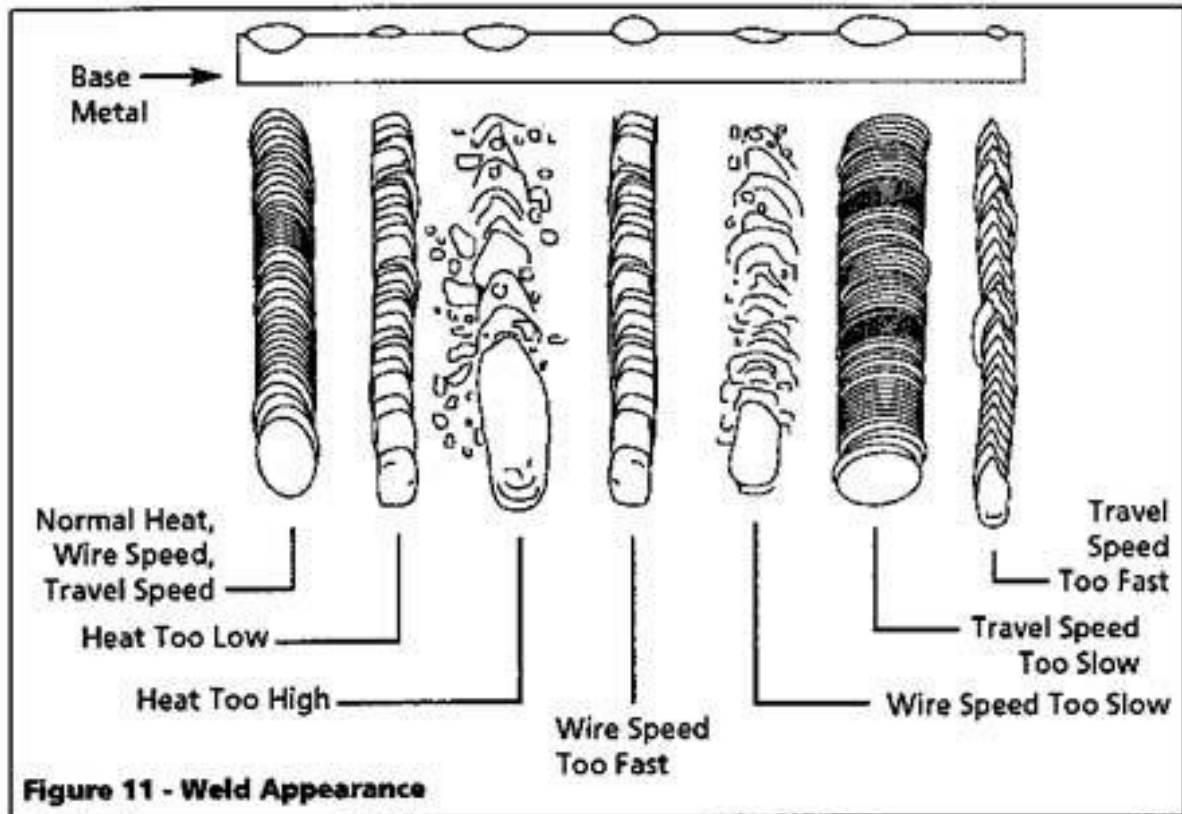


Figure 6: Weld Appearance [4]

Pros of previous roll cages, like the 2014 UC Baja Car (Figure 7), consist of design and material choice. Additional braces for safety and fuel tank protection shields help with added safety. Designing a cage with adequate bracing helps with impact in the event of a rollover (Figure 7). Choosing the proper material for the cage and bracing decides not only safety but the weight of the cage as well. Weight is an important part to have a competitive car that can be competitive in all challenges. The lighter the car, the more agile and powerful the car can be.



Figure 7: 2016 UC Baja Car [6]

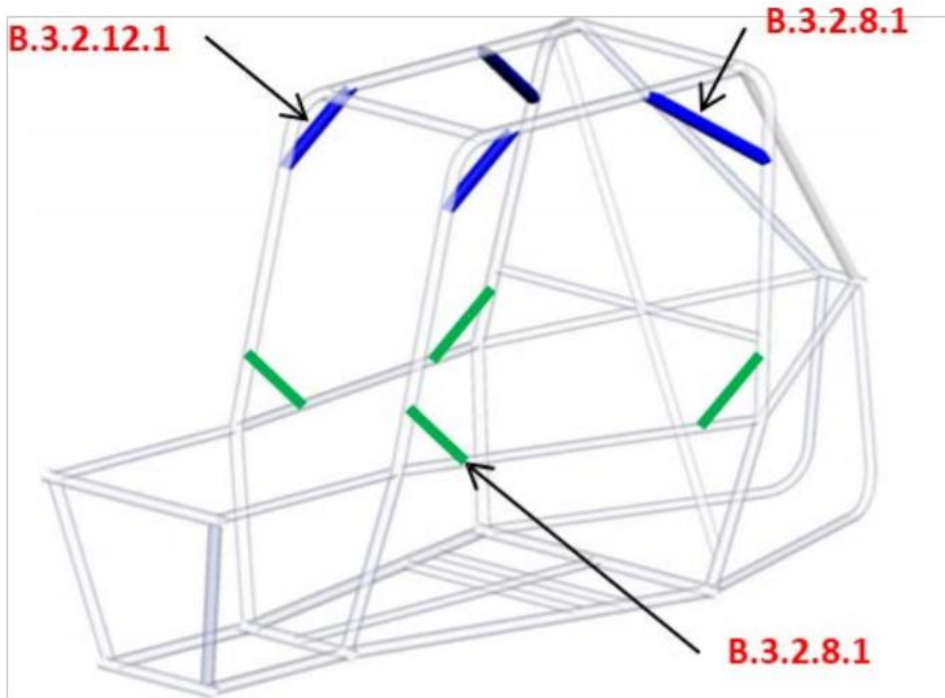


Figure B-13: Roll Cage, Gussets

Figure 8: Adequate Bracing [1]

END USER

The end user of this is going to be looking for a safe, lightweight, and ergonomic cage. Currently there are a few safety concerns with connection points, welds, and uncomfortable leg room. All of these will be addressed with a well-built cage that has proper welds to ensure no points of failure will occur during a rollover. When it comes to gaining legroom, the cage design is going to be crucial that there are no bars intruding the drivers seating area and making for an awkward operating position.

CONCLUSIONS AND SUMMARY OF RESEARCH

From my research, I have learned the rules and regulations that will be expected out of the roll cage. It will be critical to ensure all specifications are met to make sure the car passes inspection. Whether this is the bend degrees or the welds on connection points, nothing can be looked past. I will be designing and building the cage in a CAD program to perform stress testing. This will help with ensuring the safety of the cage is met and no weak points are going to cause issues for the driver in the event of a roll over. For my design, I am going to be sure to include a lightweight 4130 chromoly tubing that has added support bars for maximum safety.

CUSTOMER FEATURES

Meets Safety Requirements – 0.15
Light Weight – 0.15
Accelerates Quickly – 0.10
Maneuvers Easily – 0.10
Drives Over Large Obstacles – 0.10
Climbs Steep Grade – 0.10
Cost Efficient – 0.10
Brakes Quickly – 0.10
Ergonomical – 0.10
Low Maintenance – 0.05
Climbs Steep Grade - 0.05

PRODUCT OBJECTIVES

Driver Safety (25%)

- Cage will comply to all SAE 2018 rules
- Cage will protect all drivers from injury in the event of a crash/rollover

Vehicle Durability (25%)

- Strong welds for a reliable cage to last for many years

Vehicle Weight (20%)

- Light weight

Ergonomics (15%)

- Will comply to all Baja SAE 2019 Rules

- Comfortably fitting for all members of the team

Cost (10%)

- Cost must be within University of Cincinnati SAE Baja 2018-2019 Budget

Ease of Entering/Exiting (5%)

- Driver must be able to exit themselves from the car within 5 seconds

QUALITY FUNCTION DEPLOYMENT

Engineering Characteristics

Acceleration 0-20 (mph²)

Turning Radius (ft)

Factor of Safety (SF)

Ground Clearance (in)

Wheel Travel (in)

45 Degree Incline (Degrees)

Materials Cost (\$)

Braking Distance (ft)

Leg Room (in)

Weight (lbs)

Sustains Drop (ft)

Torque (lbf)

Speed (mph)

Stiffness (lbs/in)

House of Quality

		Engineering Requirements (units)														Customer Satisfaction Rating (0.00 - 1.00)																																																																																																							
Customer Requirements	Importance wt.	Acceleration 0-20 (mph ²)	Turning Radius (ft)	Factory of Safety (SF)	Ground Clearance (in)	Wheel Travel (in)	45 Degree Incline (Degrees)	Materials Cost (\$)	Braking Distance (ft)	Leg Room (in)	Weight (lbs)	Sustains Drop (ft)	Torque (lbf)	Speed (mph)	Stiffness (lbs/in)	CP	A	B	C																																																																																																				
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1 Accelerates Quickly	0.10	9									9		9	3		0.6	0.6	0.5	0.6																																																																																																				
2 Maneuvers Easily	0.10		9		1				1		3				3	0.5	0.7	0.9	0.7																																																																																																				
3 Meets Safety Specifications	0.15			9				3	1	1		1				0.2	0.8	0.7	1																																																																																																				
4 Drives Over Large Obstacles	0.10				9	3						3	3		1	0.6	0.6	0.7	0.7																																																																																																				
5 Climbs Steep Grade	0.05	3					9				1		9	1		0.4	0.7	0.8	0.5																																																																																																				
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Total Importance: 1.00																																																																																																																							
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		Interaction Matrix													
Engineering Requirements	Engineering Requirements	Acceleration 0-20 (mph ²)	Turning Radius (ft)	Factory of Safety (SF)	Ground Clearance (in)	Wheel Travel (in)	45 Degree Incline (Degrees)	Materials Cost (\$)	Braking Distance (ft)	Leg Room (in)	Weight (lbs)	Sustains Drop (ft)	Torque (lbf)	Speed (mph)	Stiffness (lbs/in)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Acceleration 0-20 (mph ²)	1		-3	-3	-9	-9	3	1	-9	-9	3	-9	9	3	-1
Turning Radius (ft)	2			-3	-3	-3	-9	-1	-9	-9	-9	-9	-1	-1	1
Factory of Safety (SF)	3				-3	-3	1	9	3	1	1	3	-3	1	-3
Ground Clearance (in)	4					9	1	1	-3	-9	3	3	-9	-9	3
Wheel Travel (in)	5							1	3	-3	-9	3	9	-3	9
45 Degree Incline (Degrees)	6								1	-9	-9	3	-3	9	3
Materials Cost (\$)	7									3	-3	9	3	3	3
Braking Distance (ft)	8										-9	9	-9	-3	9
Leg Room (in)	9											-9	-9	-9	-9
Weight (lbs)	10												3	3	9
Sustains Drop (ft)	11													-9	-9
Torque (lbf)	12														3
Speed (mph)	13														
Stiffness (lbs/in)	14														

DESIGN

Design Alternatives and Selection

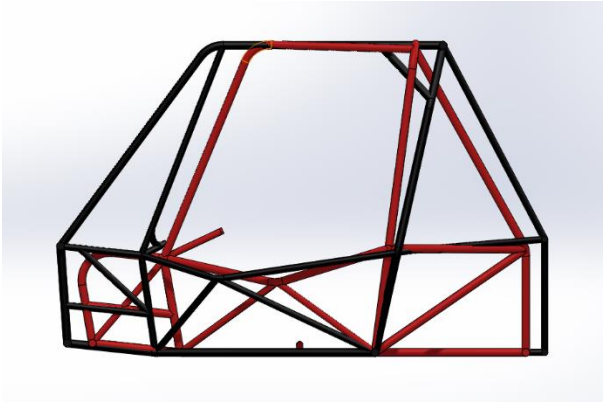


Figure 9 - 2013 Frame (Red) compared to 2019 (Black)

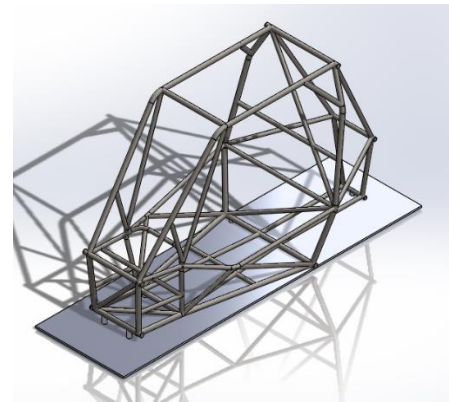


Figure 10 – 2019 Frame Design Model

As shown above, the 2019 frame had many changes made compared to a previous year’s car. The whole frame was lengthened nearly 6 inches and moved the side impact member bends forward to make room for all drivers. The previous 2013 frame was very cramped and larger drivers shins where impacting the front frame down bars.

Drawings

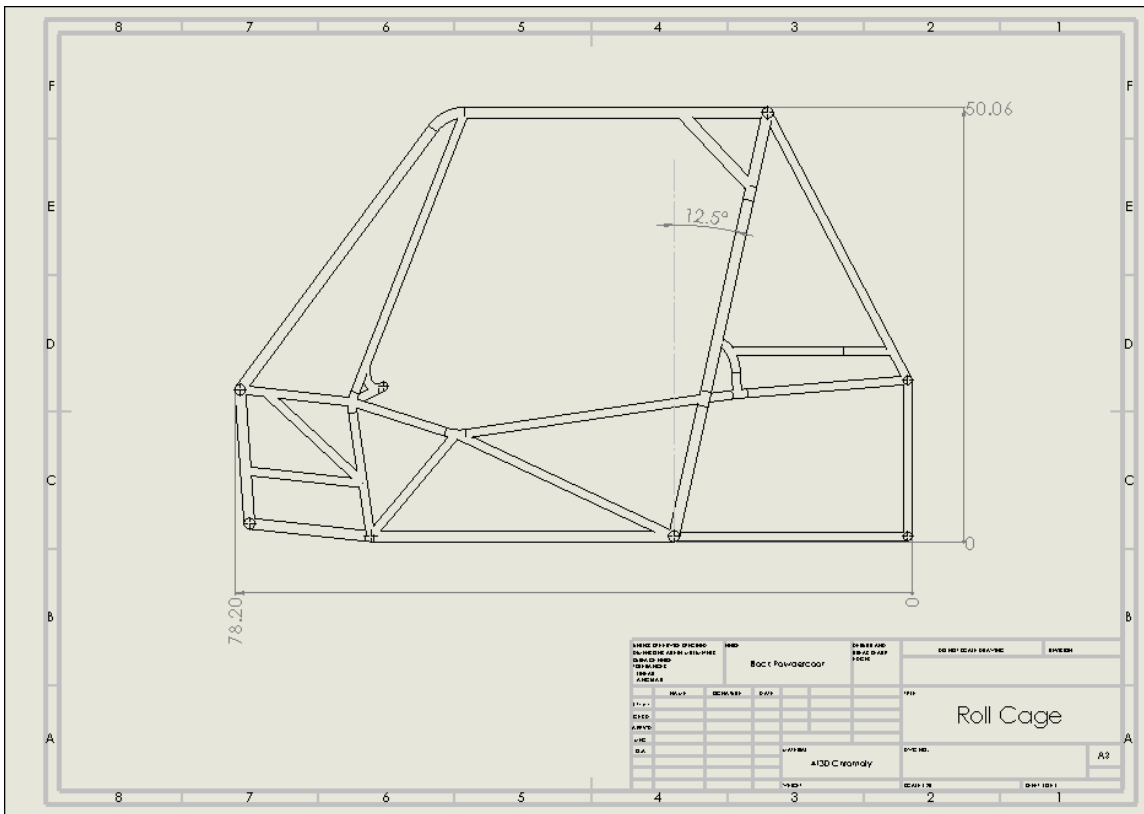


Figure 11 – Frame Dimensions Drawing

Loading Conditions

When doing the loading condition calculations, a weight of 350 pounds was assumed for the total car weight and a driver weight of 250 pounds. These weights were determined by looking back at previous years Baja analysis reports. This brings the total car and driver weight to 600 pounds. Using a G-load of 9 g's, based off of previous year's results, we could then calculate impact force that is used for final results. An estimated final top speed for the 2019 car was assumed to be 30 mph (13.4112m/s).

Impact Force:

$$f = 272kg * 9 * 9.81$$

$$= 24,014.88 \text{ N}$$

Impulse Time:

$$= 272kg \frac{13.4112 \frac{m}{s}}{24014.88N}$$

$$= 0.152 \text{ s}$$

Top Impact:

$$= 272kg \frac{9.9 \frac{m}{s} - 0}{0.152s}$$

$$= 17,715.79 \text{ N}$$

$$= 3982.67 \text{ lbf}$$

Front/Side Impact:

$$f = 272kg * 9 * 9.81$$

$$= 24,014.88 \text{ N}$$

$$= 5398.76 \text{ lbf}$$

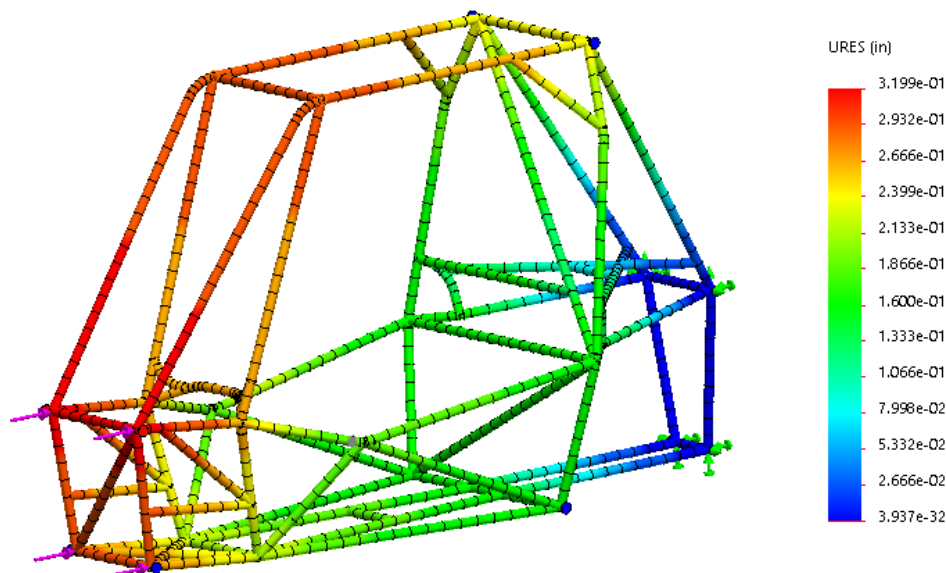


Figure 12 - Front Impact Displacement

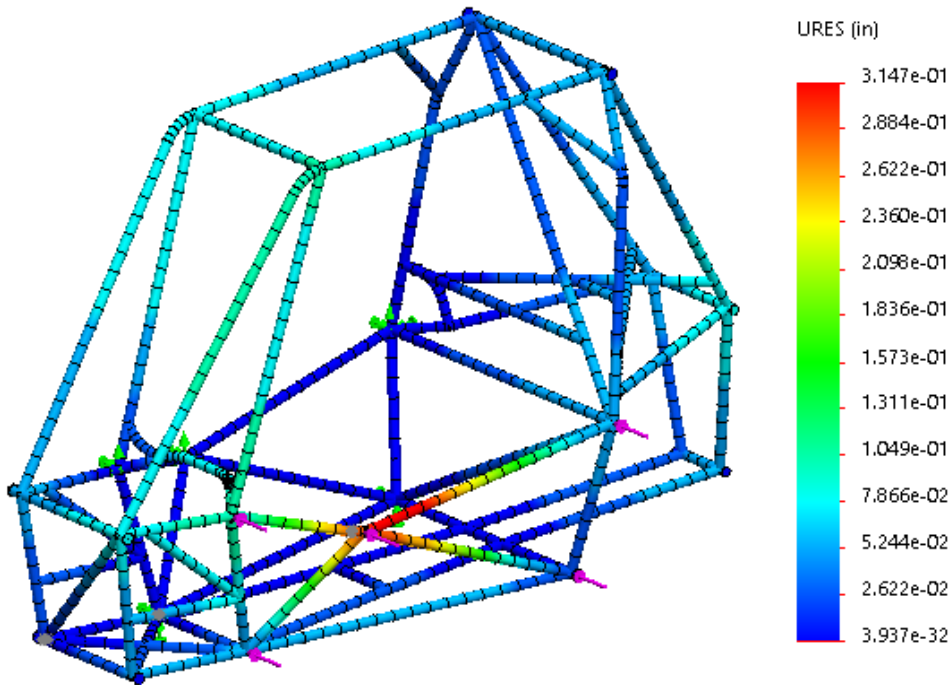


Figure 13 – Side Impact Displacement

Factors of Safety of Concern

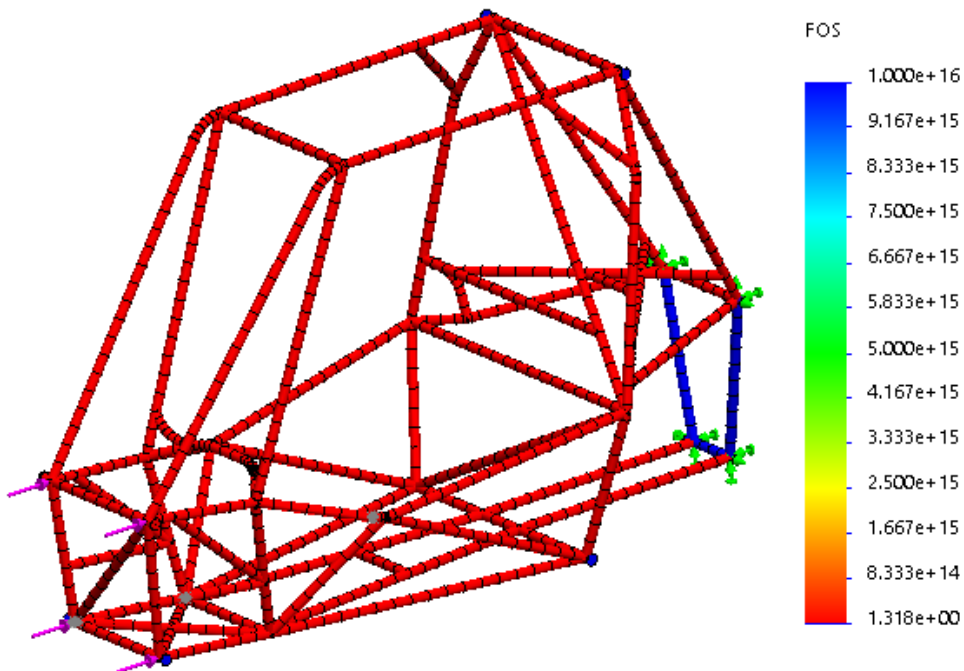


Figure 14 - Front Impact Factor of Safety

Factor of safety for the 30 mph front impact crash is 1.318. The original design factor was based around 1.5.

Component Selection

All materials used on the roll cage were based off of the given rules set by the 2019 Baja SAE Rule Book. Based off the given rules and allowances of different materials, 41130 chromoly was chosen for safety and light weight.

“The material used for the Primary Roll Cage Members and bracing must meet one of the following requirements:

- *Circular steel tubing with an outside diameter of 25 mm (1.0 in) and a wall thickness of 3 mm (0.120 in.) and a carbon content of at least 0.18%.*
- *A steel shape with bending stiffness and bending strength exceeding that of circular steel tubing with an outside diameter of 25 mm (1.0 in.) and a wall thickness of 3 mm (0.120 in.). The wall*

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thickness must be at least 1.57 mm (0.062 in.) and the carbon content must be at least 0.18%, regardless of material or section size. The bending stiffness and bending strength must be calculated about a neutral axis that gives the minimum values.

Bending stiffness, k_b , is given by:

$$k_b = EI$$

Where:

E - Modulus of elasticity (205 GPa for all steels)

I - Second moment of area for the structural cross section

Bending strength, S_b , is given by:

$$S_b = \frac{S_y I}{c}$$

Where:

S_y - Yield strength (365 MPa for 1018 steel)

c - Distance from neutral axis to extreme fiber

Documentation of the equivalency must include:

1) Typed calculations to be presented at Technical Inspection which proves sufficient bending stiffness and bending strength. All calculations must be in SI units, to three significant figures to the nominal tube sizes as specified by the invoice. Teams shall show figures for 1018 steel and the substitute material.

2) Invoices of the roll cage materials.

3) Material tests or certifications, which specify the carbon content and yield strength.” [1]

Chosen material specifics:

Primary Members

- Material: 4130 Chromoly Round Tube
- Size: 1.25 OD x 0.065 Wall Thickness

Secondary Members

- Material: 4130 Chromoly Round Tube
- Size: 1.00 OD x 0.049 Wall Thickness

	4130 - Primary	4130 - Secondary
Outer Diameter (in.)	1.25	1.0
Wall Thickness (in.)	0.065	0.049
Inner Diameter (in.)	1.120	0.902
Elasticity (ksi)	29732.7	29732.7
Density (lb/in ³)	0.284	0.284
Carbon Content (%)	0.30	0.30
Ultimate Strength (psi)	97200	97200
Yield Strength (psi)	63100	63100
Weight (lb/ft)	0.8217	0.4971

Table 1 – Material Size Comparison

Bill of Material

Item #	Manufacturer	Part Number	Quantity	Description	Vendor	Cost per Piece	Cost Total
1	All Star	ALL22062-8	3	1.25x.065 Chromoly Tube 8 ft section	D&D Racing Engines	\$56.67	\$170
2	All Star	ALL22040-12	6	1.00x.049 Chromoly Tube 12 ft section	D&D Racing Engines	\$47.92	\$287.50
3	NEIKO	11108A	10	Grinder Flap Disc	Amazon	\$1.50	\$15
4	Midwest Tungsten Service	40400-01769B	10	2% Thoriated 3/32" x 7" (Red, WT20) Tungsten Electrodes 10-Pack	Amazon	\$2.18	\$21.79
5	Harris	e70s650	1	Welding Rod ER70S-2 Box 10lb	Amazon	\$40.17	\$40.17

Table 2 - BOM

PROJECT MANAGEMENT

BUDGET, PROPOSED/ACTUAL

Estimated Cost to Build Roll Cage		
Category	Estimated Cost	Source of Income
Tubing	\$500	Sponsors/ School Team Funds
Manufacturing	\$100	Sponsors/ School Team Funds
Hardware (Bolts, Welding wire/gas, hole saws, etc)	\$150	Sponsors/ School Team Funds

Misc	\$100	School Team Funds
Total:	\$850	

Table 3 – Estimated Cost

Actual Cost to Build Roll Cage		
Category	Estimated Cost	Source of Income
Tubing	\$287.5 \$170 Sponsored	Sponsors/ School Team Funds
Manufacturing	\$0	Sponsors/ School Team Funds
Hardware (Bolts, Welding wire/gas, hole saws, etc)	\$76.96	School Team Funds
Misc	\$0	School Team Funds
Total:	\$364.46	

Table 4 – Actual Cost

SCHEDULE, PROPOSED /ACTUAL

Estimated Timeline

	August	September	October	November	December	January	February	March	April
Design Draft									
Final Proposal									
3D Cad Design									
Design Presentations to Faculty									
Design Report to Advisor									
Demonstration to Advisor									
Tech Expo									
Presentation to Faculty									
Project Report to Advisor									
Library PDF file in BB									

Table 5 – Proposed Schedule

Actual Timeline

	August	September	October	November	December	January	February	March	April
Design Draft									
Final Proposal									
3D Cad Design									
Design Presentations to Faculty									
Manufacturing									
Design Report to Advisor									
Testing									
Demonstration to Advisor									
Tech Expo									
Presentation to Faculty									
Project Report to Advisor									
Library PDF file in BB									

Table 6 – Actual Schedule

All and all the schedule was followed fairly well. A few issues came about during the manufacturing stage but didn’t directly come about because of the chassis. The chassis was completed in a timely manner and followed the timeline above with minimal changes needed. Some small changes needed to be made later on because of other parts of the car requiring different mounting location bars.

CONCLUSIONS

In the beginning we were on the track to completing the car early and giving ourselves plenty of time for testing. As the weeks went by we quickly were tasked with one issue after another. Whether this be long deliveries on parts or just designs not working the way they were thought too it set us back to the point where we had minimal time for testing before sending the frame out to powder coating. In the end the car did get completed and worked very well as the entire team had hoped it would.

PROJECT SUMMARY

The project got off to a good start as far as the roll cage manufacturing went. A jig was built to make sure the SolidWorks model and real life roll cage were as identical as possible for ease of manufacturing on any component that mounts to the frame. These parts include motor, gearbox front suspension, rear suspension, seat, steering, and all the body panels.

Below are some of the building steps taken to complete the manufacturing of the roll cage:



Figure 15 - Manual Notching

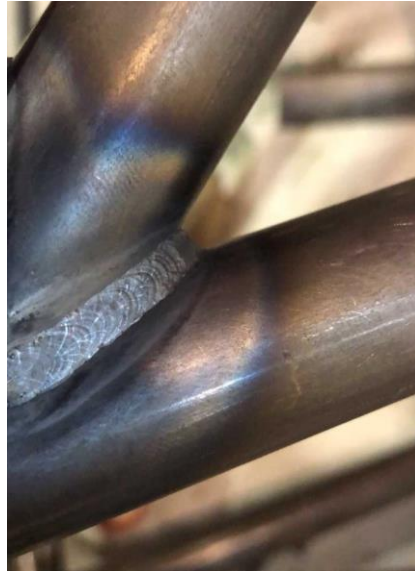


Figure 16 - Tig Weld



Figure 17 - Base Frame in Jig



Figure 18 - Completed Frame in Jig



Figure 19 - Completed 2019 Baja SAE Car

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APPENDIX A

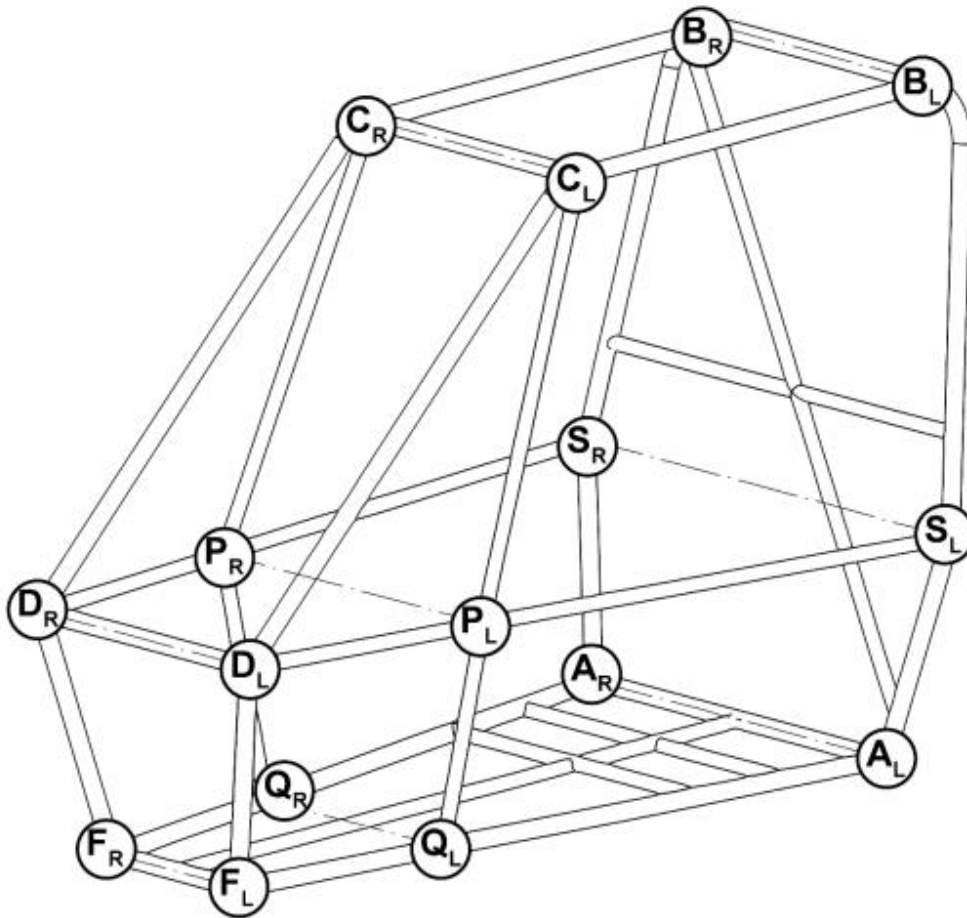


Figure 15 – Roll Cage Named Points [1]

APPENDIX B

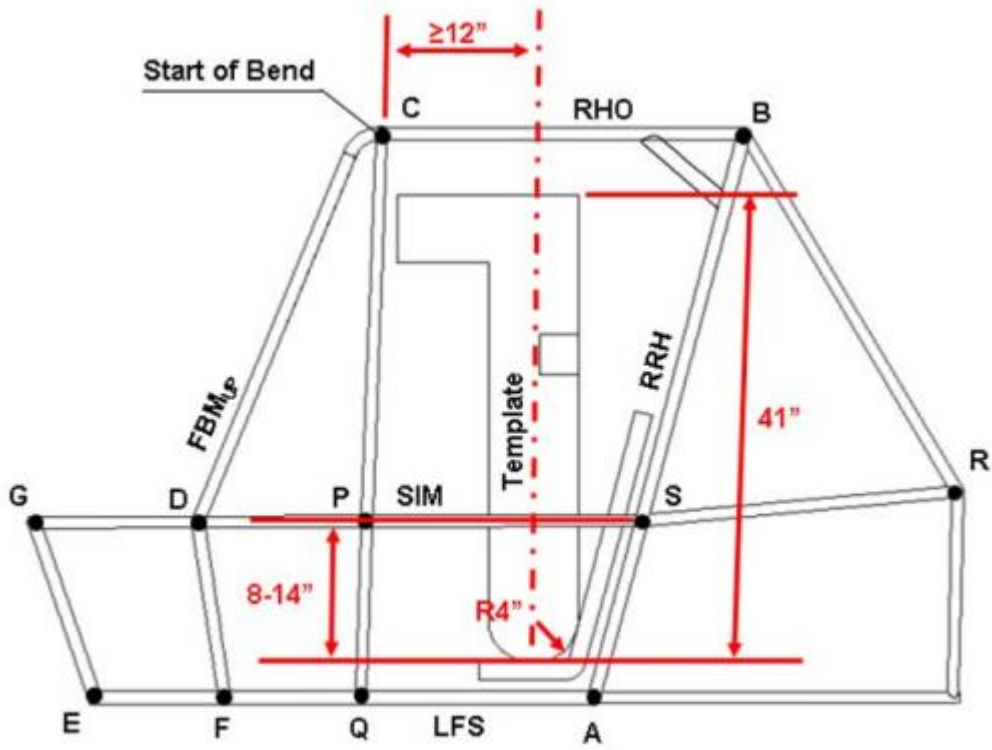


Figure 16 – Roll Cage Template Clearance [1]