

2018 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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in partial fulfillment of the
requirements for the degree of

Bachelor of Science

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by

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ABSTRACT

The Society of Automotive Engineers (SAE) Baja holds competitions every year for college students to compete in. The challenge is to design, build, then race the students' cars against other universities to determine which team is best. There will be a multitude of judging to determine which team excelled in areas such as cost, weight, and design. The cars will then undergo rigorous physical testing through a variety of courses and obstacles. Each car will utilize a 10 horse power Briggs and Stratton engine and will need to adhere to all rules set forth by the SAE Baja rules that are published for the competition year.

PROBLEM DEFINITION AND RESEARCH

PROBLEM STATEMENT

The regulations per SAE Baja rules for 2017-2018 state that the driver's helmet shall have 6-in. minimum clearance from any two points among those members that make up to top of the roll cage. Myself being the tallest member, violate the 6-in. regulation and the team will not qualify at competition if nothing is changed.

BACKGROUND

The goal in Baja SAE is to design, build and race off-road vehicles that can withstand elements of rough terrain against many different colleges around the country. These vehicles are often similar in appearance to dune buggies with large tires and a complete roll cage that completely protects the driver. One main component of these cars is the suspension which allows for the cars to travel over rough terrain at high speeds by conforming to the terrain. This is made possible by combining long wheel travel, high ground clearance, strong structural frame etc.

The University of Cincinnati currently has three cars that are in various stages of their life. The most recent is the #6 car which currently sits as a completed car however it has never been certified for competition and has many design flaws. The remaining two completed cars are both still fully functional and certified, which will serve as great models for testing.

We are proposing a redesign of multiple aspects of the #6 Baja car that include but not limited to; front and rear suspension, cage design, ergonomics and a dynamometer. These improvements are needed for the car to be fully capable within the requirements for the 2018 SAE Baja competition. These will be completed in time for the Spring 2018 competition where we will have the car certified for competition, as well as be competing.

RESEARCH

SCOPE OF THE PROBLEM

The problem with the #6 Baja is that the current design of the car does not meet the requirements of the Baja SAE 2018. This problem is being addressed so the Baja team will be able to compete in the 2018 competition in Maryland. Each individual project is important due to the car needing to meet the requirements given in the Baja SAE Collegiate Design Series 2018 Rules (1) to be certified to compete.

CURRENT STATE OF THE ART

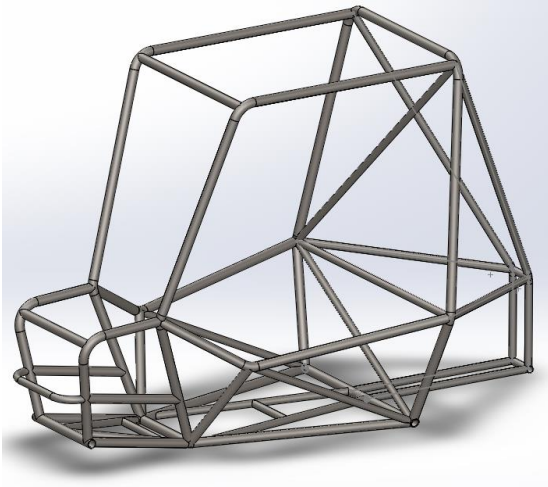


Figure 2- 2016 Frame

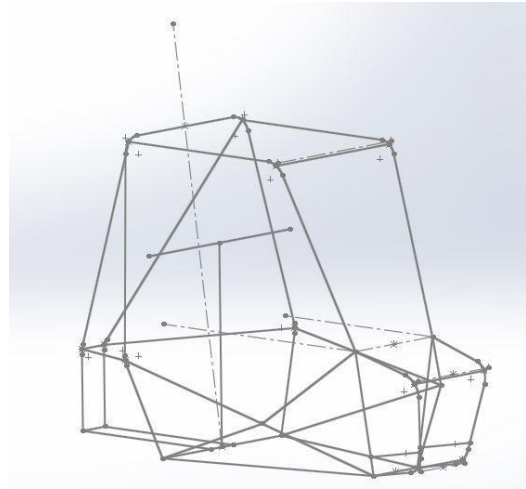


Figure 1- 2016 Wire Frame

The current design is the #6 car that was built in 2016. I plan on updating the frame of the #6 car to ensure all members meet the requirements. The cage design will be designed to specifications per SAE Baja 2018 rules. This includes member requirements (primary, secondary, lateral, and additional), roll hoop, bracings, gussets, butt joints, welding, welding inspections, and destructive testing and inspection. A roll cage specification sheet will need to be completed by technical inspection time for each competition (4).

SAFETY / ERGONOMICS

The end user will be the drivers, team, and anyone that works on the cars. Implementing shields and splash guard will help protect our team and improve the safety of anyone in or near the vehicle.

Ergonomic features will be geared towards driver comfort. Pedal and steering may be modified to capture the 95th percentile of males. Also, E-stop button may be moved to a better position to ensure safe operation in an emergency.

CONCLUSIONS AND SUMMARY OF RESEARCH

I am proposing a redesign of the cage of the #6 car that will address the 2018 SAE Baja updates as well as concerns addressed by the 2017-2018 Baja team. This cage redesign will be completed no later than the competition and the senior project deadlines.

CUSTOMER FEATURES

Weighted importance of design specifications:

- 0.25 - Driver comfortability
- 0.35 - Driver Safety
- 0.10 - Maneuvering in/out of vehicle
- 0.10 - Weight
- 0.20 - Cost

PRODUCT OBJECTIVES

- Driver Comfortability
 - Design will adhere to SAE 2018 rules
 - Design will meet 95th percentile measurements
 - Design must be comfortable for all drivers
- Driver Safety
 - Cage will meet SAE 2018 rules
 - Cage will protect all drivers from injury in the event of a crash/rollover
- Maneuvering in/out of vehicle
 - Driver must exit vehicle within 5 seconds
- Weight
 - Cage must be as light as possible in order for the engine to provide more acceleration
- Cost
 - Cost must be within University of Cincinnati SAE Baja 2017-2018 Budget

QUALITY FUNCTION DEPLOYMENT

		Engineering Requirements (units)										Customer Satisfaction Rating (0.00 - 1.00)	
		1	2	3	4	5	6	7	8	9	10		
Customer Requirements	Importance wt												
1 Accelerate Quickly	0.15	9		1	1	9				9			
2 Complete Endurance	0.15	3		9	9	3				3			
3 Safe	0.10		9	1	1	1				9			
4 Clear Tall Obstacles	0.10	1		9	9	3				3			
5 Climb Steep Hills	0.10	9		3	3	9				9			
6 Low Maintenance	0.10	3		3	3		3				1		
7 Low cost	0.05						9		9				
8 Drive Fast	0.10	9		1	1	3				9			
9 Ergonomic	0.05	3	9							9		1	
10 Brakes Quickly	0.10	9		1	1						9		
Total Importance		1.00											
Engineering requirement Importance			5.05	1.35	3.3	3.3	3.4	0.75	0.75	3.9	1.35	3.5	
Performance Current Product													
New Product Targets													

Figure 3-Quality Function Deployment

DESIGN

MATERIAL SELECTION

For the 2018 competition, SAE Baja listed two rules/requirements for material selection for the frame. The first rule addresses primary tubing. Primary tubing must abide by rule B8.3.12 which states:

“The material used for the Primary Roll Cage Members must be:

(A) Circular steel tubing with an outside diameter of 25mm (1 in) and a wall thickness of 3 mm (0.120 in) and a carbon content of at least 0.18%.

OR

(B) A steel shape with bending stiffness and bending strength exceeding that of circular steel tubing with an outside diameter of 25mm (1 in.) and a wall thickness of 3 mm (0.120 in.). The wall thickness must be at least 1.57 mm (0.062in.) 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 is considered to be proportional to:

$$EI$$

E Modulus of elasticity (205 GPa for all steels)

I Second moment of area for the structural cross section

Bending strength is given by:

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

where:

S_y Yield strength (365 MPa for 1018 steel)

c Distance from neutral axis to extreme fiber (1)”

The other requirement is taken from rule B8.3.1: “Secondary tubing... must be steel tubes having a minimum wall thickness of 0.89 mm (.035 in) and a minimum outside diameter of 25.4 mm (1.0 in) (1).”

Since the 2018 team is using the frame built in 2016, we wanted the new upgrades to use the same size metal that the 2016 team used, to remain consistent. The 2016 team constructed a table (Table 1) that compared the size of the primary and secondary tubing to the standards set forth by SAE Baja. Since there were no changes to the tube requirements from 2016 to 2018 (and since we wanted the frame’s tubing to remain consistent), we used the same chart

for comparison.

	SAE Rules (1018 Cold Drawn)	4130 Normalized Alloy Steel	4130 Normalized Alloy Steel Primary	4130 Normalized Alloy Steel Secondary
Outside Diameter (in.)	1.000	1.000	1.25	1
Wall Thickness (in.)	0.120	0.120	0.065	0.065
Inside Diameter (in.)	0.760	0.760	1.120	0.870
Elasticity (ksi)	29732.7	29732.7	29732.7	29732.7
Density (lb/in ³)	0.284	0.284	0.284	0.284
Carbon Content (%)	0.18	0.30	0.30	0.30
Ultimate Strength (psi)	63800	97200	97200	97200
Yield Strength (psi)	52939	63100	63100	63100
Second Moment of Inertia (in ⁴)	0.033	0.033	0.043	0.021
Distance to neutral axis (in.)	0.500	0.500	0.625	0.500
Bending strength (in-lb)	3463.3	4128.1	4301.1	2645.8
Bending stiffness (kip-in²)	973	973	1267	623
Weight (lb/ft)	1.131	1.131	0.825	0.651

Table 1-Material Selection (2)

Based on Table 1, the standards set by SAE Baja for the 2018 competition must be better than 1018 Cold drawn steel. As said before, we wanted to update the frame with the same metal that the 2016 team used so we selected 4130 chromoly steel tubing. Table 1 shows that 4130 Chromoly steel meets and exceeds the 1018 cold drawn steel by using 1.25" OD x 0.065" wall thickness for 4130 chromoly steel for our primary members. 1.00" OD x 0.065" wall thickness was selected to use as the secondary tubing because it also met the standards set forth by SAE Baja. Bending strength in the primary tubing needed to be calculated as well as bending stiffness. Below are the equations that proved the bending strength and bending stiffness met the SAE Baja standards. The results are also located in Table 1 for comparison against the 1018 cold drawn steel.

$$\text{Bending Strength} = \frac{S_y I}{c} = \frac{(63,000 \text{ psi})(0.043 \text{ in.}^4)}{0.625 \text{ in.}} = 4,301.1 \text{ in} - \text{lb} \quad (2)$$

$$\text{Bending Stiffness} = EI = (29,732.7 \text{ ksi})(0.043 \text{ in.}^4) = 1,267 \text{ kip} - \text{in}^2 \quad (2)$$

DESIGN ANALYSIS

Due to the 2018 team not meeting the clearance requirements in the 2016 car, and due to the fact that the 2018 team was reusing as much of the 2016 car as possible, some careful changes needed to be made. It was decided that the primary roll members would change positions from the middle of the bends in the rear roll hoop to the top of the bends in the rear roll hoop. Increasing the height of these primary members would allow for more clearance. The primary members would use the 1.25" OD x 0.065" wall thickness as described earlier in

the Material Selection section of this report. Because we changed the positioning of those members, we had to completely refabricate the entire rear section of the frame. The rear support members needed to change to the same positioning the primary roll members were changed to. This was to ensure that any force that was dealt to the car would distribute its load evenly throughout the frame. The rear support members will be using the secondary members that are 1.00" OD x 0.065" wall thickness as described earlier in the Material Selection section of this report.

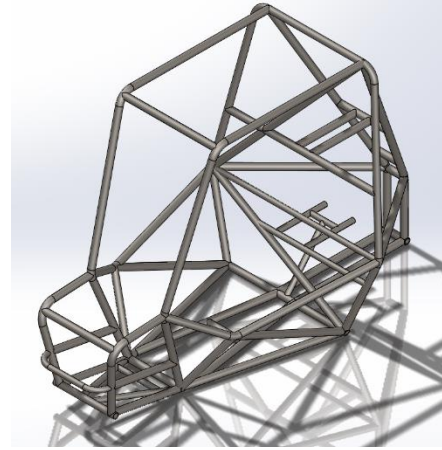


Figure 4-2018 Frame Design

Under the driver's seat are four mounting points. These mounting points connected the driver's seat to the frame of the car. The mounting points had a height of 1"-2" for ergonomic purposes for the 2016 team. To allow for more clearance, I decided to remove the mounting points and attach the seat directly to the under-seat member of the frame. This was to ensure that every member would meet the clearance standards without any question.

FORCE CALCULATIONS

Per the 2016 design, the force calculations were used with an overall weight of 600lbs or 18.63 slug. This 600lb total weight includes the 350lb weight of the car plus the 250lb weight of the driver. We also used data that the 2016 team acquired from actual crash test data that used for impulse times of 0.075 seconds (2) (3). The force was assumed from having an impact with the car traveling at 30mph into a solid, non-moving object. The 30 mph, or 44 ft/s is the assumed top speed of the car. Other 30mph impacts were calculated in the scenario that our car was not moving and another vehicle impacted it from the side or rear of our car. We also performed calculations based on the car being dropped from a 4-foot height and if the car were to land upside down. Finally, since another team member is changing the mounting position of the rear shocks onto the rear support members of the frame, calculations were performed to see how much force would be exerted onto those rear support members. The following are those calculations:

Stopping Distance

$$\Delta V = d t \rightarrow d = \Delta V \cdot t$$

$$d = (44 \text{ ft s} - 0 \text{ ft s}) \cdot 0.075 \text{ s}$$

$$d = 3.3 \text{ ft}$$

Deceleration

$$d = \frac{v^2}{2a} \Rightarrow a = \frac{v^2}{2d}$$

$$a = \frac{44^2 \left(\frac{\text{ft}}{\text{s}}\right)}{2(3.3)}$$

$$a = 293 \frac{\text{ft}^2}{\text{s}} = 9.1 g$$

Impact Force for Front, Side and Rear Collision

$$f = ma$$

$$f = 18.63 \text{ slug} * 32.2 \frac{\text{ft}^2}{\text{s}} * 9.1 g$$

$$f = 5470 \text{ lbf}$$

Drop Impact

$$mgh = \frac{1}{2}mv^2 \Rightarrow v = \sqrt{2gh}$$

$$v = \sqrt{2(32.2 \frac{\text{ft}^2}{\text{s}})(4ft)}$$

$$v = 16.05 \frac{\text{ft}}{\text{s}}$$

$$f = ma = m \frac{\Delta V}{\Delta t}$$

$$f = ma = 18.63 \text{ slug} * \frac{16.05 \frac{\text{ft}}{\text{s}}}{0.075 \text{ sec}}$$

$$f = 3986.82 \text{ lbf}$$

Shock Impact Force Calculation on Rear of Frame

$$f = \frac{mgh}{d}$$

$$f = \frac{18.63 \left(32.2 \frac{\text{ft}^2}{\text{s}} \right) (4ft)}{0.666}$$

$$f = \frac{4942 \text{ lbf}}{2}$$

$$f = 2,471 \text{ lbf}$$

$$f = \frac{2471}{\sin(90)} = \frac{x}{\sin(57)}$$

$$f = 2072 \text{ lbf Vertical}$$

$$f = \frac{2471}{\sin(90)} = \frac{x}{\sin(56)}$$

$$f = 2048 \text{ lbf Horizontal}$$

FINITE ELEMENT ANALYSIS

The forces calculated were tested against the frame using Solidworks. Solidworks has its own finite element analysis simulator that generates the worst possible outcomes that the forces would act on our frame. These simulations helped us to determine whether or not the design would be safe to use in real life. All tests were performed using static testing on the frame with impact forces focused on specific areas of the frame. The yield strength was then determined and the highest concentration of stress was located. The following is a result of our FEA:

Front Impact

Impact Force: 5470

Upper Bound Axial and Bending: 106.0 ksi

Max Stress: 48.53 ksi

Safety Factor: 2.18

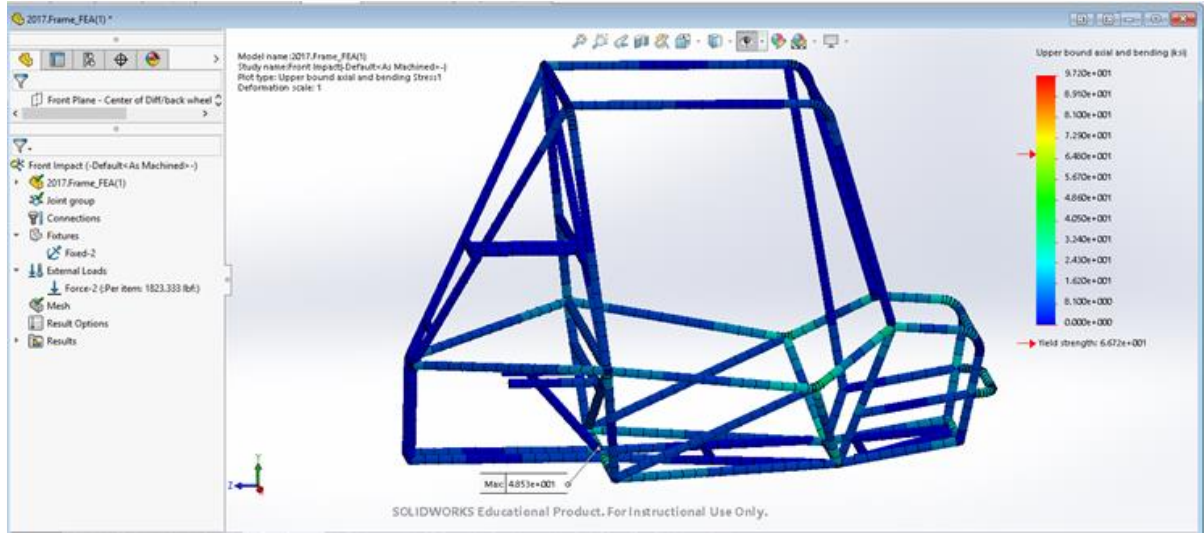


Figure 5-FEA Front Impact

Rear Impact

Impact Force: 5470

Upper Bound Axial and Bending: 106.0 ksi

Max Stress: 76.8 ksi

Safety Factor: 1.38

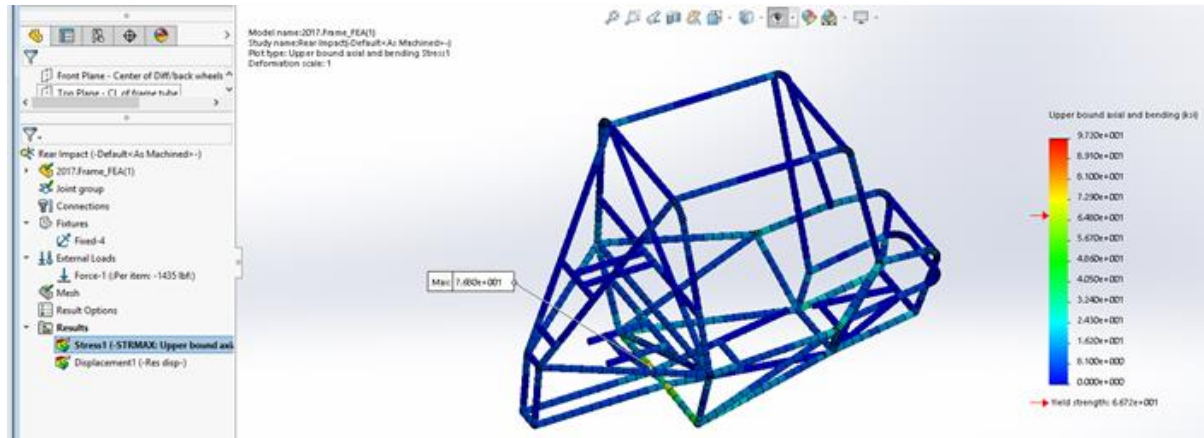


Figure 6-FEA Rear Impact

Side Impact

Impact Force: 5470
 Upper Bound Axial and Bending: 106.0 ksi
 Max Stress: 39.1 ksi
 Safety Factor: 2.71

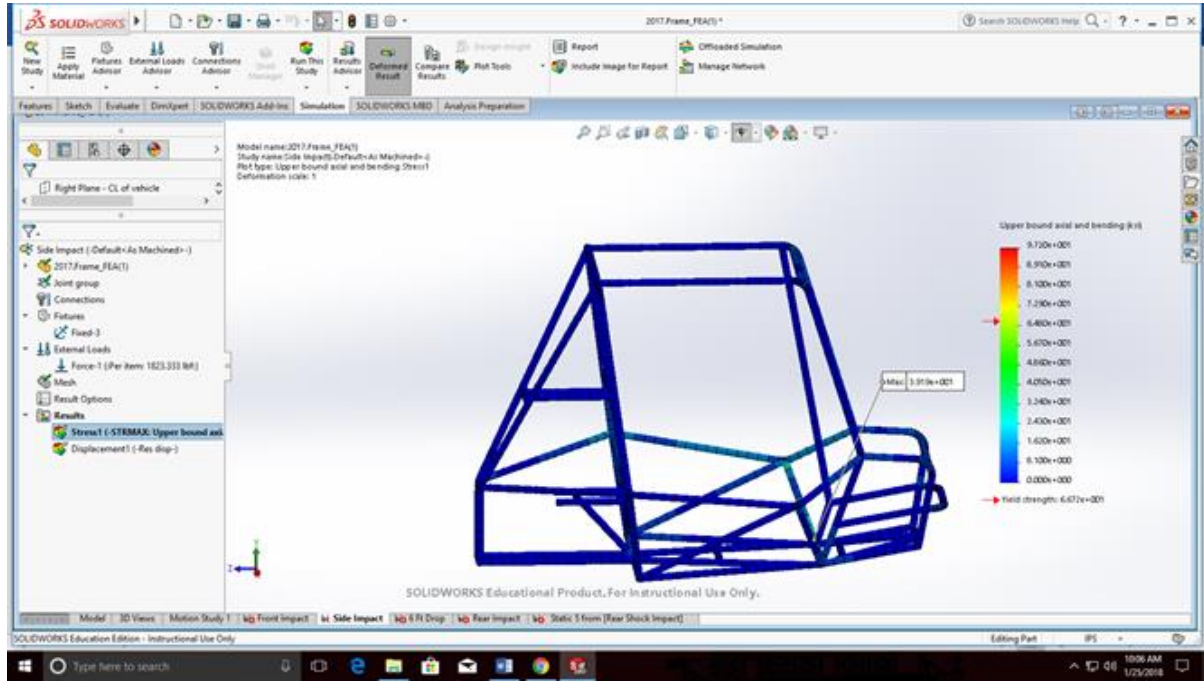


Figure 7-FEA Side Impact

Top Impact

Impact Force: 3986.82
 Upper Bound Axial and Bending: 106.0 ksi
 Max Stress: 18.11 ksi
 Safety Factor: 5.8

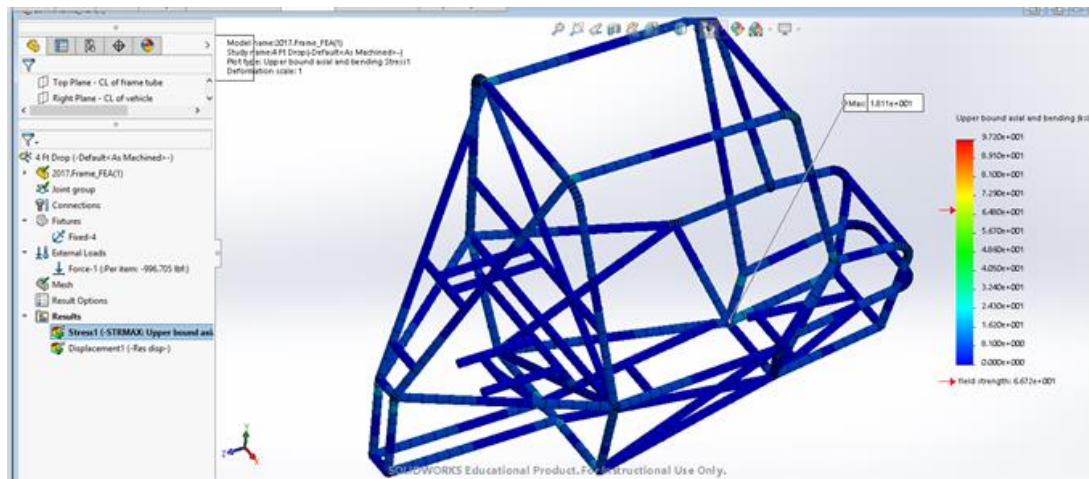


Figure 8-FEA Top Impact

Shock Impact

Impact Force: 2048 Horizontal; 2072 Vertical

Upper Bound Axial and Bending: 106.0 ksi

Max Stress: 21.69 ksi

Safety Factor: 4.88

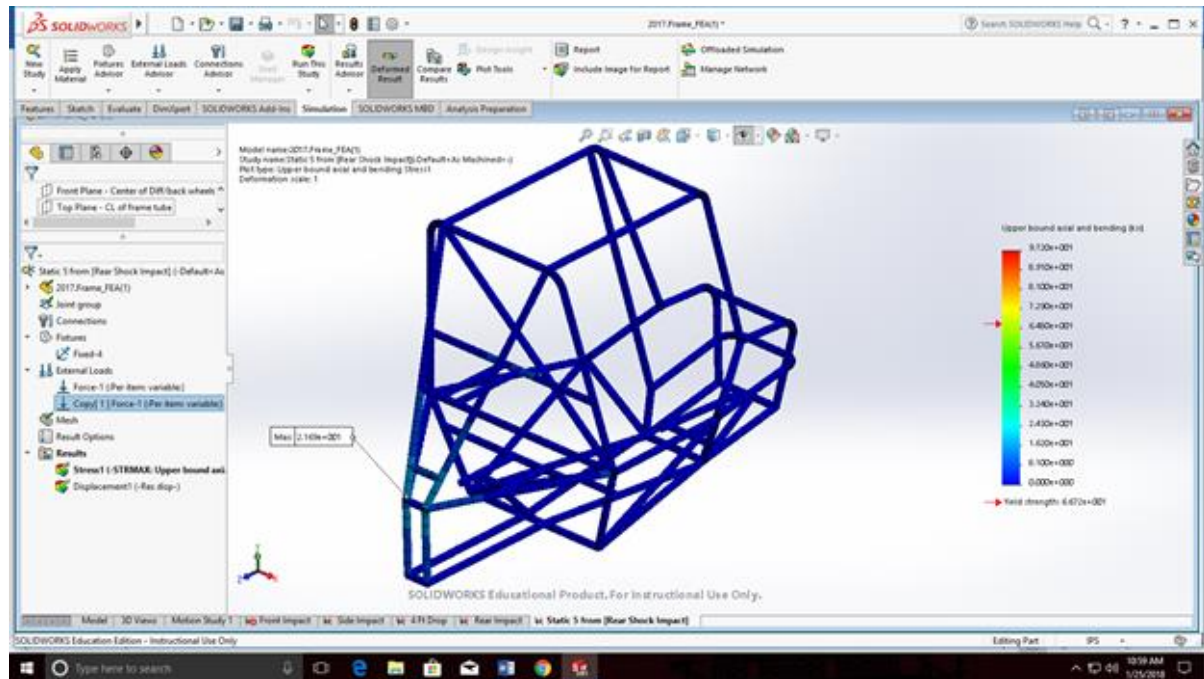


Figure 9-FEA Shock Impact

Based off the results of the Finite Element Analysis, it can be concluded that the design will be safe in the event of an impact. In order for the vehicle to be considered safe, the safety factor needed to be above 1. All of our tests conclude that all safety factors are above 1 and the design is safe enough to protect the driver in the event of an impact. The areas of high stress will be used for testing purposes and will be referenced in the Testing portion of this report.

MANUFACTURING

BENDING

The only bending that needed to be performed was the rear support members of the frame. Because there were only two bends that needed to be made, it was decided that we would bend them in-house. The bends were made using a manual tube bender and were bent to the appropriate specifications. Bending the tubes in house allowed us to save money and time by not shipping it out and waiting for the finished parts to come back.

WELDING

Tungsten Inert Gas (TIG) welding was used to assemble the frame. TIG welding was chosen due to success from prior years experiences and because it's a cleaner welding process. We also had access to plenty of filler weld in the shop and based off research, it is an acceptable welding method to use with 4130 chromoly steel. The filler material selected was ER70S-2 because of its high strength capabilities and it was the best filler available in the shop that worked with TIG welding 4130 chromoly Steel.

TESTING

PROOF OF DESIGN STATEMENT

The frame will withstand an impact force from a 4ft drop as well as withstand applied forces during off-road conditions. The 4ft drop will be conducted in the VP shop using an overhead crane, tow straps, and a quick release mechanism and will be repeated four more times for a total of 5 drops. Off road conditions will be conducted at Haspin or around the Victory Parkway campus. Testing will be conducted between April 1-April 14th.

Strain will be gathered using 3 strain gauges positioned on the frame where the FEA results showed areas of high stress. One strain gauge will be placed where the under-seat member and the rear support member meet on the rear roll hoop. A strain gauge will be placed at location QL in Figure B-5 located on page 26 of the 2018 SAE Baja rule book. Finally, a strain gauge will be placed where the rear support member connects to the shock mount of the rear shock.

The frame will also meet the vertical clearance standards of 6in. from the top of the driver's helmet to the bottom of the overhead roll support members and the adjustment of the seat belt will be no higher than level of each driver's shoulders and no lower than 4in below each



Figure 10-Manual Tube Bender

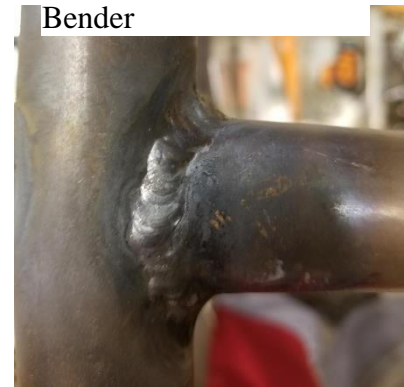


Figure 11-Example TIG Weld

driver's shoulders.

TESTING METHOD

Testing was conducted on the frame to physically determine if the frame could withstand normal racing conditions/forces. Actual testing methods were conducted by running the car through an impact test. The test consisted of dropping the unloaded car off a 3-foot height for a series of 5 drops. Due to the limited resources of dropping the car from a certain height and safety concerns of placing a person in the vehicle while testing, this was the best option. The strain gauges as discussed in the previous section determined how much strain is actually being created at those points. Due to unforeseen circumstances, the drop test was the only test that was able to be performed.



Figure 12-Drop Test

TESTING RESULTS

As previously stated, the car was dropped for a total of five times at a three-foot height. The system that recorded strain also calculated the force, in Newtons, acting on the frame. Out of the five tests, the highest force that was recorded upon impact was 186.4 lbs acting on the frame. This is well within our limits. The simulation data showed that with a nearly 3,000 lbf acting on the frame wouldn't deform the frame, so a 186.4 lbf acting on the frame is perfectly within its limits. Factors such as the rear shocks and the rear tires could have been a reason why the force was small as well. Some of the force is being absorbed by the spring of the rear shock as well as the tires. This means that not all the force is impacting the frame which decreases the chance of deformation on the frame.

One issue we ran into with testing is that the system that collected the impact data collected information every 0.1-0.25 seconds. There is an extensive amount of time in between intervals where the system collects data. Because of this large gap of time in the collection of the data, only 1 out of the 5 tests were able to collect results. The team later discovered this lapse in sample taking was due to the number of strain gauges that were being tested at once. With the data collection system we were using, the sample frequency decreased by $\frac{1}{2}$. Since there were four strain gauges connected at the time of testing, the sample frequency decreased by $\frac{1}{16}$; therefore, it is possible we missed the highest point of stress during our testing. It is my recommendation to future teams to use one strain gauge at a time during testing to attain better results.

CONCLUSION

In conclusion, the frame was able to achieve its clearance goal. All members of the team met and exceeded the 6-in. clearance set forth by SAE Baja. Also, the frame was able to withstand all racing and testing performed on it. The project was completed on time and under budget, so I was able to meet my goals in those respective portions of my project. The 2018 team was placed on the waiting list for the 2018 competition, so we were not able to compete or certify our vehicle for this year's competition. Although we were not able to compete in competition, I am confident that the frame will pass all certifications and will be acceptable to use in the future should the rules of the frame remain the same as the rules published by SAE Baja for the 2018 competition.



Figure 13-Finished
Frame Front

Figure 14-Finished
Frame Rear

ACKNOWLEDGEMENTS

I would like to thank Dean Allen Arthur for his knowledge and advice throughout the senior design process. I would also like to thank all other team members on the 2018 SAE Baja team for their cooperation and understanding during my portion of the project. A big thanks to Nicholas Plataniotis for his help with tube bending and access to tooling and a big thanks to Jordan Graff for his advice on welding techniques and letting me in his night class to practice my welding skills. Finally, I want to give a big thanks to all friends, family, and professors who have all helped me throughout my time as an undergraduate.

WORKS CITED

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APPENDIX A-SCHEDULE, PROPOSED AND ACTUAL

	Research	Design	Modeling/FAE	Ordering of Materials	Manufacturing	Testing
September	■					
October	■	■				
November		■	■			
December		■	■	■	■	
January				■	■	
February					■	
March						■
April						■

APPENDIX B-BUDGET, PROPOSED/ACTUAL

#	Supplier	QTY	Part	Description	Price/Part	Total
1	TW Metals	4	1" x 0.065" x 4ft	4130 Alloy Steel Tube	11	264.00
2	TW Metals	2	1" x 0.065" x 5ft	4130 Alloy Steel Tube	9	90
3	TW Metals	3	1.25" x 0.065" x 8ft	4131 Alloy Steel Tube	9	144
4	Lowes	1	890013	Dremel 28 piece rotary tool kit	59.99	59.99
						557.99

Proposed

The budget for the frame design will be \$3000. This limit was set from researching last year's frame design budget of \$3,200. Being that majority of the frame will be saved, I am aiming to not spend as much as last year's group spent. Part of that fund will be a mistake/emergency fund.

Actual

Table 2 lists the bill of Materials and the total cost of the frame. Overall, I spent a total of \$557.99 of the \$3,000 budget. Because I was able to reuse a majority of the frame, I was able to save a lot of money by not having to buy as much metal tubing. By remaining under my budget goals, it allowed the remaining funds to be allocated for other team member's projects if they needed it.

APPENDIX C- NAMED ROLL CAGE POINTS

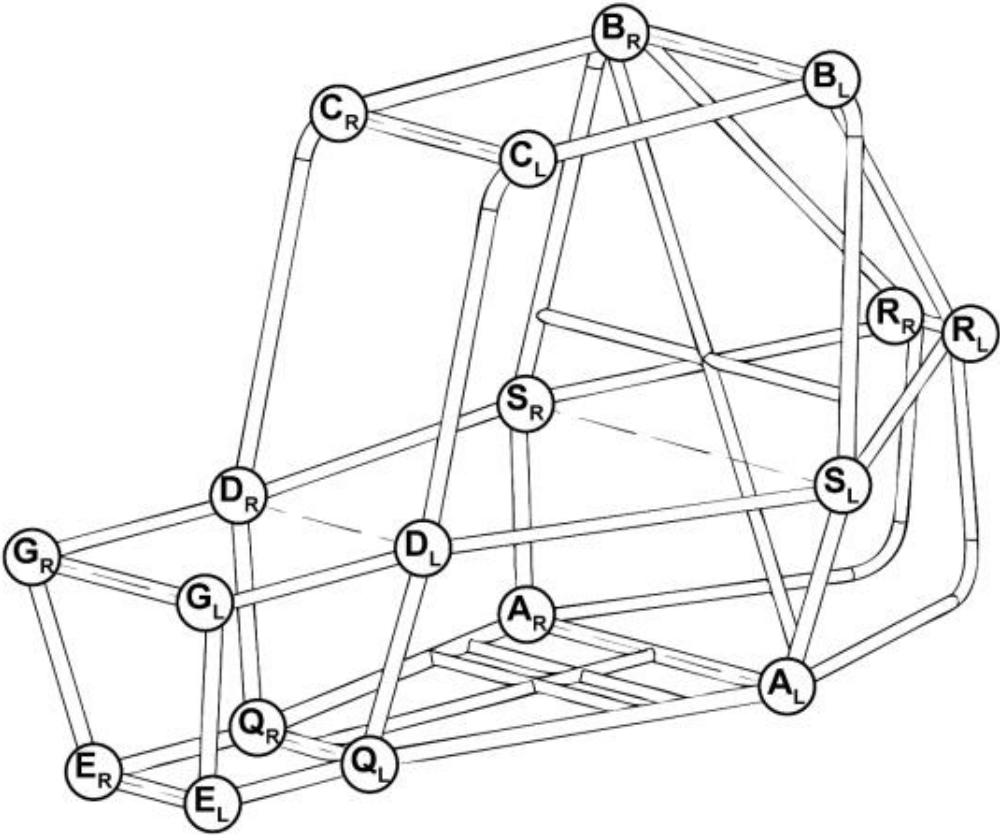
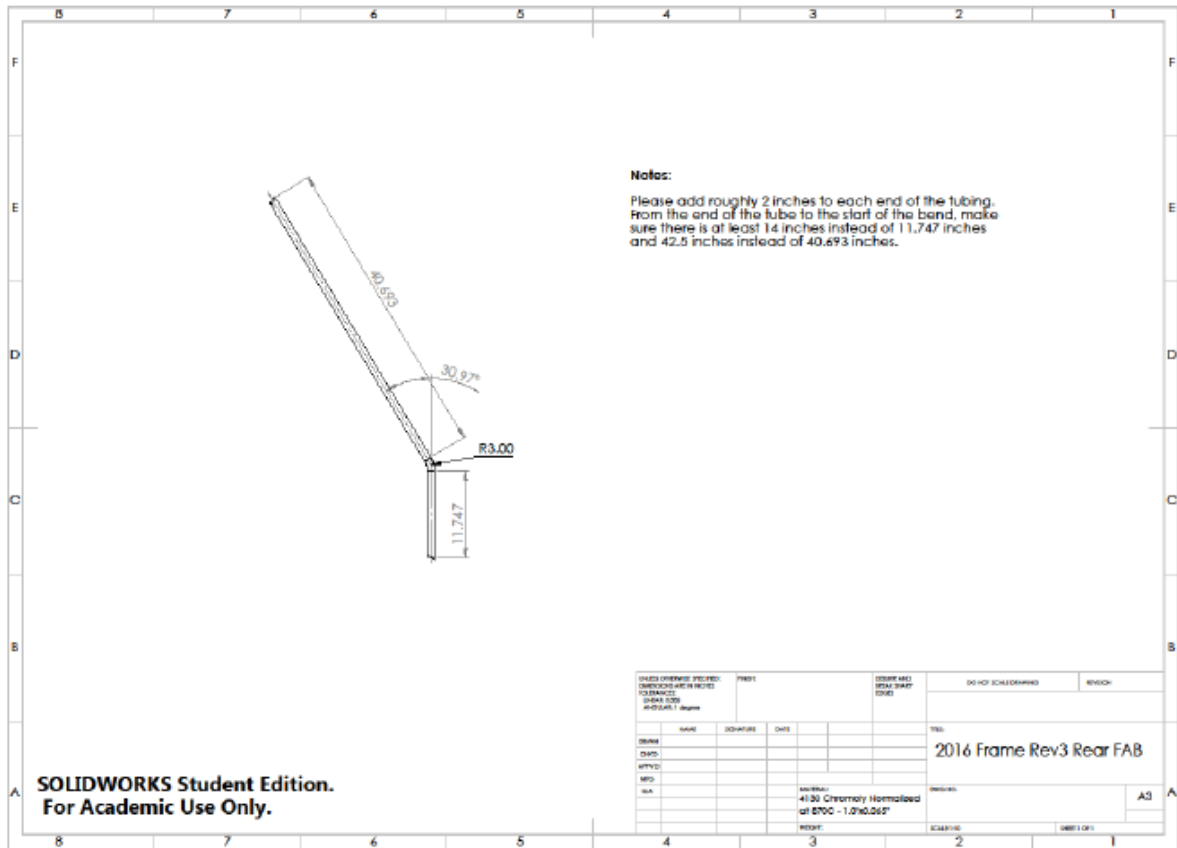


Figure B-5 located on page 26 of the 2018 SAE Baja rule book. (1)

APPENDIX D-REAR FAB DRAWING



2016 Frame Rear FAB Drawing (2).