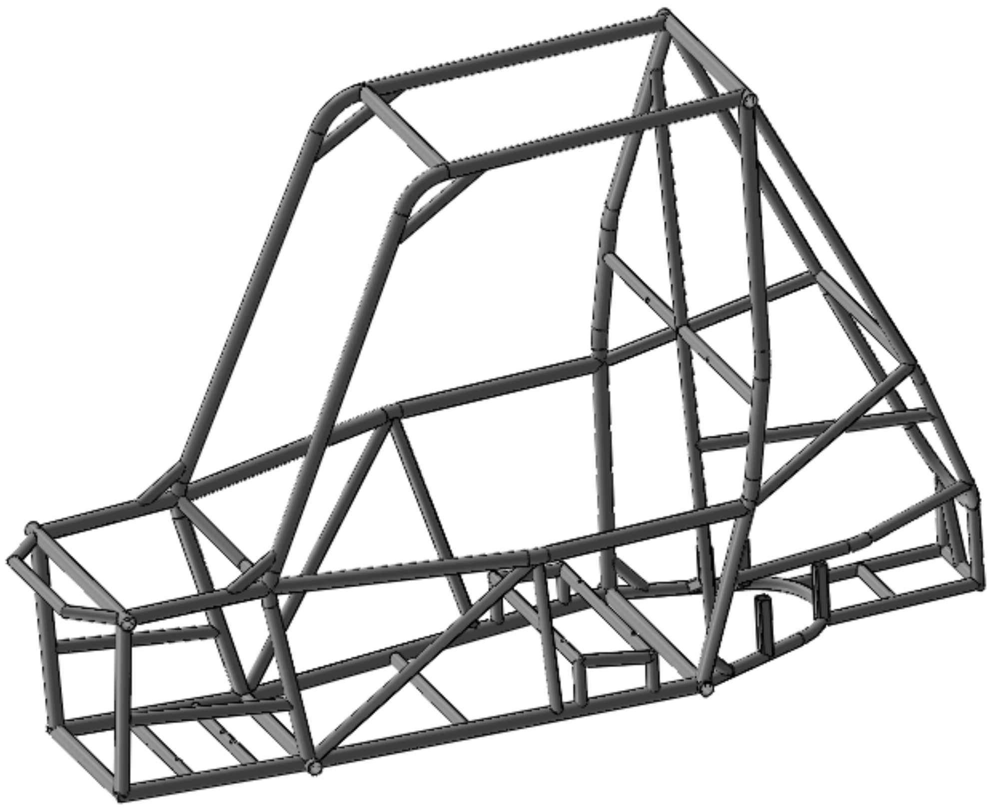
Northwestern Baja SAE

2022-2023 Frame Design



Presented By: Hannah Huang

1. Introduction

The Society of Automotive Engineers (SAE) hosts annual Baja competitions, in which about a hundred collegiate teams build and race their own off-roading vehicle. The Northwestern Baja SAE team builds an entirely new car every year, which makes for an incredibly busy and tight timeline. The frame of the car, also referred to as the “roll cage” in official Baja SAE rules, has the responsibility of properly housing all the components of the car, such as the powertrain and suspension, while also keeping the driver safe in all foreseeable collisions.

The goals of this year’s frame was to decrease its weight and number of tubes from last year. Decreasing weight allows the car to accelerate quicker and reach a higher max velocity, while decreasing the number of tubes makes it easier and quicker to manufacture the frame because there are less parts to weld together. The 2022 frame was 76.14 lbs and made of 80 tubes (see Figure 1). This frame was very sturdy last year and never failed during the 2022 competition, yet there is a lot of room for improvement in both weight and manufacturability.

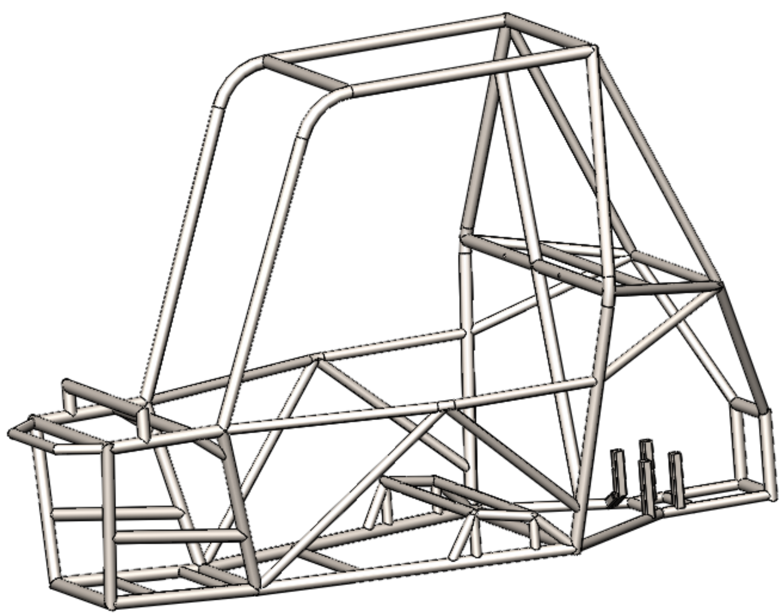


Figure 1. The 2022 frame design.

2. Design of the Car

First, let us define acronyms for major members, which correspond to acronyms used throughout SAE guidelines. Figure 2 shows the rear roll hoop (RRH), roll hoop overhead members (RHO), side impact members (SIM), lower frame side members (LFS), fore-aft bracing members (FAB), and front bracing members (FBM). These are specific to a rear-braced frame, which we choose over the front-braced frame because it gives us more space in the back to house powertrain components that are necessary for our implementation of four-wheel drive.

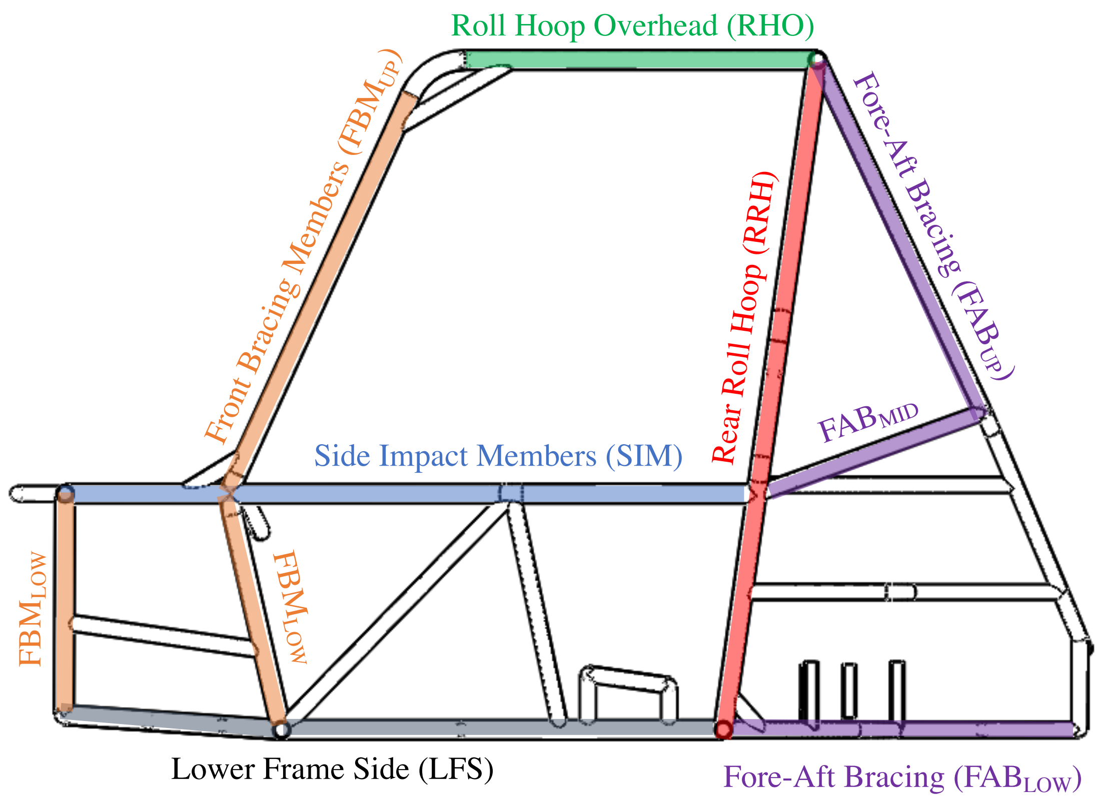


Figure 2. Important members and their names for a rear-braced frame.

2.1. 2023 Considerations

There are a couple of new considerations this year that affect the frame design, particularly in the powertrain. First, the required engine has changed; this year it is bigger than before. Second, the position of the engine and CVT were exchanged this year to allow for better packaging of the engine inside the frame. Finally, the differentials were custom-designed this year to be smaller.

2.2. SAE Rules and VR3 Restrictions

The 2023 Baja SAE rules outline all the requirements of the frame design in the entirety of Part B, Article 3 – Roll Cage. Major rules from that document will be discussed here in brief, along with restrictions from VR3, who are responsible for procuring, bending, and coping the tubes. All continuous tubes are categorized as Primary members or Secondary members. All tubes may be bent, but they cannot be bent more than 30° unless it is supported at this bend. According to B.3.2.16 - Roll Cage Materials, Primary members must have the stiffness and bending strength exceeding that of circular 1018 steel tubing 25mm (0.984 in.) and a wall thickness of 1.57mm (0.118 in.). Stiffness k_b and bending strength S_b are defined as

$$k_b = EI \qquad S_b = \frac{S_y I}{c} \,,$$

where E is the elastic modulus, I is the second moment of area, and c is the maximum distance from the neutral axis (half of the outer diameter, D). The area moment of inertia for a hollow circular cross section in transverse bending is given by

$$I = \frac{\pi}{4}\left(\left(\frac{D}{2}\right)^4 - \left(\frac{D}{2} - t\right)^4\right) .$$

We use 4130 steel because of its weldability, strength, and cheap price. The tubes are restricted to discrete diameters and wall thicknesses that VR3 provides. Thus, we could easily iterate through the possible tube diameters and wall thicknesses to find a combination that exceeded the given conditions of 1018 steel while minimizing the cross-sectional area of the tube (to minimize the mass of the tube). This resulted in 1.25” 4130 with a 0.065” wall thickness, which is summarized in Table 1.

Table 1. Comparison of properties of 1018 steel in SAE guidelines with those of 4130 steel. The last two columns show that the combination of outer diameter D and wall thickness t of the chose 4130 steel surpass those of 1018 steel.

Steel	D (in.)	t (in.)	c (mm)	E (GPa)	I (m^4)	S_y (MPa)	$\boldsymbol{k_b}$ **(kN/m)**	$\boldsymbol{S_b}$ **(kNm)**
1018	0.984	0.118	24.9936	205	1.28E-08	365	**2.62**	**0.186**
4130	1.25	0.065	31.75	205	1.77E-08	460	**3.64**	**0.257**

Secondary members are allowed a minimum wall thickness of 0.035” and outer diameter of 1”. Figure 3 indicates which members on the car must be Primary members. All other members, including those not pictured, are considered Secondary members.

The Baja SAE rules also indicate a template which must fit inside the frame. It makes sure that all of a driver stay inside the frame of the car at all times, especially in the case of a collision. These specifications can be seen in Figure 4.

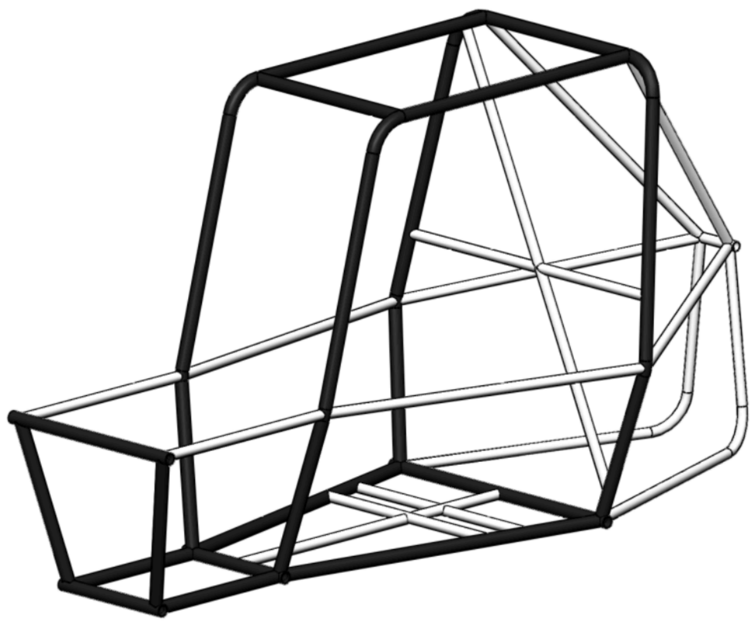


Figure 3. Diagram provided by SAE (Figure B-5) to indicate Primary members (black) and Secondary members (white).

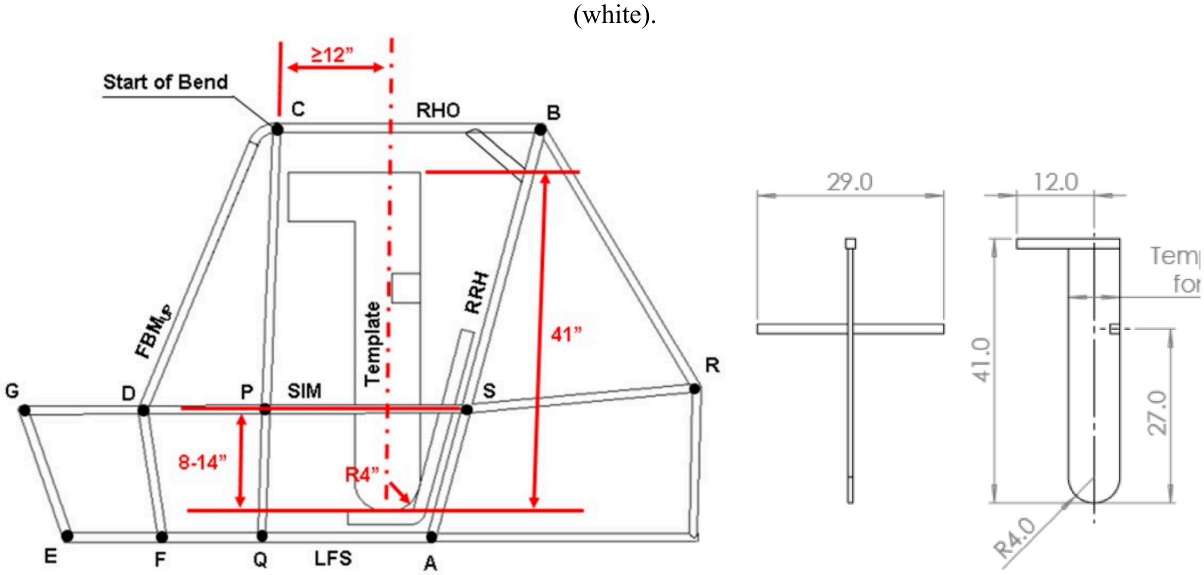


Figure 4. Diagrams provided by SAE (Figures B-11 and B-12), which demonstrate the template that must fit inside the car.

2.3. Designing in SolidWorks

Modelling Conventions

The origin of the entire model must be in the middle of the bottom tube of the "rear roll hoop" (RRH). This is indicated as the blue dot in Figure 5. This is a convention that all the sub-teams follow and use to determine their separate assemblies (e.g. placement of suspension points). The model should also be oriented such that "up" is in the z-direction and the car faces in the -x direction (refer to Figure 5). This is necessary to match the convention of Lotus, which the team uses to analyze suspension.

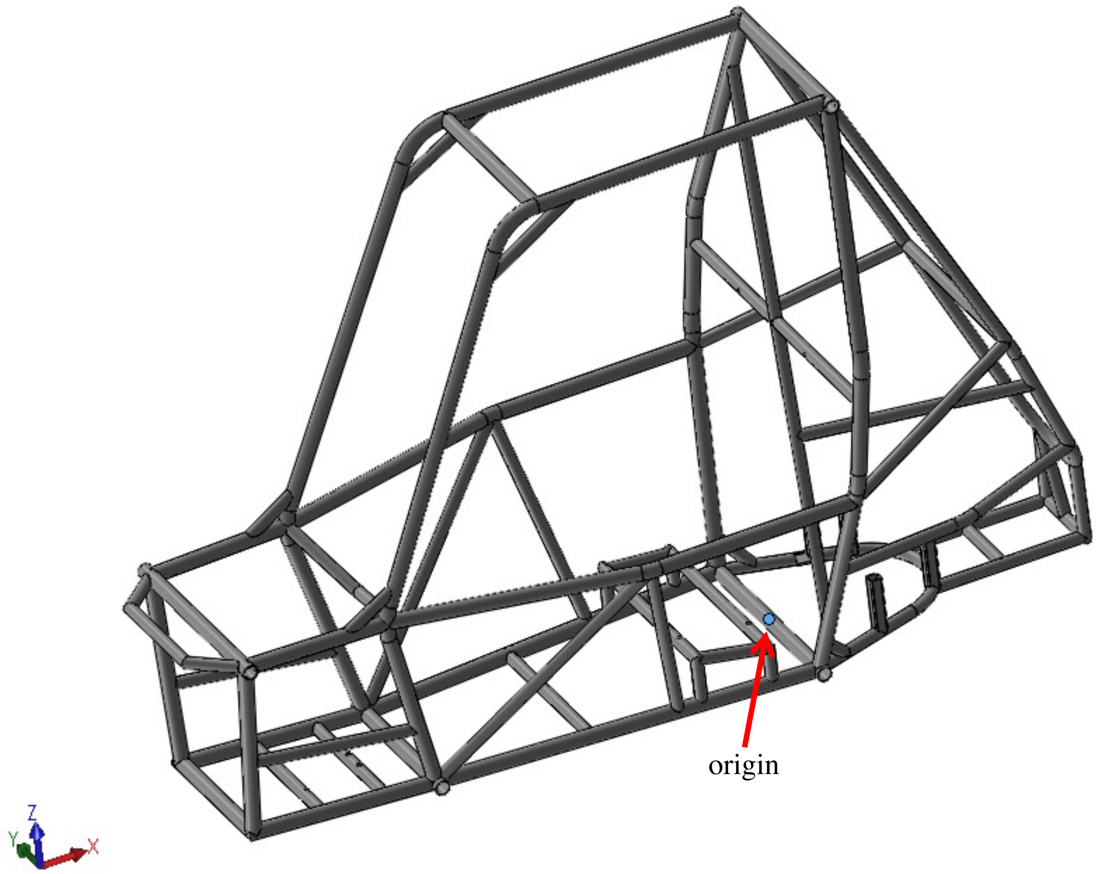


Figure 5. The origin of the model (blue dot) must be at the bottom of the RRH.

Sketches

This model was begun by first drawing all the member ranges defined in the Baja SAE guidelines. This includes the template dimensions discussed earlier, the range of acceptable angles for the RRH as outlined in B.3.2.6, the acceptable range of heights of the SIM as outlined in B.3.2.10, and the range of acceptable angles for the FBM as outlined in B.3.2.12. All the measurements are defined within the Baja SAE guidelines except (a), (b), and (c). Note that measurement (c) does not need to be exact but should be close. The measurement can be updated later depending on the bottom location of FBM_{LOW}. Next, a skeleton sketch is made based on the outline sketches (see Figure 7). This sketch is then used to make important planes for other sketches as shown in Figure 8. The car sections was sketched in the following order: RRH → back powertrain area and FABs → Toe Box → SIM/FBM/RHO → under seat members → gussets.

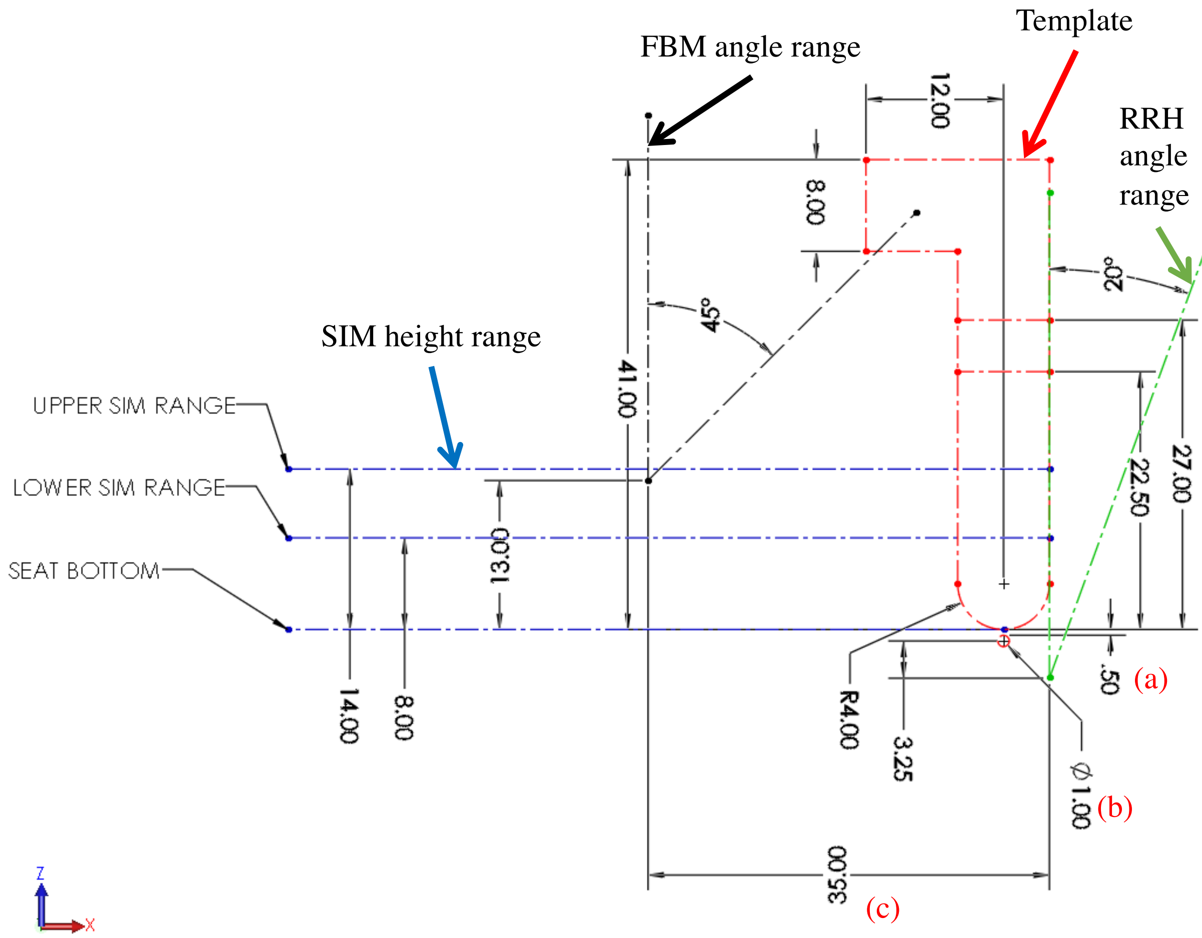


Figure 6. Sketches for outlining different ranges. All dimensions are based on specifications from the Baja SAE guidelines except for (a) the dimension between the inner bottom of the seat and seat mounting tube (essentially the width of the seat), (b) the diameter of the seat mounting tube, (c) and a length between the bottom of the RRH to the bottom of FBM_{UP}.

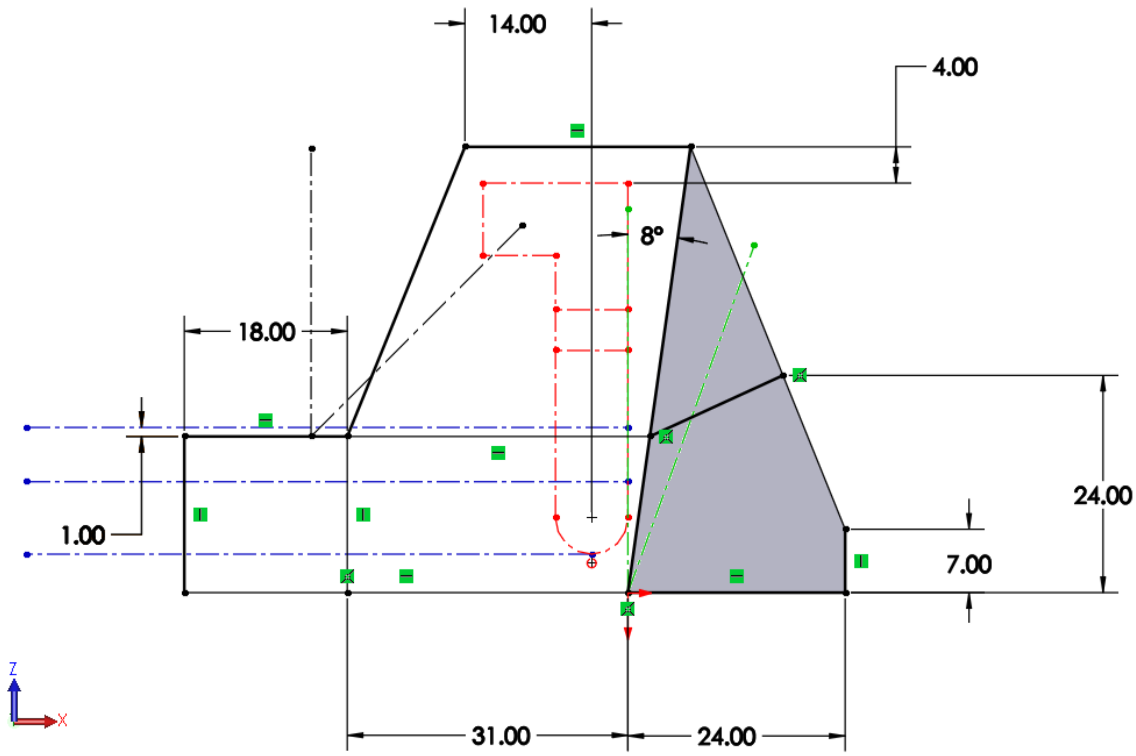


Figure 7. Skeleton sketch based off outlines.

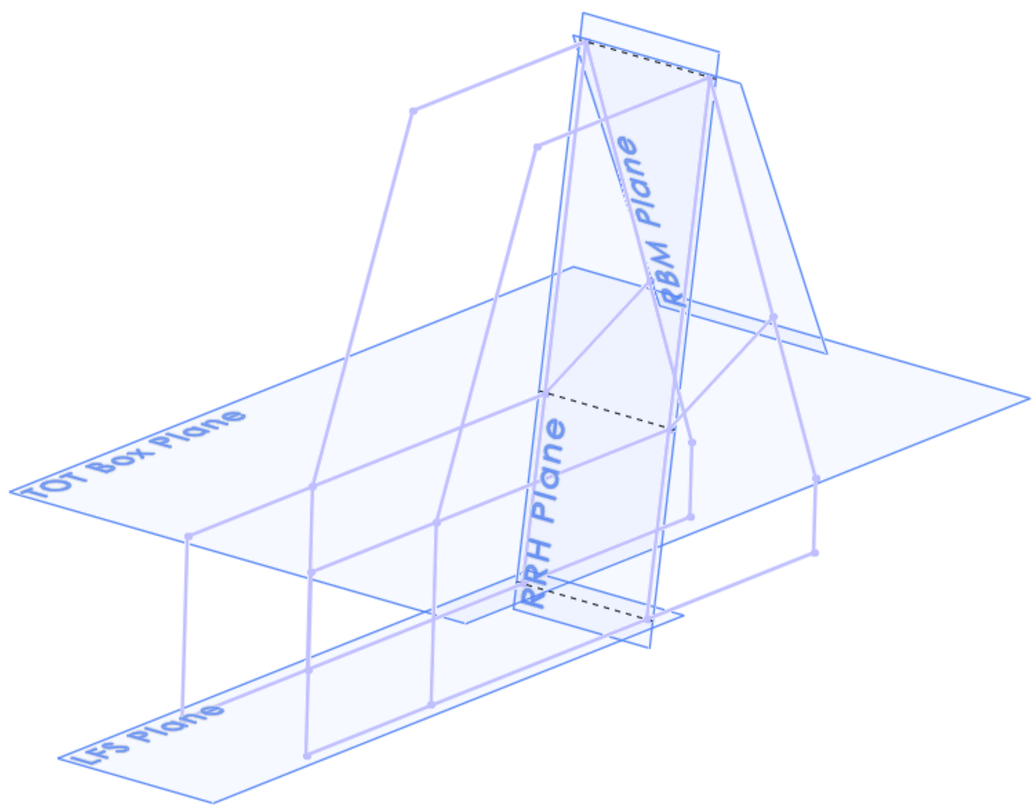


Figure 8. Planes from skeleton sketch.

To interface with the suspension points, we open an assembly that has both the frame and the suspension assembly. We make sure to mate each of their origins to the origin of the assembly and align their axes. Then, the suspension lines were copied to the frame with the "Convert Entities" tool as shown in Figure 9. Notice that the FAB, powertrain, and toe box sketches were based off of the suspension points. There is an offset between the suspension components and the car sketch because there must be room for suspension mounting tabs. These offsets should be decided by consulting the suspension lead. Additionally, because these lines are a copy from the suspension assembly, they can easily lose their reference when the suspension assembly is updated. Thus, it is also important that the suspension lead communicates with the chassis lead on these changes. The full car sketch is shown in Figure 10.

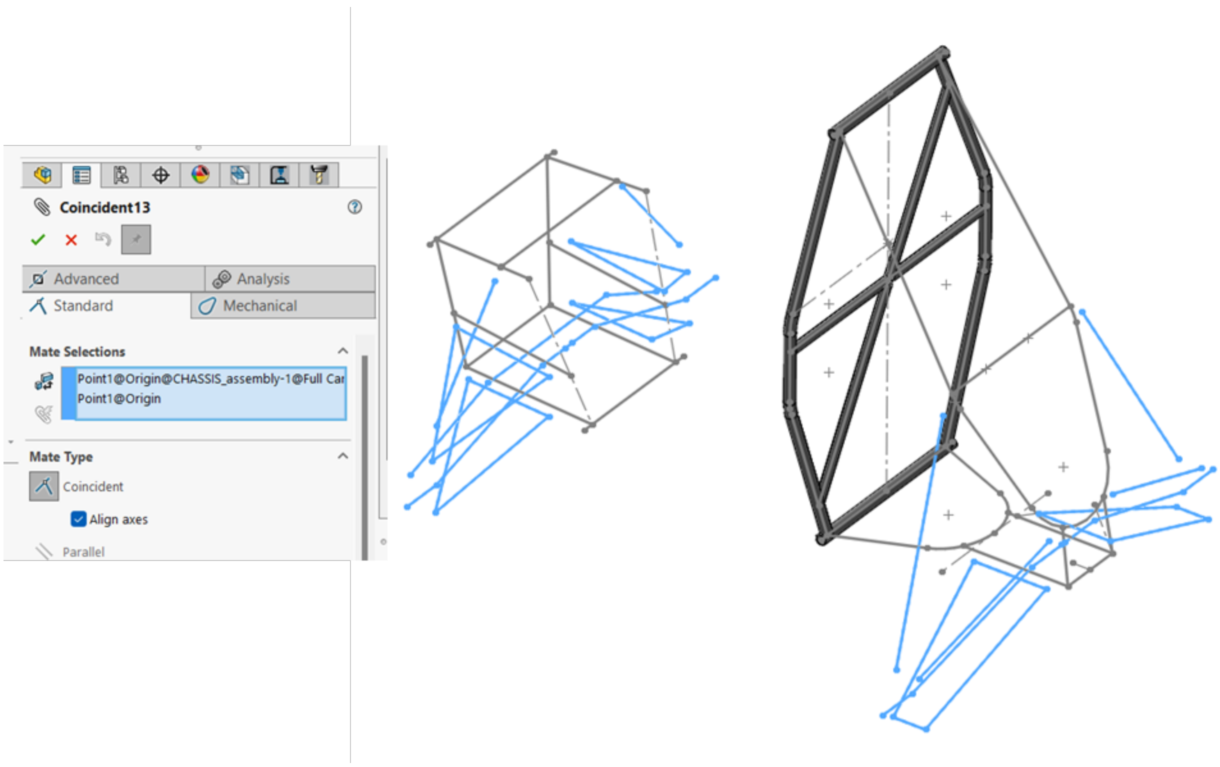


Figure 9. Example of mating assemblies to the origin and the suspension lines copied to the frame.

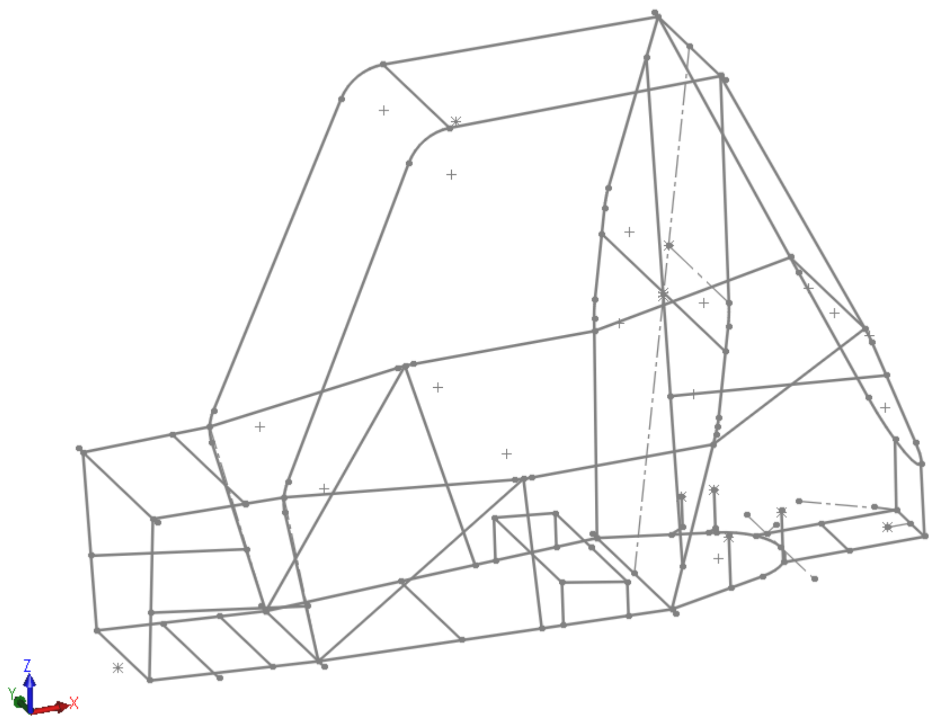
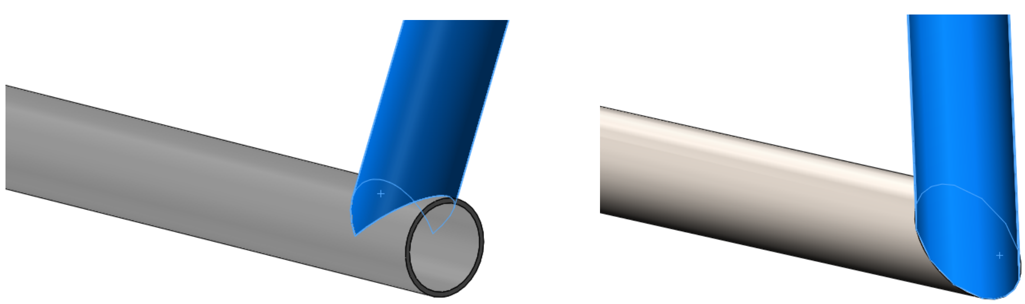


Figure 10. Full sketch of car.

Weldments

The tubes were created using SolidWorks Weldments, and the specific profiles were downloaded from VR3's website. As determined earlier, primary members are 1.25" tubes of 0.065" wall thickness. Most secondary members are 1.00" tubes of 0.035" wall thickness (the minimum allowed dimensions per Baja SAE guidelines), except for a few that had to be thickened to pass FEA simulations. This year's car utilized a couple of coped welds as an experiment to replace the traditional mitered joints we use (see Figure 11). These welds are theoretically stronger because the weld length is longer in the coped case than the mitered case. There are only a couple instances of these because they have an increased risk of getting dirt in these during competitions, which would be very difficult to remove. We will be plugging these holes with rubber caps.

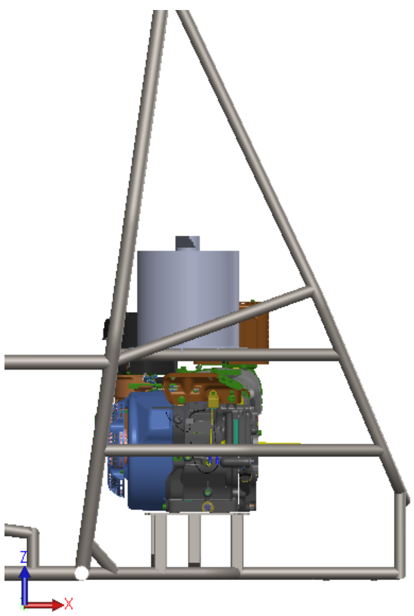


(a) (b)

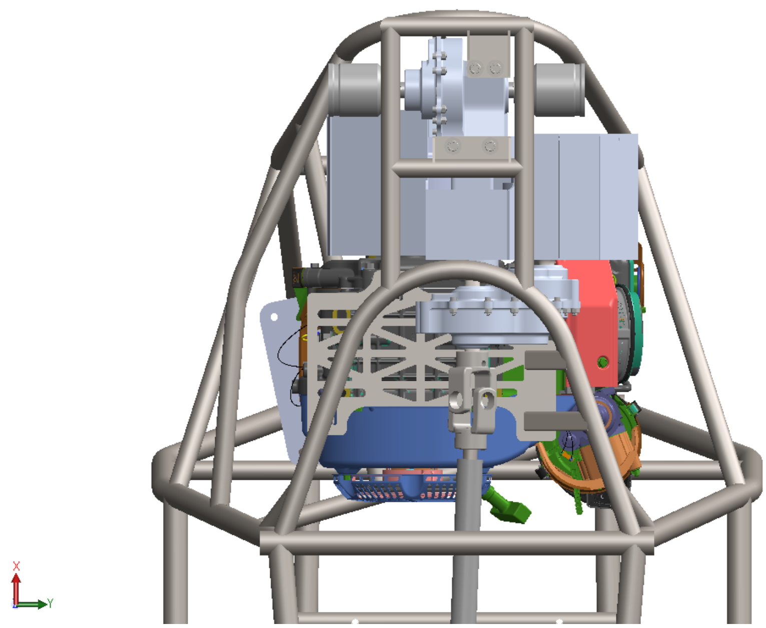
Figure 11. A (a) coped joint of 4.88" weld length vs. a (b) mitered joint of 4.54" weld length.

Fuel System Containment and Interference Check

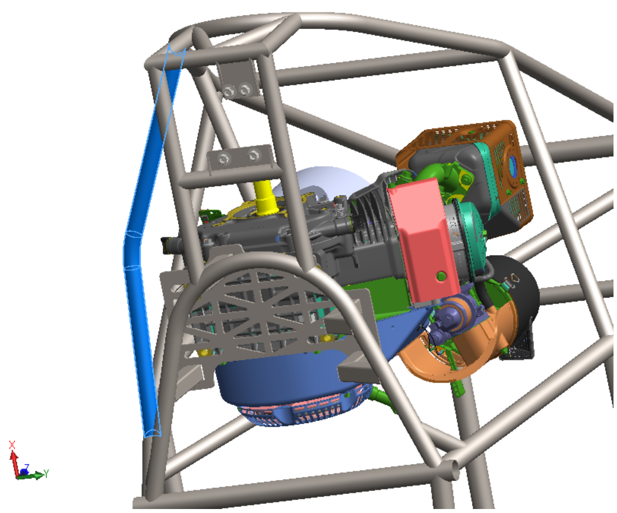
According to rule B.6.3, “The entire fuel system, including fuel tank, fuel hoses, fuel mounts, carburetor, air cleaner cover, splash shield, and engine must be located within the envelope of the vehicle’s roll cage.” Thus, it is important that we check that these components are well within the limits of the roll cage. See Figure 12 for checking the containment of fuel components within the frame. Notice that an extra tube had to be added to protect the engine on the left side of the car. Additionally, the air cleaner cover currently sticks out past the RRH in the model, which would lead to interference with the “firewall” that is supposed to be installed on the front of the RRH. This cover will be rotated in real life, such that it does not interfere with the firewall.



(a)



(b)



(c)

Figure 12. Different angles to check that the fuel components fully fits in the frame of the car, including a (a) side angle, an (b) underside angle, and an (c) an angle that demonstrates the addition of a tube on the left of the car to shield the engine. Notice from the side angle that the air cleaner cover sticks out past the RRH. This component can be rotated in real life to prevent this interference.

Then, we conduct an interference check to ensure that the differentials do not interfere with the frame. This can easily be done with the interference detection tool as demonstrated in Figure 13, making sure that “Treat subassemblies as components” is checked. This is done on both the front and back differentials.

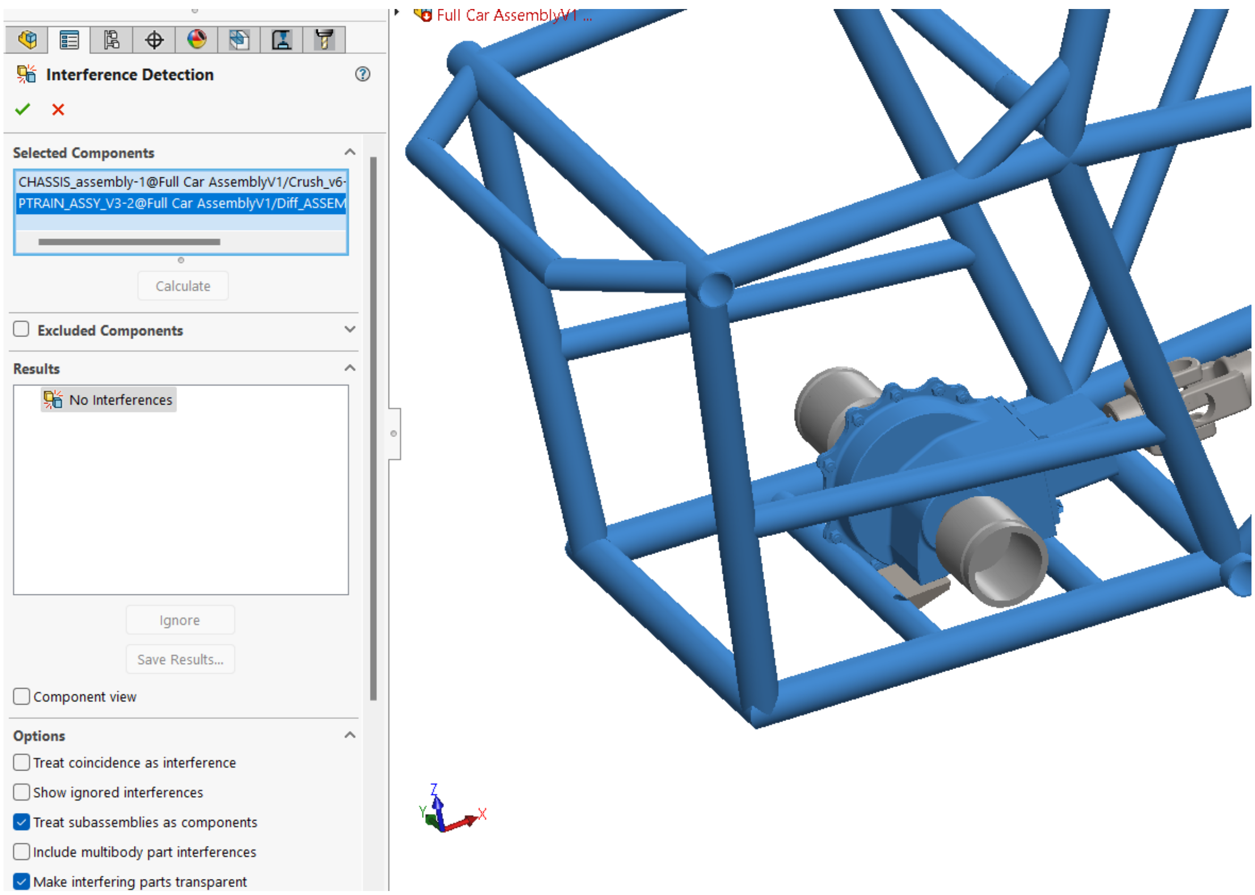


Figure 13. Interference detection for front differentials and the frame.

3. FEA Analysis

3.1. Load Cases

Baja traditionally tests four static load cases, which are the extreme cases that are all possible to occur during the actual competition:

1. Front impact
2. Roll over

3. FBM impact (45° impact)
4. Rear impact

Unfortunately, the team does not have good data for impact forces as this would require purposefully impacting the car at top speed, which could be very unsafe for the driver. We also do not take data on the car during competitions; however, that is something that we plan on doing this year. Yet, the team has still come a long way in calculating the impact load cases. In 2014, load cases of 40,000N were used, which corresponds to $16g$'s of force—more than enough to knock the driver unconscious and even be fatal. More recently, frame designers has been using gross over-approximations of the car's final weight and assuming a max acceleration of $5g$'s. This has led to a load case of 13,300 for the 2021 and 2022 cars. Now it is worth noting that the frame has never failed in previous cars. This is largely a result of the rules put in place by Baja SAE, which ensures that all drivers will remain safe, even if the team cannot perform FEA. With that said, FEA is still important to prevent the frame from yielding during impact and being pulled out of the endurance race. Thus, we look for a better way to estimate the load cases.

To calculate the impact load, we use the impact equation $F_{avg} = m\Delta v/\Delta t$, where m is the mass of the car, Δv is the change in speed from top speed to zero, and Δt is the time of impact. Last year, the total weight of the car with all its components was 473 lbs, and we measured that it went a top speed of 23 mph. By the time of doing FEA, the frame had saved 16 lbs and powertrain had saved at least 10 lbs (with much more savings projected). Thus, this analysis assumed this year's car to weigh 450 lbs; however, it will likely be even lighter. The maximum weight of a driver who will be driving the endurance race this year is 165 lbs, making a combined weight of 615 lbs. By decreasing the weight of the car, we hope to increase the speed of the car. Thus, the top speed is assumed to be 25 mph. The impact time is assumed to be 0.25 s.

$m = 615 \text{ lbs} = 278.96 \text{ kg}$

$\Delta v = 25 \text{ mph} = 11.18 \text{ m/s}$

$\Delta t = 0.25 \text{ s}$

$$F_{avg} = m\frac{\Delta v}{\Delta t} = (278.96 \text{ kg})\frac{11.18 \frac{\text{m}}{\text{s}}}{0.25 \text{ s}}$$

$$F_{avg} = 12{,}470.59 \text{ N}$$

We can cross verify this by calculating how many g's of acceleration this corresponds to.

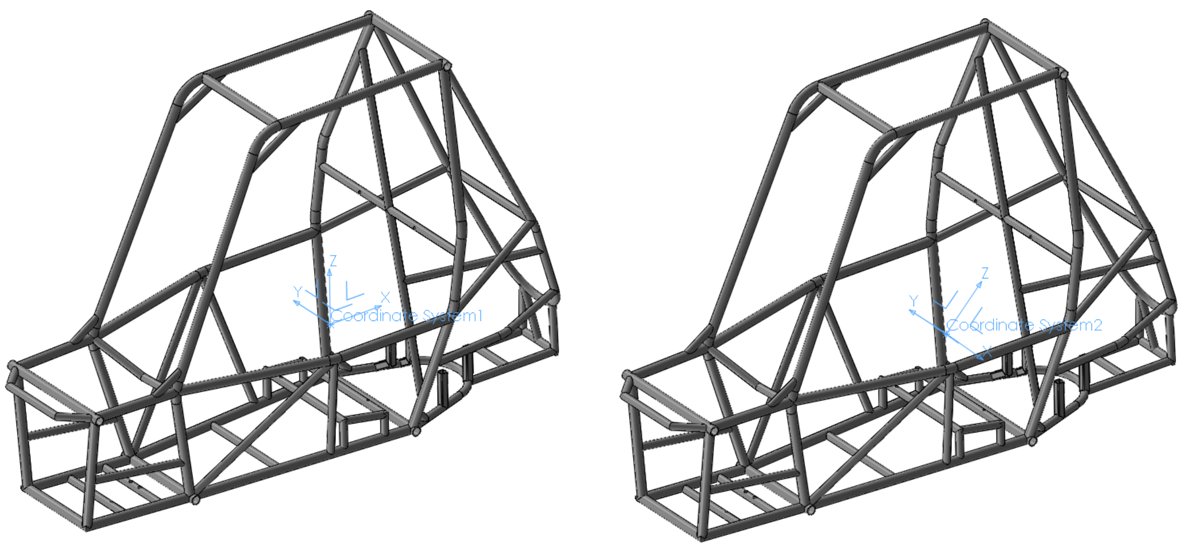
$$g's = \frac{F}{m(9.81 \text{ m/s}^2)} = \frac{12470.59 \text{ N}}{(278.96 \text{ kg})(9.81 \text{ m/s}^2)}$$

$$g's = 4.56$$

This is a reasonably high amount of acceleration, as this is already enough acceleration to have serious physical damage on the driver. We use a 12,500 N impact force for all impact cases except rear impact, which we will discuss further later.

3.2. Setting up FEA

The FEA was performed in SolidWorks Simulation. First, the center of mass was estimated using SolidWorks' built-in center of mass tool on the full car assembly and then decreasing the height a bit to account for the driver. The center of mass was estimated as $(x, y, z) = (-5.8618, 0, 13)$. A coordinate system was made at the center of mass with axes aligned with the global coordinate system, and then a secondary coordinate system was made by offsetting the first coordinate system by 45° (see Figure 14). The latter will be used for the FBM impact case.



(a) (b)

Figure 14. Two coordinate systems setup at the center of mass. (a) One that is aligned with the global coordinate system, and (b) another that is 45° offset about the y-axis.

Once doing this, a static simulation was created in SolidWorks, and the material "AISI 4130 Steel, annealed at 865C" was applied to all the bodies. All the bodies were treated as beams, which drastically simplifies and speeds up calculations by breaking up a beam into elements along the length instead of small tetrahedrons along all surfaces of the tube. We can make this beam assumption because the tubes have a high diameter to length ratio and a constant cross-section. Each element is given a width of 0.2" and a height to base ratio of 1.4. We want the largest elements possible, while not sacrificing that much accuracy. If we compare the max stress from the front impact case calculated with a width of 0.05", we see that it is the same (up to four significant figures) as with a width of 0.2" (see Figure 15). Note that meshing took over a minute with 0.05" elements, while it took less than 10s with 0.2" elements.

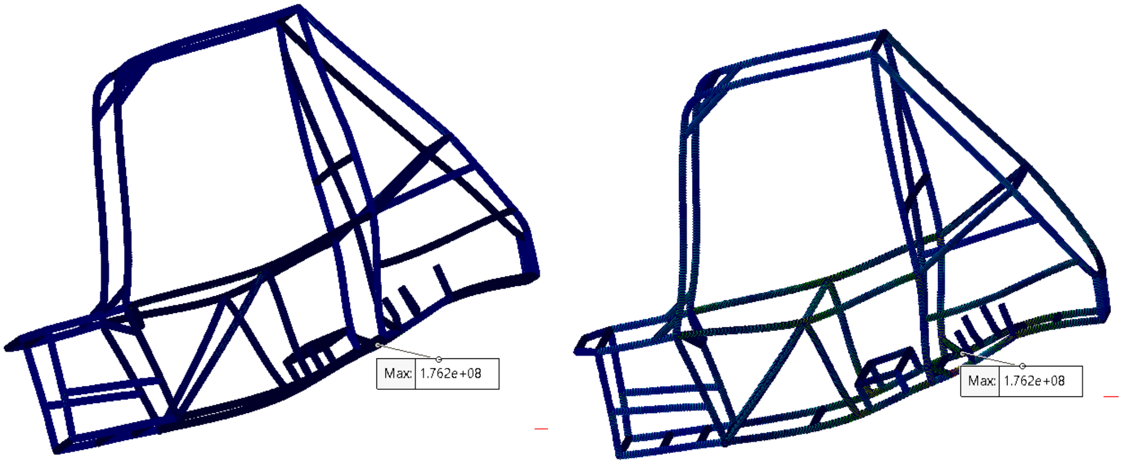


Figure 15. Max stress from front impact for an element width of (a) 0.05”, compared to (b) 0.2”.

Front Impact

The front impact case simulates the car crashing at full speed into a rigid wall. Four nodes are fixed at the front of the car and a remote load is applied at the center of mass pointing towards the front of the car (using the first coordinate system). This makes sense as a rigid wall impedes motion of the front of the car, and the momentum of the rest of the car will be into the wall, putting the car in compression. The remote load allows us to simulate the impact on the frame without including the rest of the car assembly in the model. The remote load nodes were chosen as shown in Figure 16.

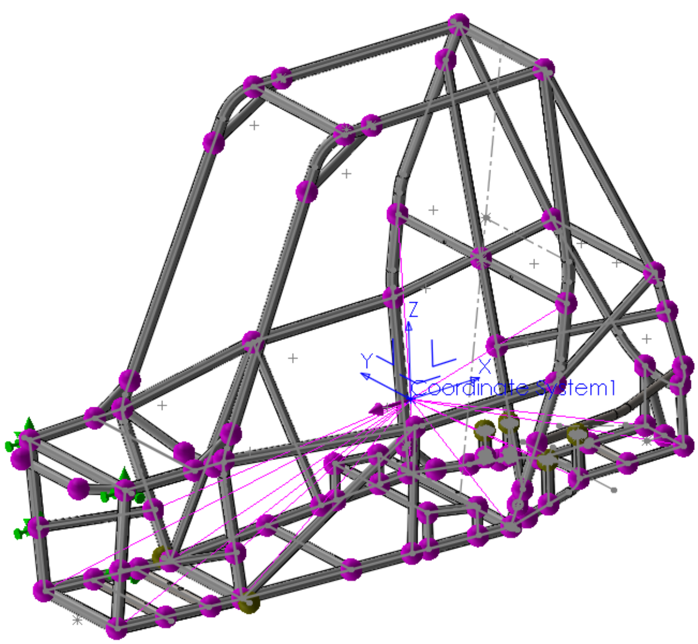


Figure 16. Front impact case FEA setup. Green nodes are fixed, and the lines show the nodes that are connected to the remote load.

Roll Over

The roll over case simulates the car flipping and landing upside down on the RHO members. In this case, there are four fixed points at the top of the car, and the remote load points upwards using the first coordinate system (see Figure 17).

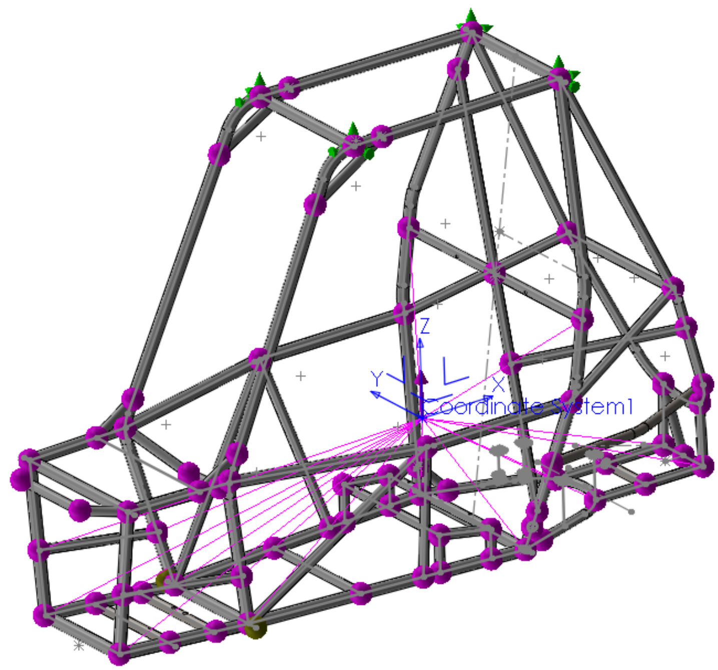


Figure 17. Roll over case FEA setup. Green nodes are fixed, and the lines show the nodes that are connected to the remote load.

FBM Impact

The FBM impact case simulates a partial roll over case, in which the card is impacted at an angle. Thus, the four points are fixed that correspond to the nodes that would get hit at an angled impact (note that we do not care about the tubes in front of the toe box as these are not structural members, they are required by rules in case the car must be towed off the track). The remote load is angled 45° towards the FBM as shown in Figure 18.

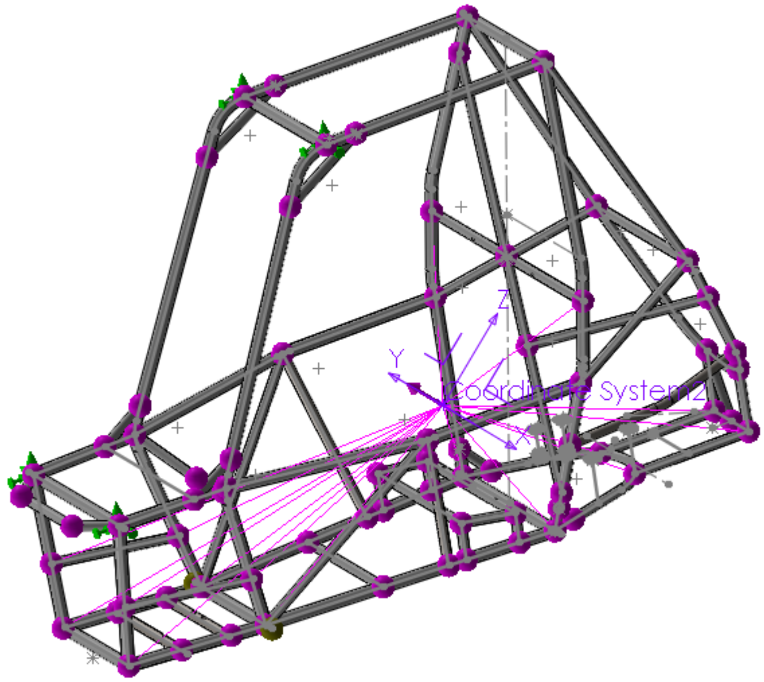


Figure 18. FBM impact case FEA setup. Green nodes are fixed, and the lines show the nodes that are connected to the remote load.

Rear Impact

The rear impact case tests impact from the back by another car. This case has been notoriously difficult to pass with the current load case without the addition of inner trusses that would make it impossible to fit powertrain components. However, using the force calculated is a wild overestimate because it assumes that the car crashes into a rigid wall at full speed backwards, or another car impacts our car while our car does not move at all. The first case is impossible, as we do not have the ability to back up the car. The second case is highly unlikely because cars that get stuck on a tree/wall are quickly pulled out to avoid getting impacted by another car and sandwiched. Thus, the only instances of rear collision is really when

1. a faster car impacts our car from the back while we are going close to top speed, or
2. if our car was idle while waiting for obstructions on the track to clear up, and a car impacts at full speed from behind.

In case 1, we can calculate the new impact force by assuming a difference in top speed of 15 mph (6.71 m/s). In case 2, we assume that the other car can have a max speed of 35 mph (15.65 m/s), but the impact time doubles such that Δt is 0.5s, since our car rolls forward after impact.

$$F_{rear,1} = (278.96\ \mathrm{kg})\frac{6.71\,\frac{\mathrm{m}}{\mathrm{s}}}{0.25\ \mathrm{s}} = 7{,}482.35\ N$$

$$F_{rear,2} = (278.96\ \text{kg})\frac{15.65\,\frac{\text{m}}{\text{s}}}{0.5\ \text{s}} = 8729.41\ N$$

Because the second case shows a great force, a value of 8,800N was used for the rear impact analysis. Previous years have fluctuated between choosing the FAB as the fixed points and the small square at the rear of the car. Years that have chosen the square have had very large rear squares (a foot in height) or the cars have had really high ride heights. This year, the car's ride height has been decreased and the small back square is only half a foot in height. Thus, fixed points for this case were chosen as four points on the FAB, since it is likely that other cars would impact the FAB much more than the small square. The remote load faces towards the back of the car and uses the first coordinate system (see Figure 19).

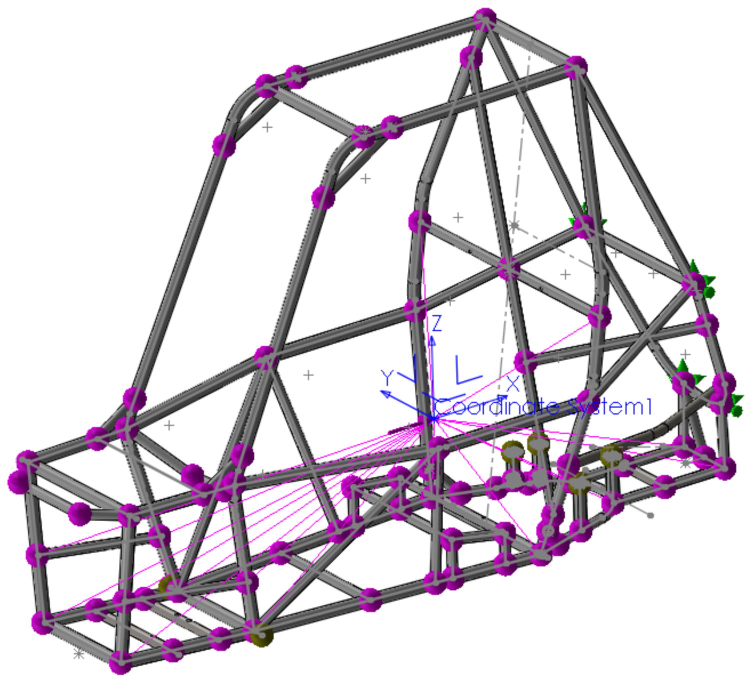


Figure 19. Rear impact case FEA setup. Green nodes are fixed, and the lines show the nodes that are connected to the remote load.

3.3. FEA Results

For each case, we aim for a factor of safety of at least 1.2. This is a somewhat high factor of safety because we do not have good data or methods of testing. For the following results, we care the most about the factor of safety plots, which are based on the yield strength of the material and the calculated von Mises stress throughout the frame. The von Mises stress is used because it is a single quantity that describes the combined effect of complex three-dimensional stresses. This single value can be compared to a uniaxial stress limits to determine yielding or fracturing in a material. While this section highlights factor of safety plots, the stress plots are included in Appendix A.

Front Impact

For front impact, the factor of safety was pretty high, at 2.61 (see Figure 20). Normally, we would like to be closer to our goal of 1.2, but there was not much that could be done to reduce weight without compromising the other factors of safeties.

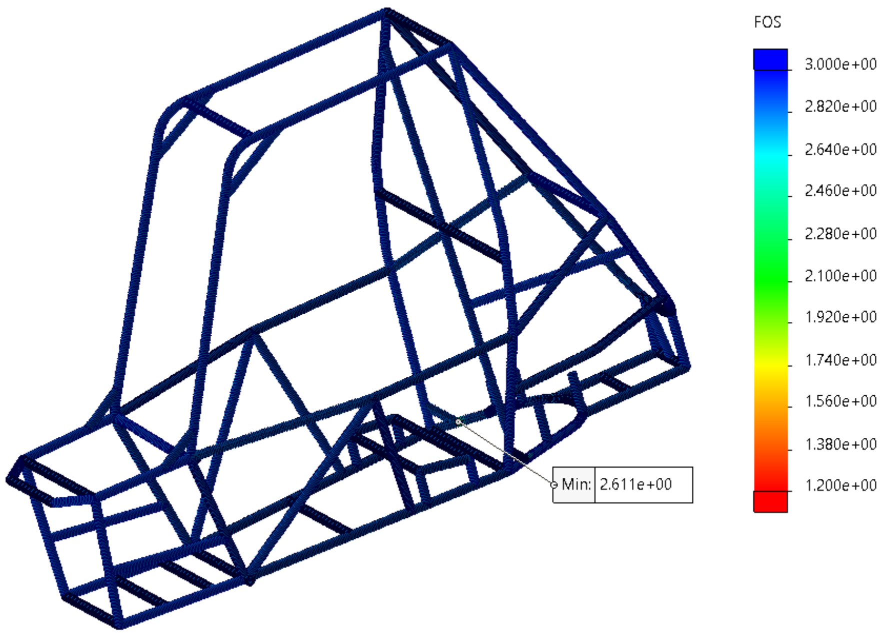
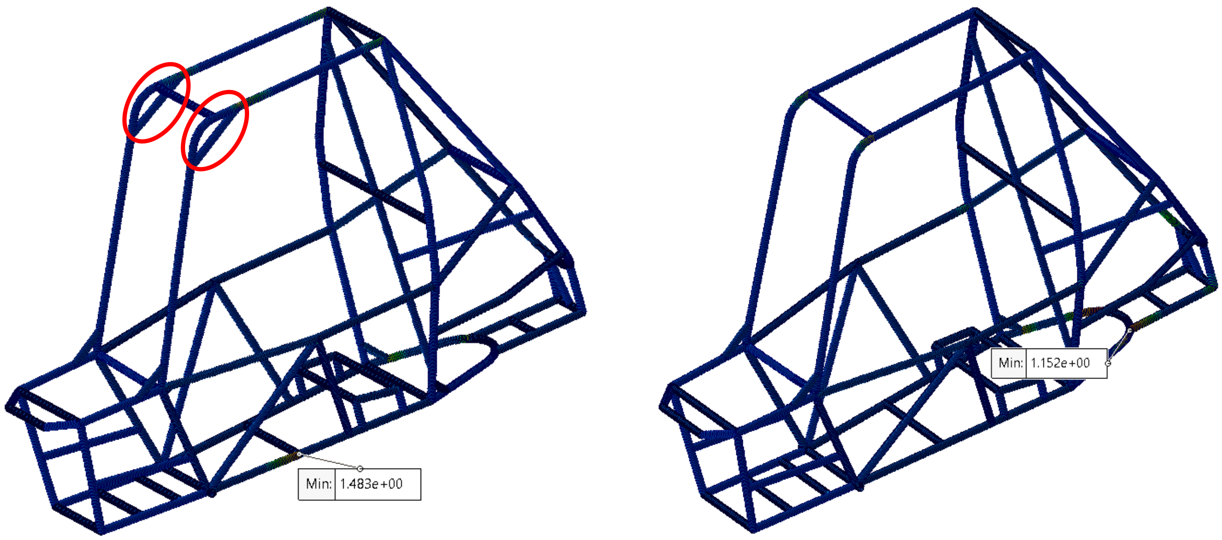


Figure 20. Factor of safety plot for the front impact case.

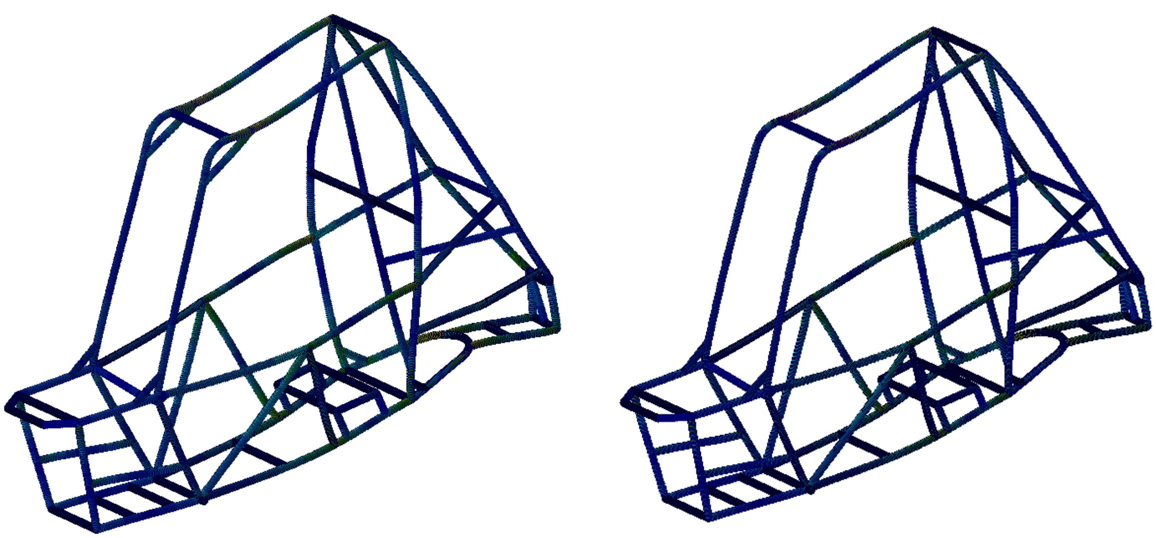
Roll Over

The roll over case also had a somewhat high factor of safety of 1.48 (see Figure 21a). This is because gussets were added between the RHO and FBM members. Before adding these gussets, Figure 21b shows that this case was not passing FEA. It was found that thickening the tubes in the weak area to get above the 1.2 factor of safety would add more weight than adding the gussets shown. Just by looking at the factor of safety plots, it is not very intuitive why these gussets should drastically increase the factor of safety. However, if we look at the stress plot without gussets (see Figure 22b), we see that that the FBMs are allowed to flex so much that they take very little of the load. By adding the gussets, as shown in Figure 22a, the FBMs are restricted from flexing as much and now take more load.



(a) (b)

Figure 21. Factor of safety plots for the roll over case (a) with RHO/FBM gussets and (b) without RHO/FBM gussets.

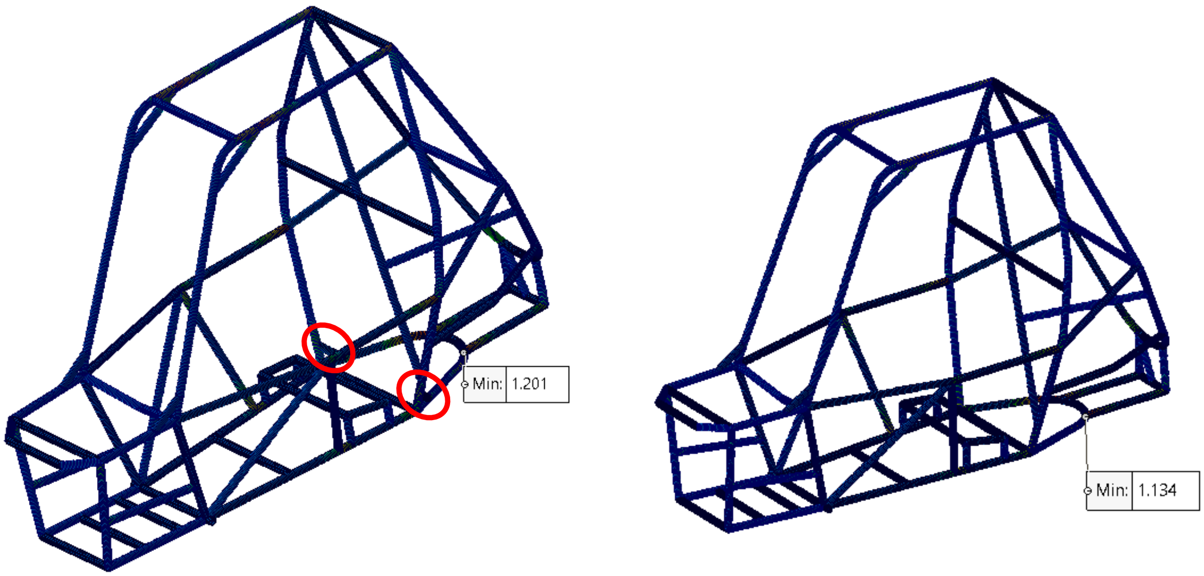


(a) (b)

Figure 22. Stress plots for the roll over case (a) with RHO/FBM gussets and (b) without RHO/FBM gussets.

FBM Impact

The FBM impact case has a factor of safety of 1.20, which is exactly on target (see Figure 23a). To pass this case, small gussets had to be added to the RRH (see Figure 23b, where FEA was not passing). These gussets allowed FEA to pass because it braced that bottom section against the RRH; thus, drastically decreasing the amount of deflection allowed in that area and causing the RRH to take more of the load.



(a) (b)

Figure 23. Factor of safety plots for the FBM impact case (a) with RRH gussets and (b) without RRH gussets.

Rear Impact

Finally, the rear impact case has a factor of safety of 1.27 (see Figure 24). Getting this to pass included thickening the tubes in the rear square to 0.058" wall thickness and adding a gusset inside the rear back square (see Figure 25). This gusset is asymmetric to avoid interference with the differential housing.

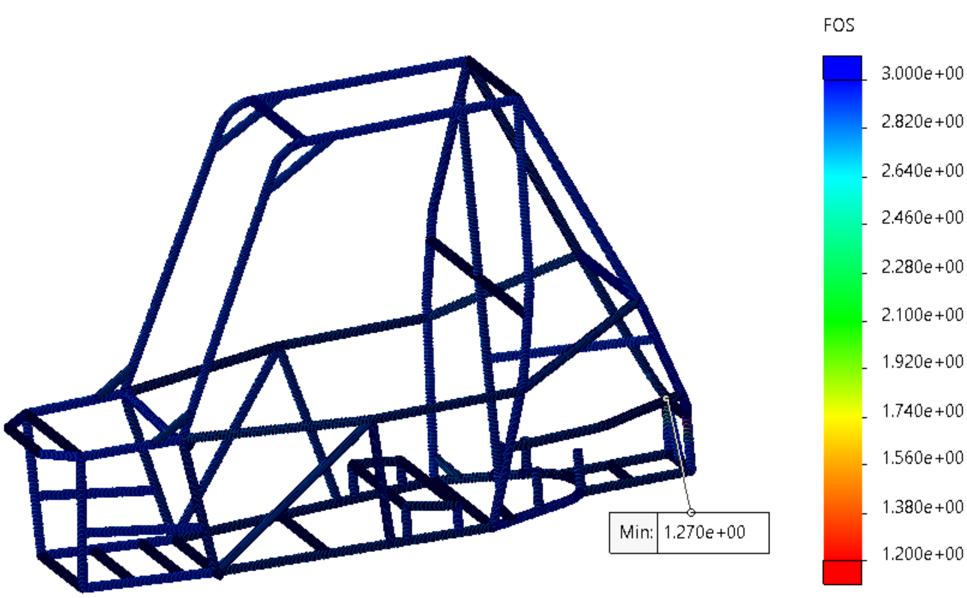


Figure 24. Factor of safety plots for the rear impact case.

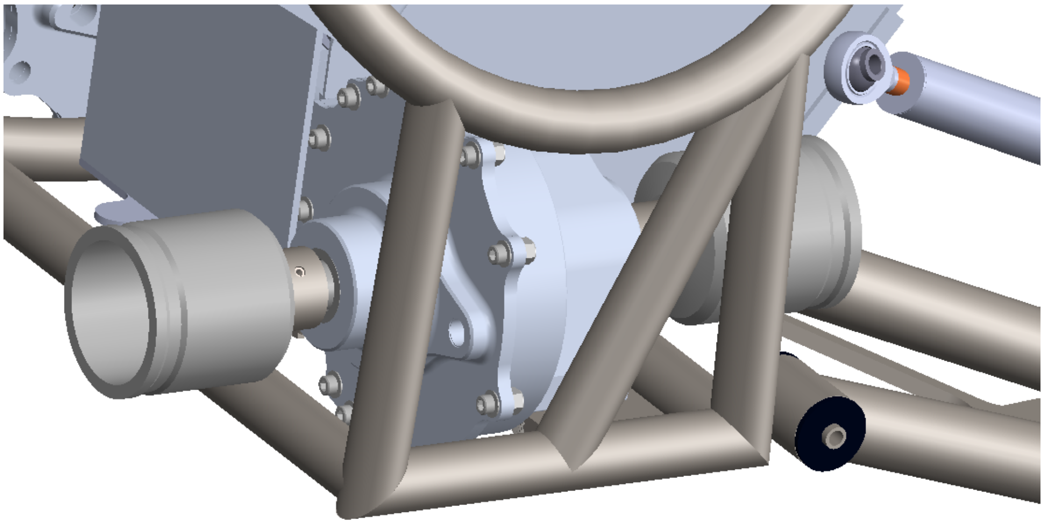


Figure 25. Gusset added in the back of the car.

4. Conclusion

The final frame model is shown in Figure 26. There were a couple major changes that were made to reduce the quantity of tubes. This year, a lot more bent tubes were utilized to combine multiple tubes.

1. The FBM_{UP} and FBM_{LOW} were combined into a single tube, compared to last year where it was two tubes (see Figure 27).
2. The FAB members on the back of the car were also combined into a single tube. In previous years, it was five separate tubes.
3. The tubes under the powertrain were also combined into a "U" shape, which used to be three separate tubes last year.
4. The car was narrowed by making the RRH an octagon instead of a hexagon.
5. A couple tubes were also removed, such as the tubes above the FAB_{MID}. These tubes have been on the car for the past two years, but are not necessitated by rules and the frame passed FEA without them.
6. Secondary members used to be 0.049" wall thickness, but were replaced with 0.035" wall thickness secondary members instead of 0.049".

The comparison of this year's car to last year's car is outline in Table 2. The resulting frame is 60.71 lbs and made of 69 tubes. The length is slightly longer than last year as a result of the larger engine. Thus, the design goals were achieved this year, including decreasing the weight of the car by 20% and quantity of tubes by 14.8%.

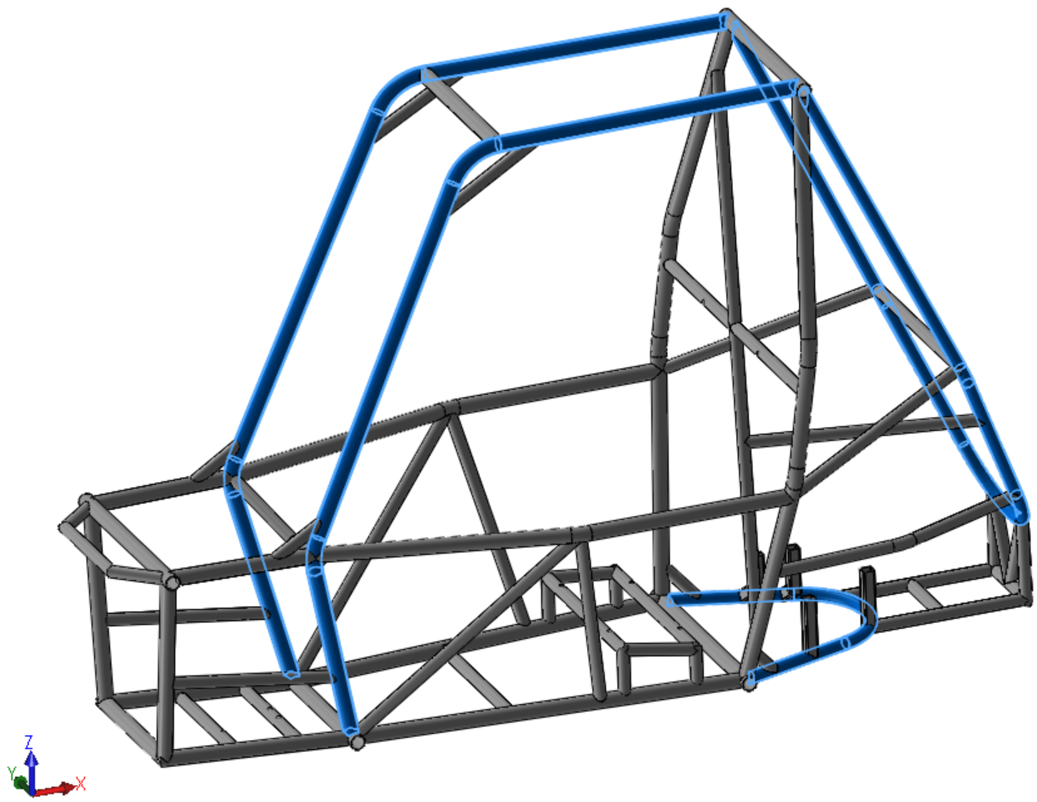


Figure 26. Final frame design. Highlighted tubes show major changes.

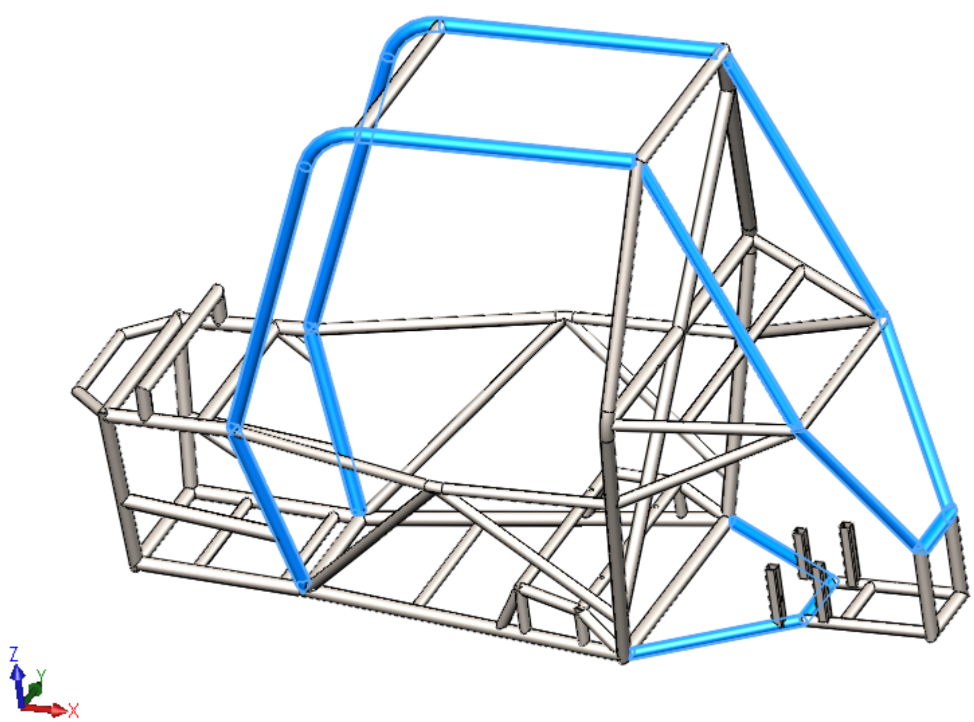


Figure 27. The 2022 frame with major change areas highlighted.

Table 2. Comparison of the 2022 and 2023 frame metrics. The weight, quantity of tubes, and width have decreased, while the height and length have increased negligibly.

Year	Weight (lbs)	# Tubes	Height (in.)	Width (in.)	Length (in.)
2022	76.14	81	50.39	34.42	75.44
2023	60.71	69	50.46	31.00	75.72
% Change	-20.03	-14.81	+0.10	-11.03	+0.37

While this report presented the design of the frame in a very streamlined way, the reality was not nearly as linear. The initial design phase was daunting and involved reading design docs from previous leads. A basic frame was first made, with all the minimum requirements as established by Baja SAE guidelines. There is a constant back-and-forth between the chassis lead and other sub-team leads, trying to make sure there is enough room to fit everything but also wanting to keep the frame as small and light as possible. It is important that by the time the frame is sent out to VR3, all the sub-teams have finalized placements of major components, such as powertrain components and suspension points.

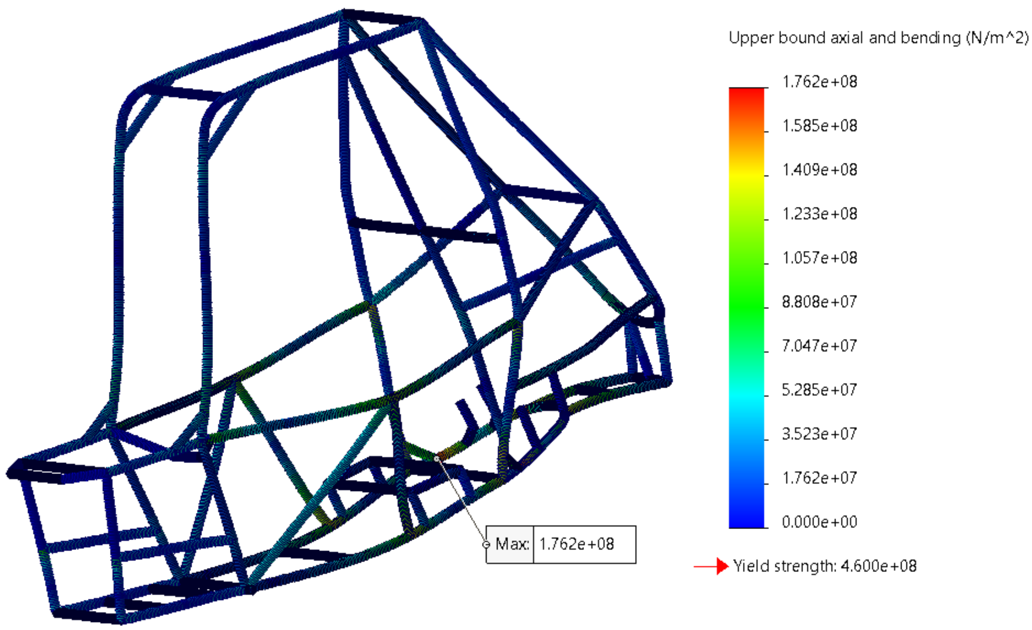
The FEA stage is another cycle of constant iterations. Thus, it is important to carefully analyze FEA results before going into a new iteration because mindlessly adding gussets or thickening tubes will be time-consuming and often fruitless. By looking at the stress concentration plots, we can see the location of weakness. At this point, there are a couple options: thickening tubes in that area/increasing the diameter to increase the stiffness, adding gussets in that area to increase the stiffness, or decreasing the stiffness in that area to allow the load to be distributed to stiffer parts in the frame that can better take the load. The first two options have the same effect; however, the second option will typically increase the stiffness with less added weight because it allows the load to be redistributed to multiple tubes. The first option does not change the load distribution, but allows the same tube to bear more load since the cross sectional area increases (and $\sigma = P/A$). Such a reasoning can be seen in the typical truss design of bridges, where more trusses are added to increase the amount of load the structure can bear, instead of increasing the cross section of the beams.

The documentation that was sent to VR3 is included in Appendix B. When the tubes arrived, the frame was welded by two other members of the Baja team, Frank and Laura. Both have been involved with welding the frame in previous years. Frank mentioned that having lots of continuous tubes really decreased the amount of welding that had to be done, and thus welding this frame is seemingly much quicker than in previous years. Laura mentioned that decreasing the wall thickness makes welding a bit more difficult, as thinner walls makes it much easier to melt right through a wall and make a hole. As of the writing of this report, the frame is about 80% welded (see Figure 28).

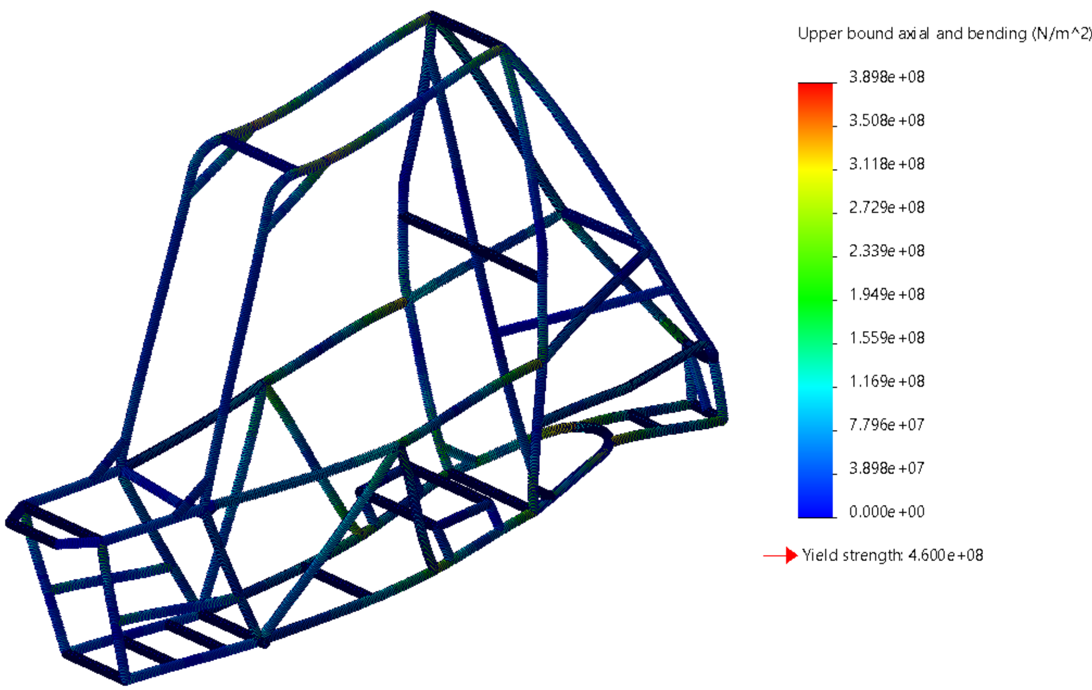
Figure 28. Current state of frame welding.

Appendices

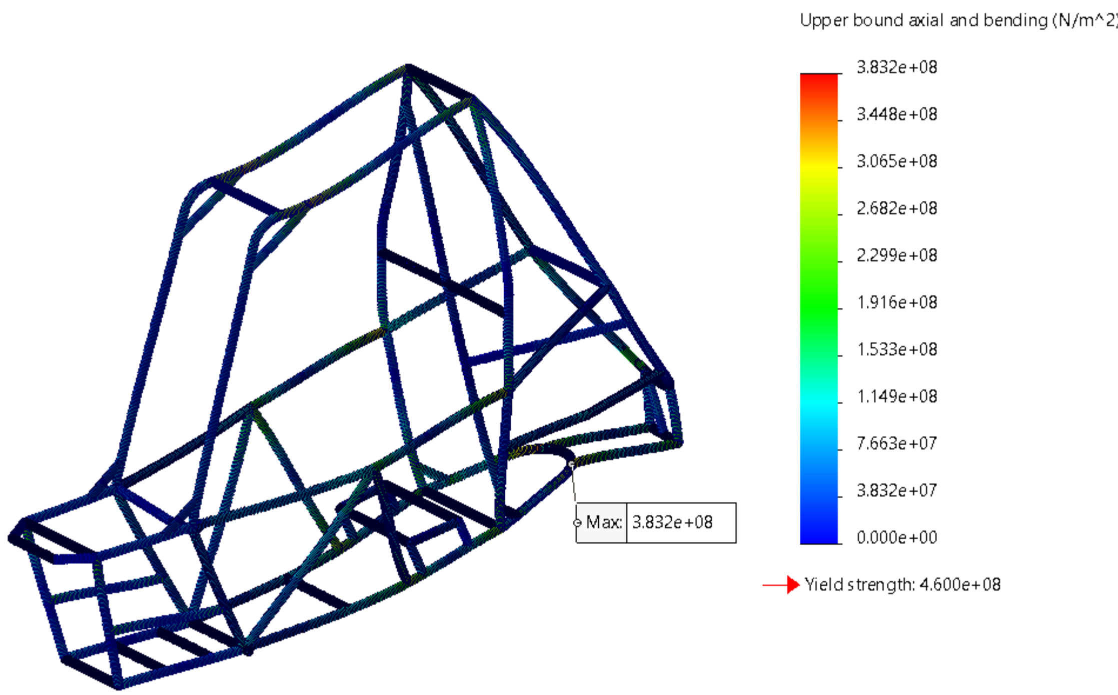
Appendix A: Von Mises Stress Plots



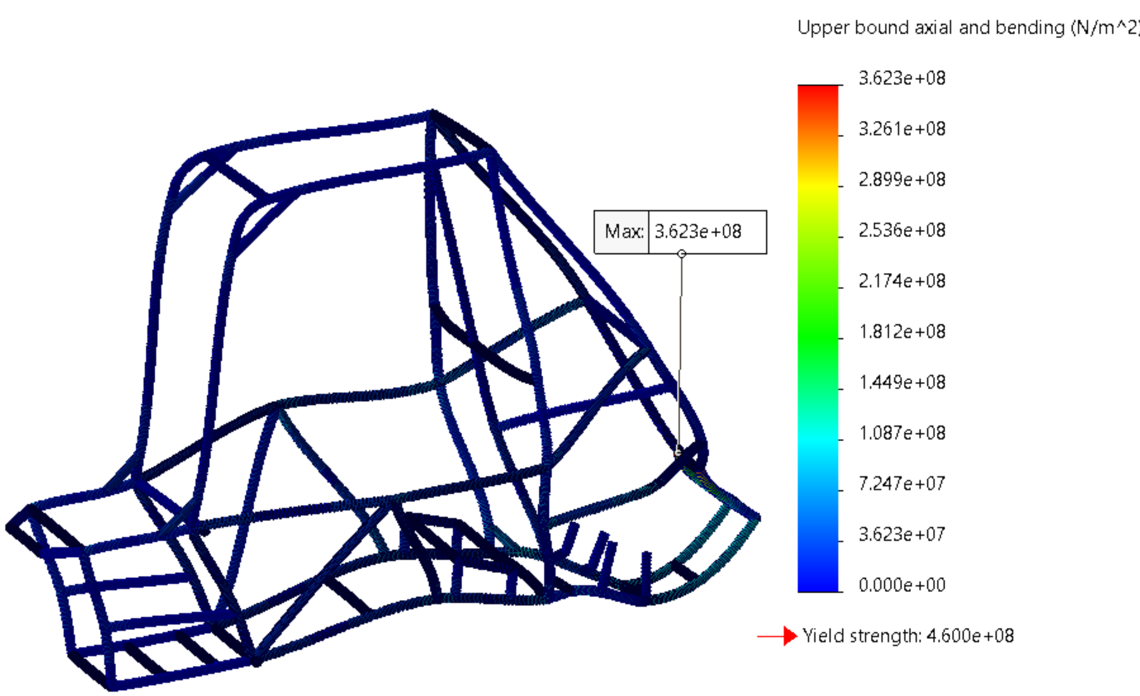
Von Mises stress for front impact.



Von Mises stress for roll over case.



Von Mises stress for FBM impact.



Von Mises stress for rear impact