SAE Mini Baja Frame Analysis

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Team 01

Analysis of the Baja Frame

Document

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Mechanical Engineering Design I – Fall 2013

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Contents

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. 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. The frame will be physically tested in early January to confirm our predictions before the competition in April 2014.

Introduction

Off-road race vehicles are required to navigate rough non-paved terrain while maintaining competitively high speeds. For this competition the vehicle will compete in a 4 hour endurance event in which it must navigate terrain with jumps, logs, rocks, mud, and hills all while maintaining a speed of 20-30 mph. The frame needs to be designed to handle the regular shock loads constant impacts from jumps and drop offs. It also must be able to ensure driver safety during extreme impacts and collisions.

The frame for the SAE Baja is a space frame, which is a truss style structure deriving it’s strength from the rigidity of interconnecting triangular frames. Loads are transferred through either bending moments or axial forces [1]. In the design concept selection the team chose to use AISI 4130 steel tubing with 1.25” diameter and 0.065” wall thickness to construct the frame. The frame design chosen in the design concepts selection became frame version 5. Since then it has been gradually modified and improved, to the current frame version 8. This analysis includes frame versions 5, 6, 7, and 8.

SolidWorks Simulation

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 1. Frame Analysis For the analysis of the solid frame components, tetrahedral elements were used, as shown in Figure 2. 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.

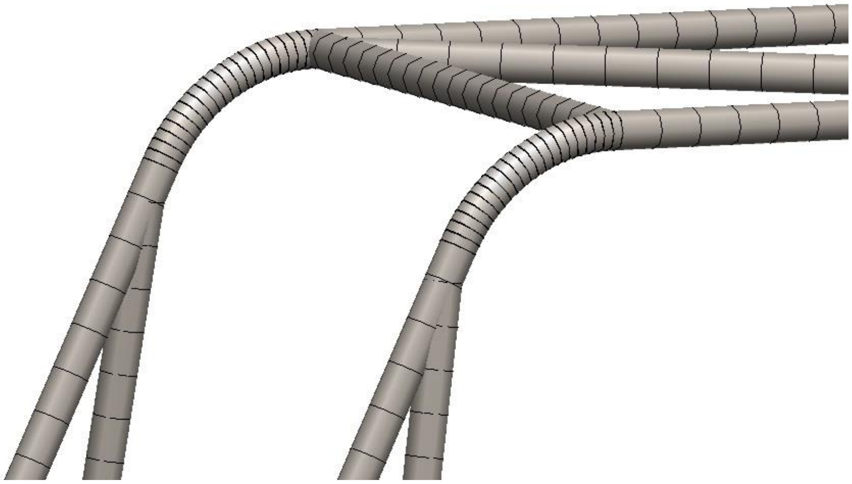


Figure 1. Frame Analysis

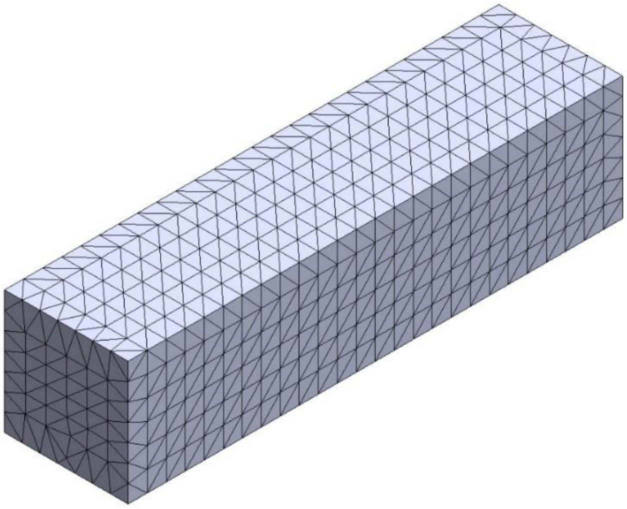


Figure 2. Tab Analysis

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.

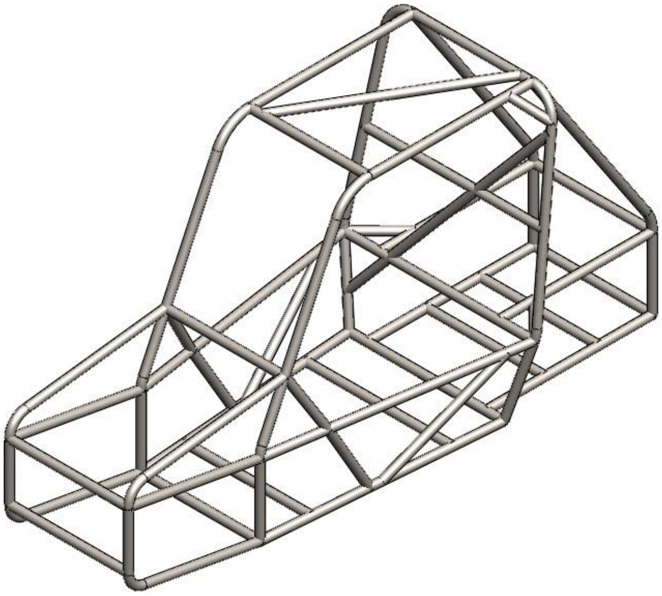


Figure 3. Design 5

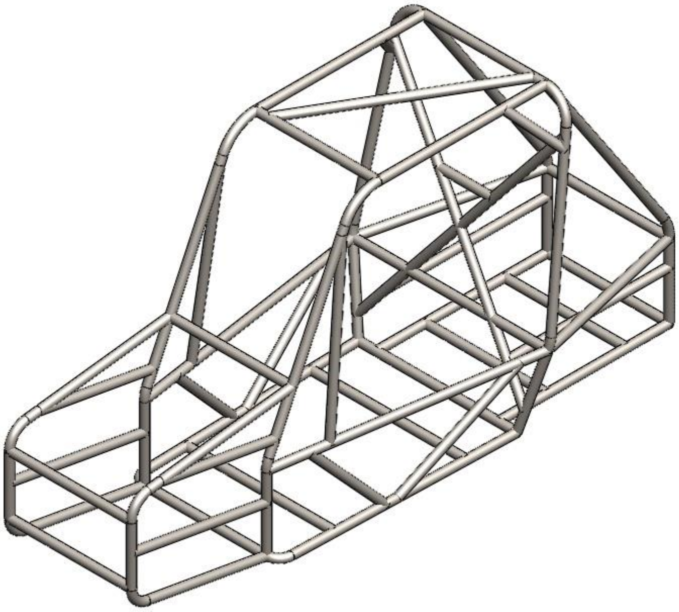


Figure 4. Design 6

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.

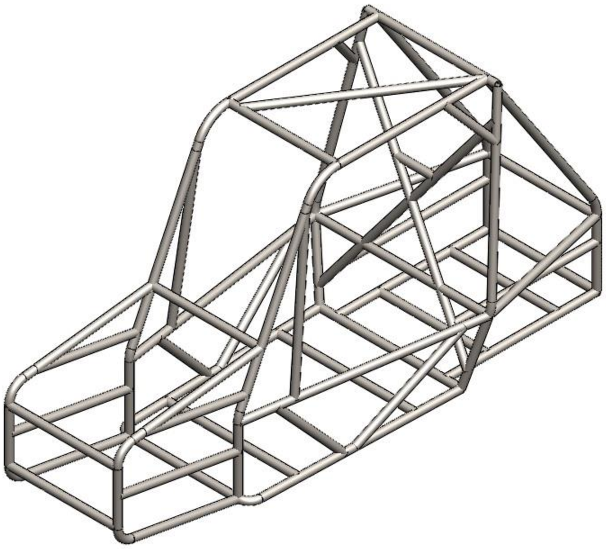


Figure 5. Design 7

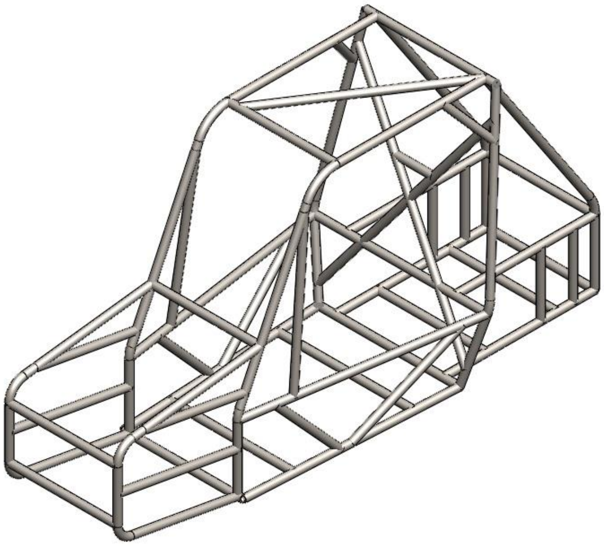


Figure 6. Design 8

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 1.

Table 1. 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.

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.

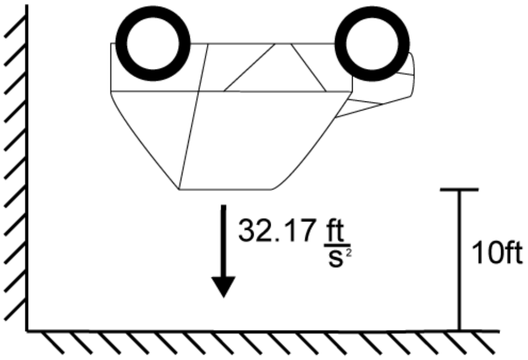


Figure 7: Drop Test

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 8. 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 9). 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 10). 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.

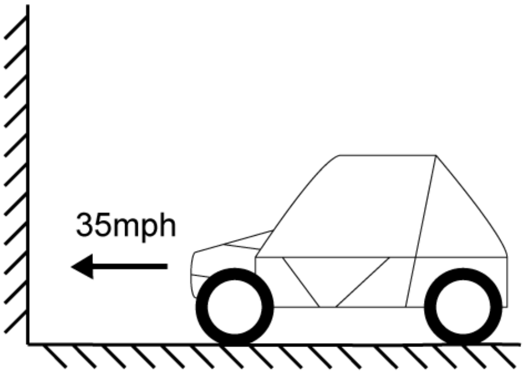


Figure 8: Front collision Test

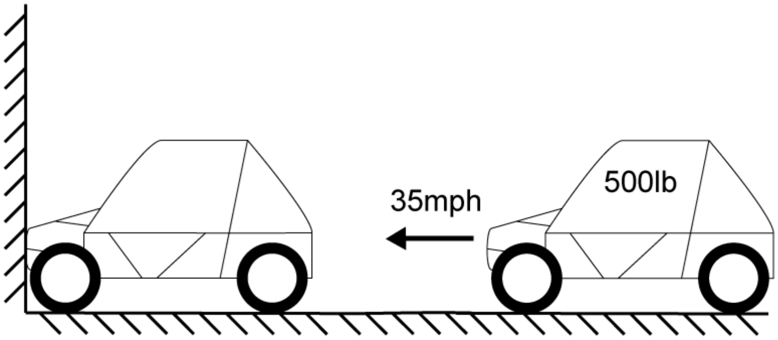


Figure 9: Rear Collision Test

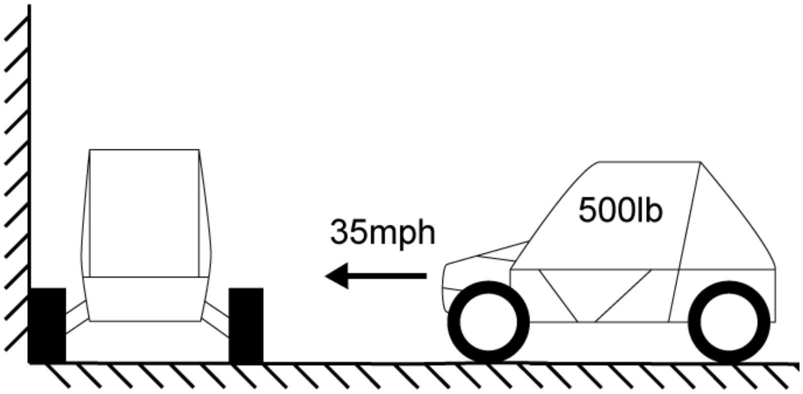


Figure 10: Side Collision Test

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

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 11 shows an example loading condition with the various loads applied in the correct locations.

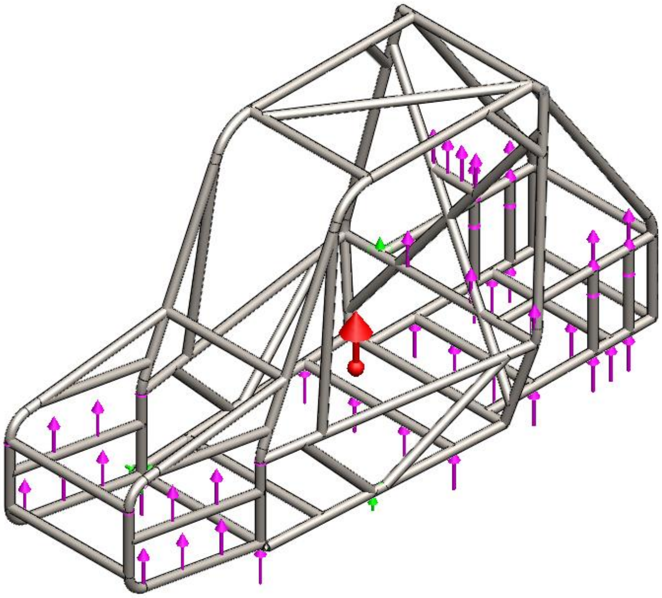


Figure 11. Example Frame Loading

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 2 shows the maximum displacements and the minimum factor of safety for each test.

Table 2. 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.

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 3. 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 B 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.

Engineering Design Targets

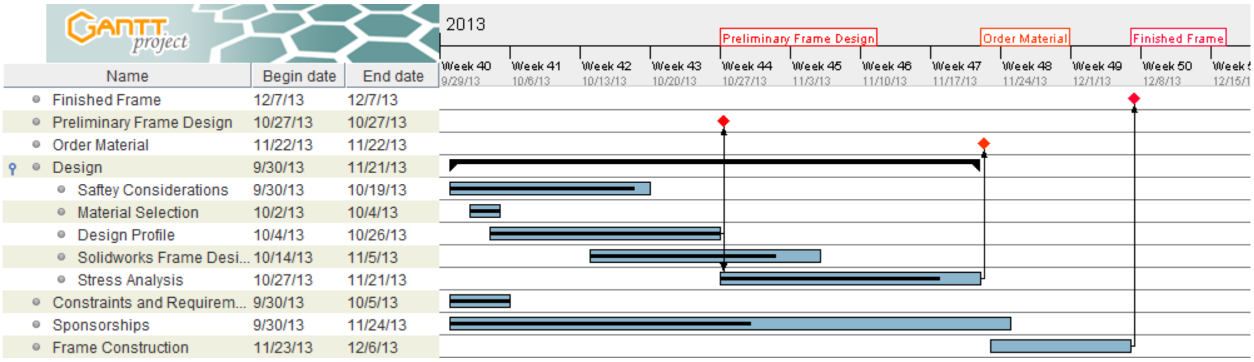
The following table lists our engineering design targets from the QFD matrix and compares them to the actual values of our current frame design. All of the targets have been met with the exception of the frame height. The original requirement was unrealistic because of the required empty space between 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 4. 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

Project Plan

The team is currently on schedule to complete the frame by the end of the semester. Since the last report the team has completed the design profile task and met the original deadline for the stress analysis. Some additional time has been allocated to verify the analysis results and make any further design modifications. The team is still distributing the donation packet to companies to ask for donations. An order for the material has also been submitted. The team is waiting on a reply from Page Steel to see if they will donate the steel or if the team has to purchase it. If everything continues according to plan, the frame will be completed by the end of the semester.



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 12: Team 01 Gantt Chart

Conclusion

The team's goal is to build the lightest possible frame to maximize performance. Four iterations of the frame design were analyzed. A simple loading case was applied to the different frame versions, and the frame design with the highest factor of safety was chosen for more in-depth analysis. A drop test, front collision test, rear impact test, and side impact test simulations were performed. Basic assumptions were made in order to perform the impact simulations. Version 8 of the frame passed all the tests with a minimum yield factor of safety greater than 1. The tabs for the safety harness and the suspension components were also analyzed. Both are well within the safety limits. The team is currently on schedule to complete the vehicle frame by the end of the semester, and some extra time was allocated to verify the stress analysis on the frame. This will allow the team to perform any additional calculations and design modifications before the frame material arrives.

References:

Owens, T., Anthony, Jarmulowicz, D., Marc, Jones, Peter "Structural Considerations of a Baja SAE Frame," SAE Technical Paper 2006-01-3626, 2006.

Tester, John, Northern Arizona University, personal communication, Nov. 2013.

Appendix A: Frame Simulation Results

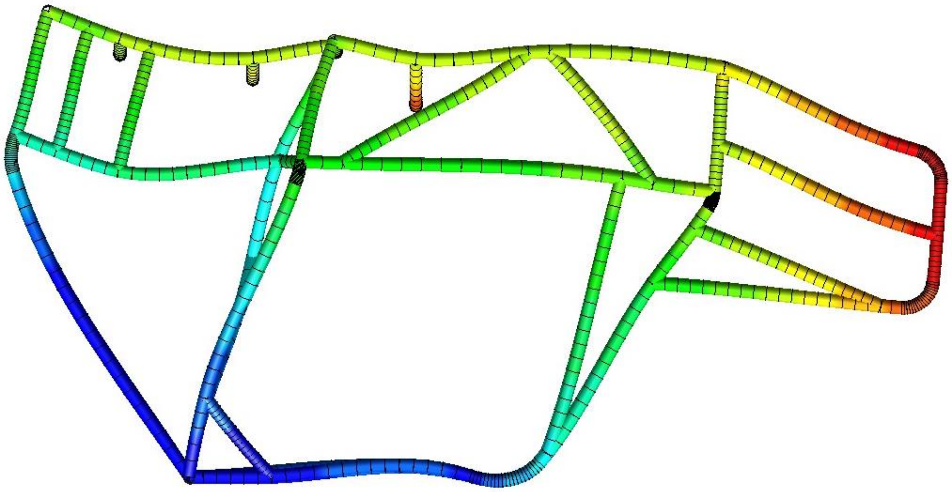


Figure 13. Drop Test Deflected Shape

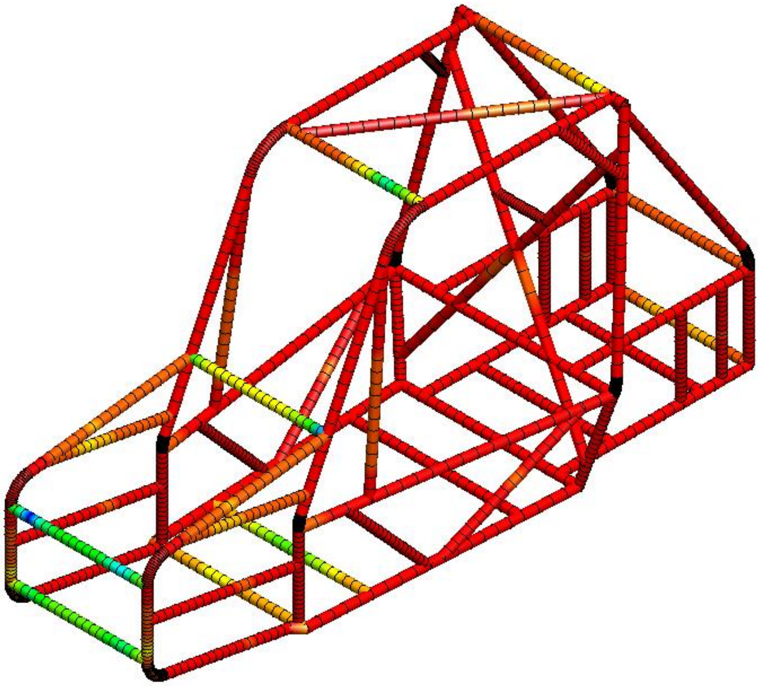


Figure 14. Drop Test Stress Distribution / Safety Factor

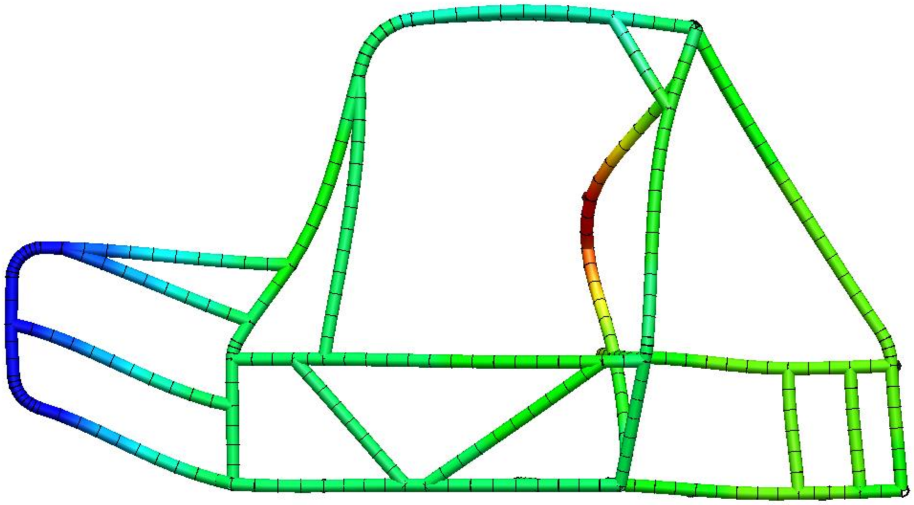


Figure 15. Front Collision Deflected Shape

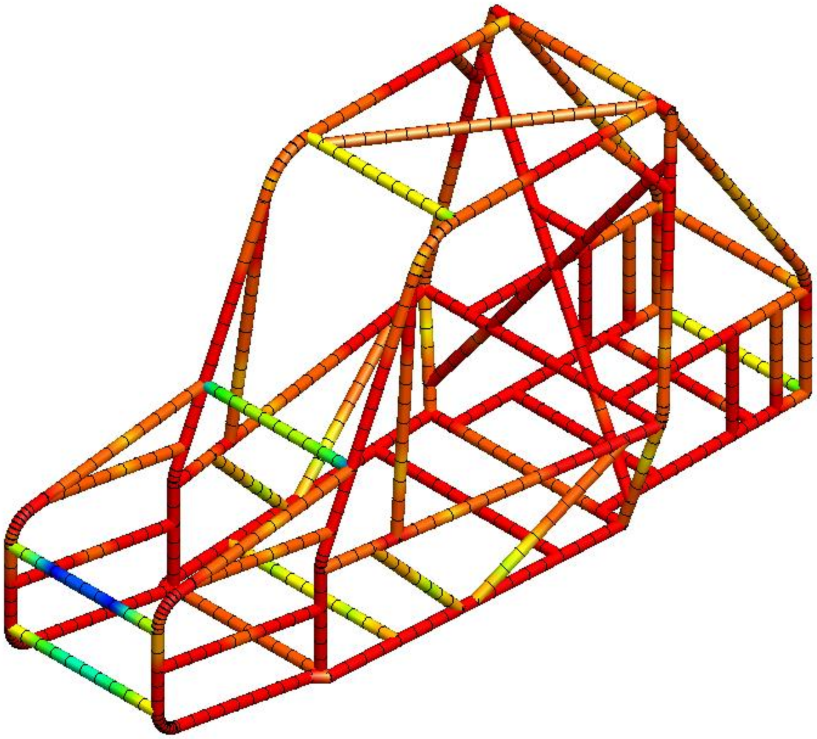


Figure 16. Front Collision Stress Distribution / Safety Factor

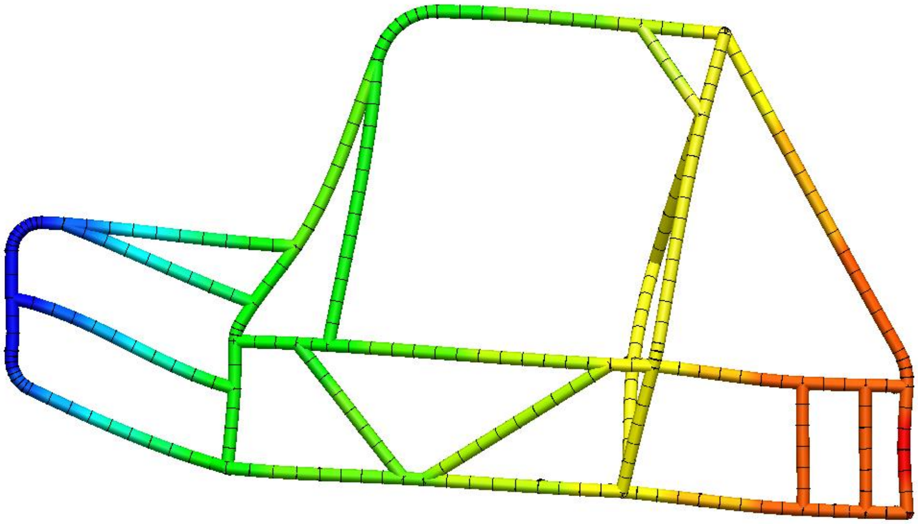


Figure 17. Rear Impact Deflected Shape

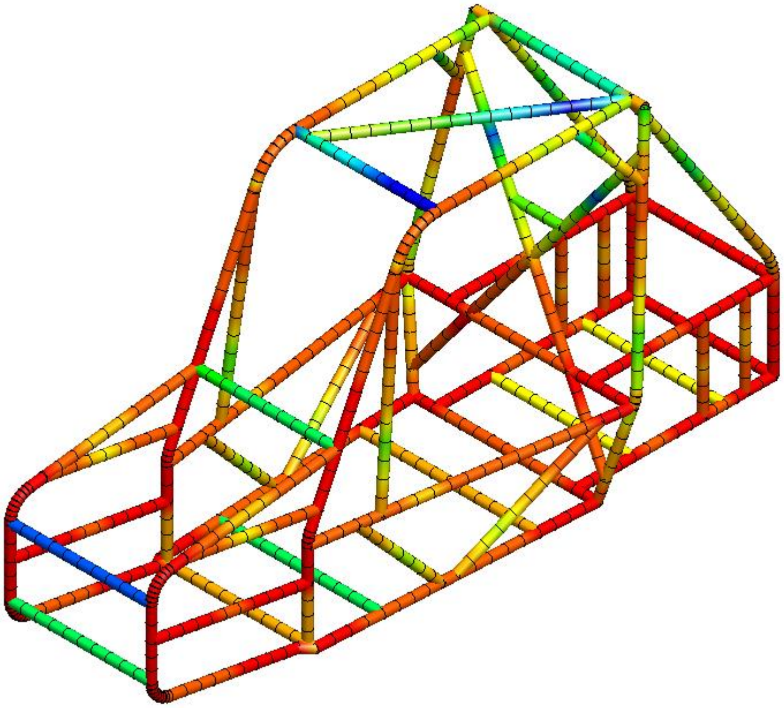


Figure 18. Rear Impact Stress Distribution / Safety Factor

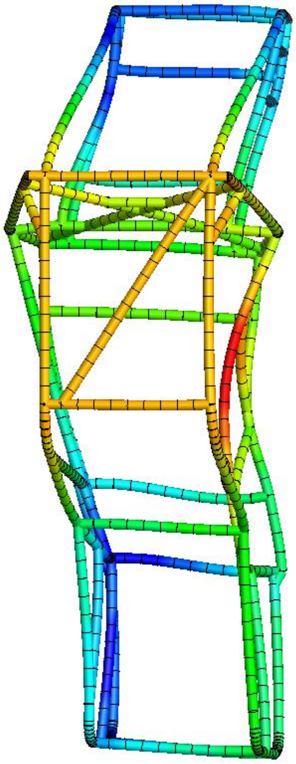


Figure 19. Side Impact Deflected Shape

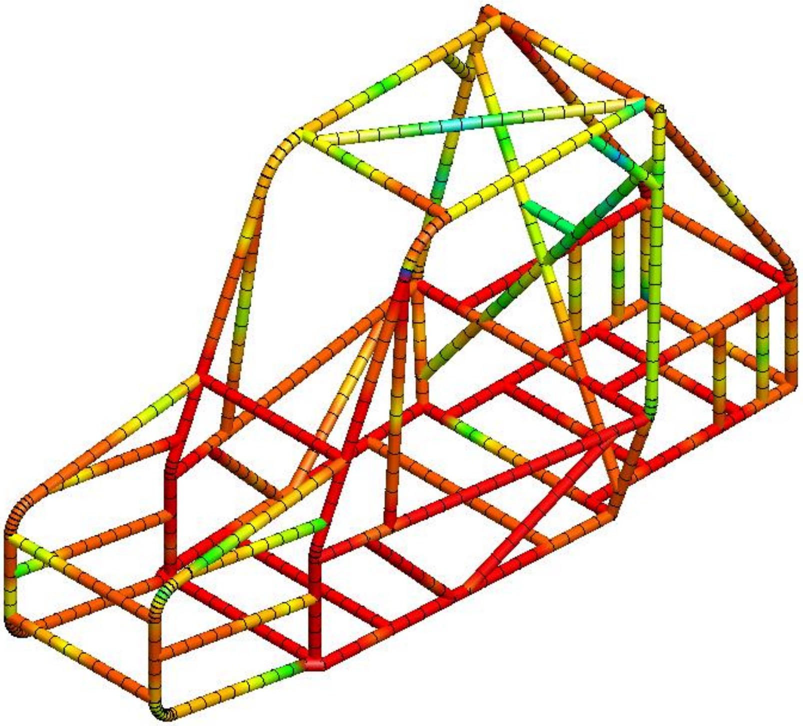


Figure 20. Side Impact Stress Distribution / Safety Factor

Appendix B: Tab Shear Simulation Results

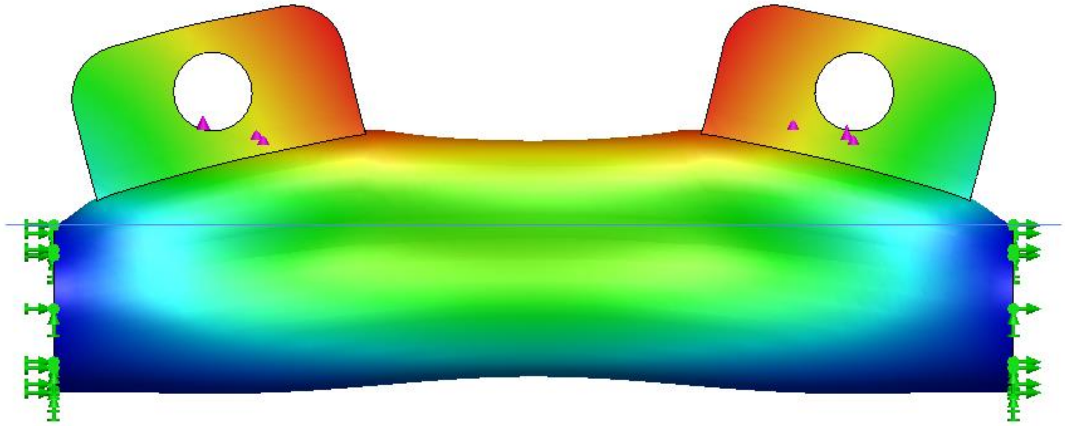


Figure 21. Seatbelt harness tab deflection

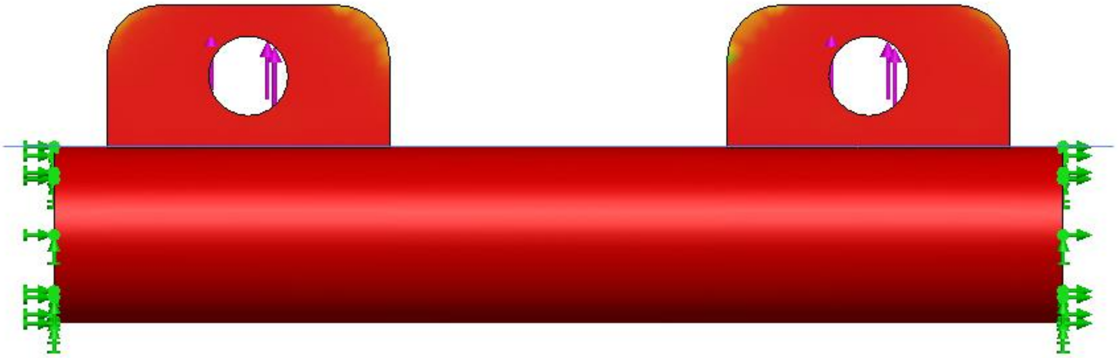


Figure 22. Seatbelt harness tabs factor of saftey

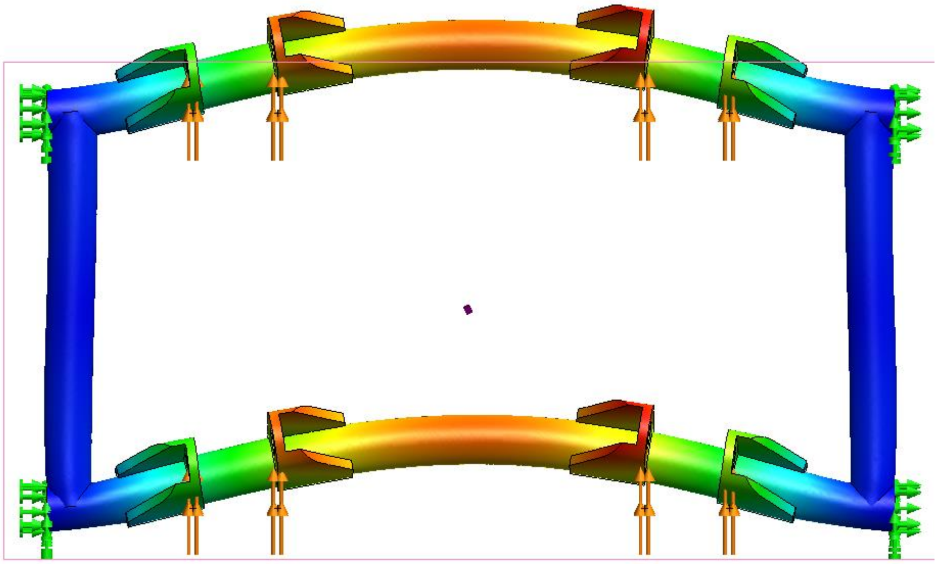


Figure 23: Tab deflection

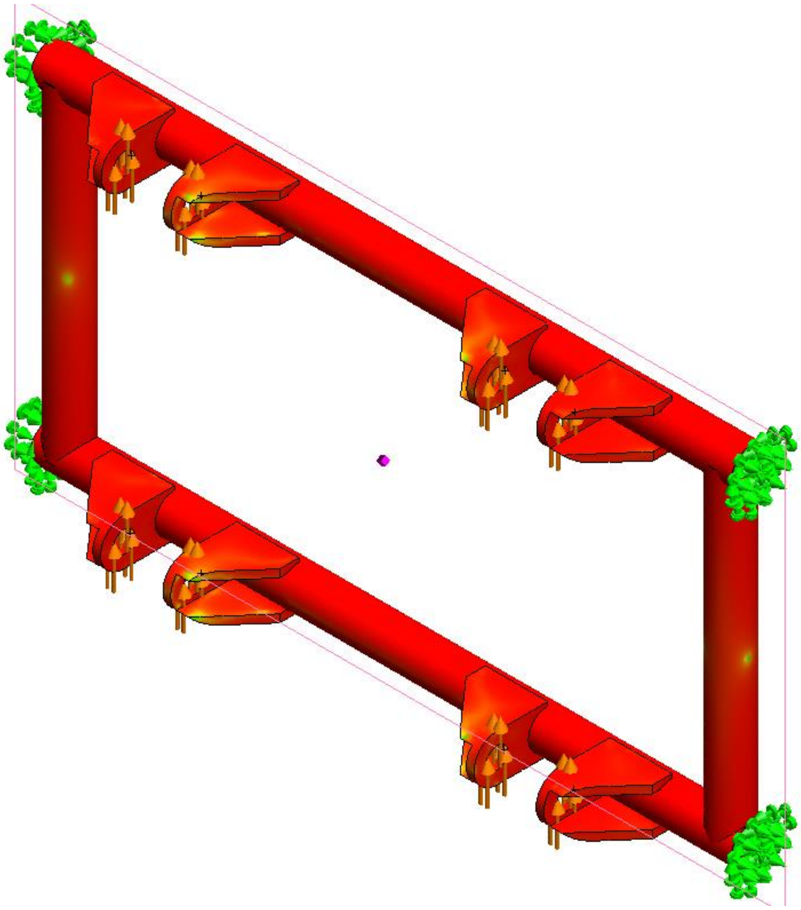


Figure 24. Tab factor of safety