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SCU Mini Baja

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Department of Mechanical Engineering

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ENTITLED

SCU Mini Baja

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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SCU Mini Baja

By

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SENIOR DESIGN PROJECT REPORT

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ABSTRACT

Baja SAE (Society of Automotive Engineers) is an intercollegiate competition to design, fabricate, and race a small, single passenger, off-road vehicle powered by a 10 HP Briggs & Stratton 4-Stroke gasoline engine. The purpose of this project was to optimize the design of a baja vehicle appropriate enough to compete in the SAE competition held in California and perform finite element analysis (FEA) for the verification of the frame and overall design of the vehicle. The design of this vehicle was created through outside research of previous baja buggies made for the competition and the group was split into three subdivisions (frame, suspension, and drivetrain) to make the environment more efficient. For the design of the vehicle, a steep caster and a negative camber gains through the suspension cycle was created. The desired specification of 5 degrees positive caster were met better handling and self-centering steering. The design process focused on minimizing redundant members by applying three different Finite Element Analysis approaches that helped develop an efficient geometry, operating within the stress limits. The status of the vehicle is that it was not fully completed and therefore unable to compete in the competition. It is currently in the Machine Shop at Santa Clara University to better assist the future SCU all-girls design team in 2018.

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1 | Introduction

1.1 | Background

The first SAE Mini Baja competition was held in 1976 and was comprised of three different competitions: Mini Baja East, Mini Baja Midwest, and Mini Baja West. Due to Santa Clara University's location, our team had planned to compete in the Mini Baja West, which was located in the Southern California desert. This event required a Mini Baja design that involved designing and building a single seat, all-terrain, sporting vehicle for competition and presentation.

In terms of competition and presentation, all participating schools are judged based on how they determined the most reliable, maintainable, and ergonomic vehicle for production by a fictitious firm. Ultimately, teams must make a sales presentation to a panel of judges on the feasibility and benefits of the vehicle as a consumer product. During the competition, the design and fabrication of the vehicle will be tested through hill climb, endurance, maneuverability, acceleration and specialty events. Our team was divided into three subdivisions so that each subsystem can be optimally designed and thoroughly analyzed. These groups are: suspension team, frame team, and the drivetrain team.

1.2 | Motivation

The main motivation for creating the Baja SAE competition was to offer students who are transitioning from school to the workforce a chance for a real-world type experience. This project provides ample opportunity to learn about working on a team, doing cost analysis, marketing presentations, design process, engineering analysis, and hands on fabrication. Very few projects are so broad yet completely organized as the SAE Baja competition, and this is one of the main reasons that the team went forth with this project. The skills and lessons learned in this project can be directly applied to future jobs, as most companies work on projects that are even bigger in scale, thus, practicing compartmentalization and communication are key motivators. Since the last SCU team to partake in the SAE competition was twelve years ago, it was our goal to bring it back once again.

Having split up into three subdivisions, each group (suspension team, frame team, and the drivetrain team) conducted many designs and tests to come up with a final design of the vehicle.

The focus of the suspension team was to design a practical suspension system capable of withstanding the harsh off-road terrain. The front and rear suspension system will consist of a double A-arm setups.

The drivetrain team focused on developing a power transmission that coupled a CVT with two chain drive reductions. The gear ratios allow for plenty of low end torque to overcome obstacles and hillclimbs while having enough high end gearing to reach an appropriate top speed.

The frame team focused on producing a light yet structurally sound frame. Their main focus was on reducing the total weight of the vehicle while also meeting the minimum competition requirements and ensuring driver safety. They worked closely with the suspension team in order to properly mount the double A-arm front and rear suspension onto the frame. Extensive Finite Element Analysis was performed on the frame and drivetrain to optimize their design.

1.3 | Review of Literature

The design optimization of a buggy can be quite complex and multifaceted. There are so many components that go into designing the vehicle, such as frame structure, drivetrain, engine, suspension, safety, etc., that it can be hard to pinpoint what aspect of the vehicle to modify to get the desired result. In the case of this project, the team decided that the main parameter would be performance. As such, the review of literature will seek to emphasize the history of vehicle optimization in respect to performance with a focus on drivetrain, frame structure, and suspension.

The drivetrain of a Mini Baja can only be optimized by playing with the transmission as all vehicles must have the same Intek Model 19 10 HP engine. In terms of transmission, an off-road vehicle such as the one designed poses an interesting dilemma as the vehicle is expected to accelerate quickly, but also be able to traverse rough, uphill terrain. A CVT transmission would optimize acceleration, as the engine is constantly working at maximum power to ensure step-less changes in gear ratios [1]. A manual transmission would have a time lag since the engine must start from a low gear ratio and shift to a high gear ratio to accelerate. However, a manual transmission would be best if a vehicle needed to traverse rough, uphill terrain as it can achieve a lower first gear ratio, which would make rock crawling a lot easier [1]. Thus, in 2003, a team from the University of Tennessee decided to combine the two transmissions in series to create a hybrid transmission capable of achieving higher velocity ratios than either transmission could alone, as well as allow for more versatility in regards to acceleration and uphill climbing [2]. The team employed a force balance to derive equations for the pulleys of the CVT and used finite element analysis methods on Solidworks to simulate the vehicle's top speed using the new transmission.

In terms of frame structure, the design needed to optimize performance would be one that is built after considering critical loading conditions that could result in failure. According to research provided by a team from Auburn University that competed in 2006, a vehicle undergoes the most critical loading when subjected to impact loading [3]. Thus, designing for the worst-case loading scenario would make sure the frame was strong enough for any situation. That is to say that the frame should be designed such that it can withstand the loads created on the front shocks, engine deck, and seat cradle when the vehicle experiences jumps. This conclusion was drawn from analyzing a frame in ABAQUS and validating the results from said model with real experiments performed on a constructed frame [3]. Finite element analysis methods, such as explicit integration, implicit direct integration, and modal superposition were used to mathematically model and analyze the constructed frame. In order to choose the best frame design, several concepts were drafted and the one that provided the best results was chosen.

The suspension for the Mini Baja is one of the most crucial, if not the most crucial, aspects of design. Due to the terrain that the vehicle is expected to travel on, the suspension can be optimized by extending the suspension as far away from the body of the vehicle as possible to avoid the frame being hit while in motion. In 2014 a team from Northern Arizona University proved the aforementioned by experimenting with different suspension types. The team found that a double a-arm extended suspension was optimal due to the ease of tuning for camber, caster, and wheel toe angles [4]. Tuning is an important aspect of competitive racing whether it be off-road or on, and thus this type of suspension was found to be advantageous for the competition. A design decision matrix as seen in the Appendix was used to determine this suspension in which weight, cost, strength, durability and other factors were considered.

Ultimately, the vast amount of optimization that can be done to a buggy is what makes this project such an extensive learning experience. There are so many factors to consider and test that require knowledge of engineering principles covered all throughout undergraduate classes. Outside of the university, the project also holds merit as it is through design optimization that new automotive technology is discovered, such as hybrid transmissions and double a-arm suspension. It is solving problems like these that allow for innovation and better engineering.

1.4 | Statement of Project Objectives

1. Build a Baja Buggy that's reliable and drives well
2. Build a Baja Buggy that can be used as a base model for future students at SCU
3. Make our Buggy faster than any Buggy built previously at SCU

4. Attempt to have our Buggy place in the Baja SAE California Race
5. Ensure that our requirements on our Gantt Chart are consistently met

2 | Systems-Level Chapter

2.1 | Customer needs / System Level Requirements

In the U.S there is a huge market for off road vehicles and the demand for a single seater is not successfully satisfied by any current manufacturer. This is because the SCU Baja is in a class of its own; It is not quit a go kart but it's also not a full size UTV, it just combines aspects from both. The only company currently making a single seat off road vehicle comparable to the SCU buggy is Polaris but even theirs is not truly comparable as it is oversized and awkward. This is because it is intended for farm work rather than recreation. In order to better understand the market and to confirm that there truly is a demand for a single seat off road vehicle we conducted a survey of a range of college students. Using the survey results we created our Product Design Specifications (PDS) to meet the needs of the customers and just as importantly to satisfy the requirements set forth by the SAE rules. Once the basis of the design was determined we needed to prioritize certain properties of the design over others. Through the use of Quality Functional Deployment matrices weighted categories of the design were compared against each other in order to determine what we would focus the most time, energy, and money on. For the survey results, PDS, and QFDs refer to Appendices D and E.

2.2 | User Scenario

Each team's goal is to design and build a single-seat, all-terrain, sporting vehicle whose structure contains the driver. The vehicle is to be a prototype for a reliable, maintainable, ergonomic, and economic production vehicle which serves a recreational user market, sized at approximately 4000 units per year. The vehicle should aspire to market leading performance in terms of speed, handling, ride, and ruggedness over rough terrain and off-road conditions.

Performance will be measured by success in the dynamic events which are described in the Baja SAE® Rules, and are subject to event-site weather and course conditions [20].

2.3 | Functional Analysis

The buggy was designed with the notion that it will experience a great deal of impact. The front suspension will have more travel because it is necessary to absorb the impact from jumping, due to the nose of the vehicle having a tendency to drop as the vehicle jumps. The rear suspension travel will still be sufficient for the terrain, as the vehicle will still experience impact in the rear, but it will mainly be limited by the articulation angle and length of the half shafts that have been acquired for the project. Similarly, the buggy's frame was also designed with the same assumption that it will experience a large amount of impact, but with an emphasis on the safety of driver.

The main purpose of the frame is to protect the driver in case of collision, provide a shell to hold the drive-train, and provide suspension attachments. Thus, all the members of the frame serve a particular function for the overall system. Figure 1, below, displays a more general version of the frame with each member identified for functional decomposition [9].

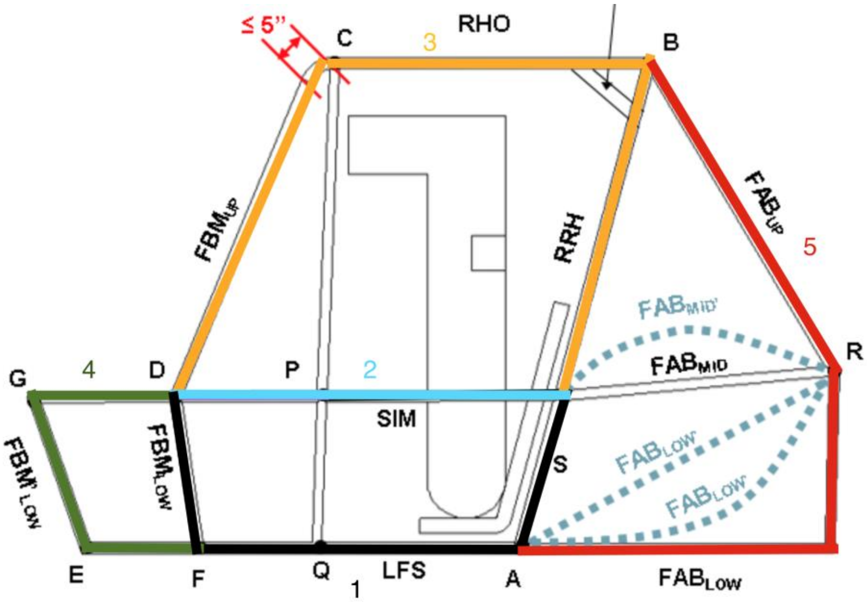


Figure 1: Generic Frame Design Highlighting All the Members Needed [SAE,12]

The side impact members (SIM) serve to protect the driver in case of side collision. These members are constrained by SAE to sit 3 inches away from the driver's hips, shoulders, torso, arms, and knees. The rear roll hoop (RRH) and roll hoop overhead (RHO) are part of the roll cage and as such serve as protection, while the fore and aft bracing members (FAB) serve to protect and hold the drivetrain. These members also strengthen the roll cage as the truss profile serves to concentrate loading in either tension or compression. Finally, the lateral cross members that run into the page of Figure 1 serve to protect the frame from bending stress. The lateral cross member configuration was chosen carefully to minimize weight and enhance speed performance. The buggy's drivetrain was designed with maximum speed and power in mind.

The drivetrain is the means by which power from the engine is delivered to the wheels. A properly designed drivetrain allows a vehicle to operate effectively and efficiently through various terrains. The transmission, gearbox, belt drives and axles all work cohesively to achieve this task. It was known early on that the buggy would be rear-wheel drive. This greatly reduced the complexity of the drivetrain system.

2.4 | Layout of System-Level Design

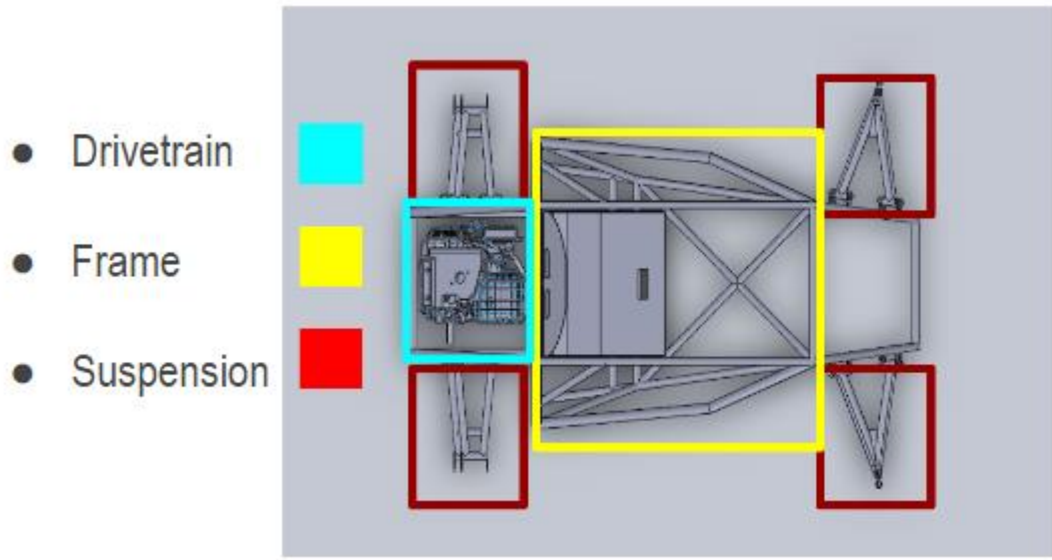


Figure 2: System Overview

Figure 2 shown above highlights the different subsystems that the overall vehicle system was separated into. The team was organized into separate smaller teams that could focus on specific areas in order to optimize them. Even though there was separate teams working on different parts of the vehicle most of the design process involved working alongside another subsystem team because changes made to one aspect of the vehicle affected another aspect. For example the frame team was constantly making changes to the frame to allow for desired mounting specifications set forth by drivetrain and suspension team. The same can be said for the other teams as it was not uncommon for suspension team to make changes to accommodate request from the frame team.

2.5 | Team and Project Management

2.5.1 | Budget

The total cost of manufacturing and assembling the baja buggy was determined to be around 18,000 dollars. The initial donation from Santa Clara University was 4,500 dollars, with additional donations of 600 dollars from the baja team and 300 dollars from the Bank of America also being contributed. The budget of the Santa Clara Baja SAE senior design team is shown in Table 1.

Table 1: Costs for Santa Clara Baja SAE

			Subassembly Costs		Labor Cost		Subtotal				Judges
Sect #	Item	Description	Material	Labor	Time(min)	Cost	Material	Labor	Cost Adj. Form	Adjustment	Adjusted Cost
1	Engine		$929.21	$87.50		$0.00	$929.21	$87.50			$1,016.71
2	Transmission		$689.30	$70.00		$0.00	$689.30	$70.00			$759.30
3	Drive Train		$919.78	$245.00		$0.00	$919.78	$245.00			$1,164.78
4	Steering		$234.44	$39.40		$0.00	$234.44	$39.40			$273.84
5	Suspension		$2,633.56	$140.00		$0.00	$2,633.56	$140.00			$2,773.56
6	Frame		$2,520.73	$6,687.50			$2,520.73	$6,687.50			$9,208.23
7	Body		$197.71	$352.10		$0.00	$197.71	$352.10			$549.81
8	Brakes		$1,169.99	$51.78		$0.00	$1,169.99	$51.78			$1,221.77
9	Safety Equipment		$235.00	$17.50		$0.00	$235.00	$17.50			$252.50
10	Electrical Equipment		$266.72	$0.00		$0.00	$266.72	$0.00			$266.72
11	Fasteners		$58.57			$0.00	$58.57	$0.00			$58.57
12	Miscellaneous		$0.00	$0.00		$0.00	$0.00	$0.00			$0.00
13	CAL Event		$381.86	$0.00		$0.00	$381.86	$0.00			$381.86
14	KAN Event		$0.00	$0.00		$0.00	$0.00	$0.00			$0.00
15	ILL Event		$0.00	$0.00		$0.00	$0.00	$0.00			$0.00
		CAL Total:	$10,236.87	$ 7,690.78		$ -	$ 10,236.87	$ 7,690.78			$17,927.65
		KAN Total:	$ 9,855.01	$ 7,690.78		$ -	$ 9,855.01	$ 7,690.78			$17,545.79
		ILL Total:	$ 9,855.01	$ 7,690.78		$ -	$ 9,855.01	$ 7,690.78			$17,545.79

The SAE Baja competition evaluates each team on the “true” cost of their vehicle. These “true” costs are essentially what it would cost a random person to go out into the market and build and fabricate our buggy. This final true cost is show in row 13 of Table 1 in the judges adjusted cost column. Each team is evaluated on this cost and judged accordingly, obviously the lowest overall cost was the team that was awarded the most points for this section of the competition. Out buggies total “true” cost was found to be 18,000 dollars.

One of the main concerns for the Santa Clara Baja SAE project team was funding, with an estimated $5,400 available to the team. With only two sources of funding, the team was left with a huge challenge. Obviously this amount is much less than the anticipated costs to build the the Baja Buggy. Because of this, our team reached out to potential sponsors outside of the university, within the Silicon Valley. Team members contacted banks, small businesses, large corporations, and even local automobile repair and manufacturing shops to try and acquire funding for the Baja Buggy. Meetings with companies interested in sponsoring the team were met with limited success, it was very hard for the team to get actual money out of these businesses, and in the end the most outside money we received was the 300 dollars from a generous local Bank of America representative.

Despite these discouraging setbacks, our team managed to find workarounds. For example, looking at Table 1, one can see that the labor costs associated with fabricating our frame amounted to roughly 6,700 dollars. Our team managed to work around this by fabricating the frame ourselves. All notching, bending, grinding, tacking and cutting of our tubing was done by our team. The frame then was brought to a certified welder who was willing to finish up our tack welds for free. In addition to this, our Fox Suspension was donated by a friend of one of our team mates, who works at Fox in San Diego and was able to get us a sponsorship. This amounted to an additional 1,500 dollars in savings. In summation, approximately $7,700 was saved through donated labor and the equivalent of $5,800 was raised in the form of professional services, parts, and cash, thus allowing us to be able to finance our Baja vehicle.

2.5.2 | Timeline

As one can see in Appendix F, our goals for certain parts of the buggy were continually pushed back. For example, we initially wanted to have the frame completed at the end of the winter break and then this became the end of winter quarter and actually it was just completed around week four of our spring quarter.Various setbacks like this occurred for a number of our manufacturing deadlines. The main issues we faced in hitting these deadlines were primarily due to personal obligations of the manufacturing team. However it must be noted that most SAE baja teams typically already have a buggy from previous years, and the necessary funds to outsource all of the required labor for the buggy. We knew going into this project that it would require a lot of our time, but unfortunately it just wasn't enough to work with our schedules. That being said, we were able to meet all of our class deadlines, and all of our SAE paperwork obligations as well. Refer to appendix for detailed Gantt chart.

2.5.3 | Risks and Mitigations

Aside from the obvious physical risk associated with this project, there are a few more areas that can pose significant risk to the overall success of this project. First and foremost, time was the biggest thing we had going against us. If we couldn't stay on schedule and maintain constant forward progress on this buggy then we would not be able to succeed in our goals. To mitigate this risk, our team relied on group responsibility. By having team leaders report to the project manager and advisors each week, we tried to ensure that we would stay on track with the project.

Another sizeable risk this project faced was a financial one. If we were unable to come up with sufficient funding for this buggy we may have had to resort to funding it ourselves depending on how much money we come up short. However this risk was mitigated effectively through donated labor and parts..

2.5.4 | Team Management

Team management of Santa Clara's Baja SAE project is conducted by Matthew Nagy. Underneath the project manager there are 5 subteams. They are frame, suspension, drivetrain design, financials/logistics, and manufacturing. The team leaders are as follows- Christian Ruiz (frame), Mauricio Jimenez (suspension), Ruben Contreras (drivetrain), Christian Hellmers (finance and logistics).

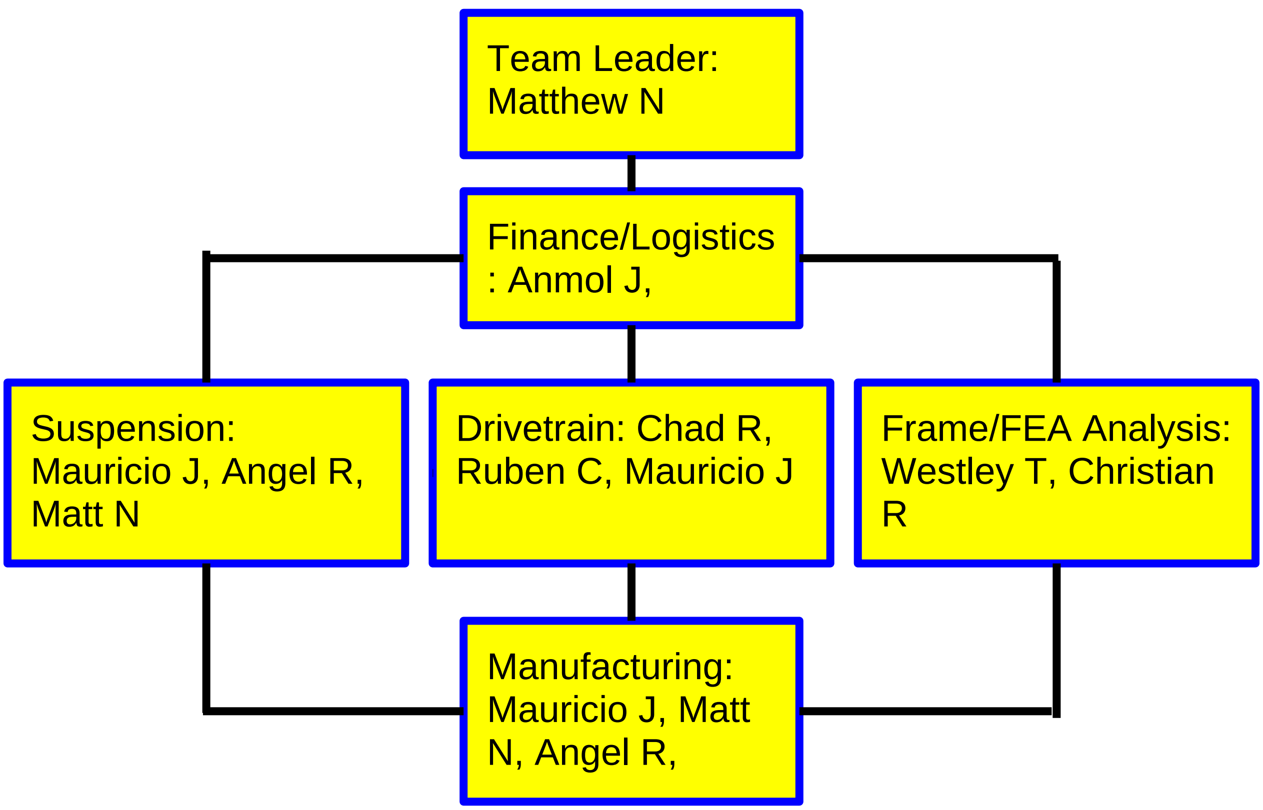


Figure 3 : Team Management Flowchart

In addition to the team management detailed above, there are also two Santa Clara advisors assigned to our team to ensure we are on track for completion. Our administrative and financial advisor is Professor Timothy Hight and our technical advisor is Professor Michael Taylor.

The guiding principles behind our team management strategies are simple. Our team leaders are in charge of accomplishing various tasks each week. These tasks and goals are set during our Sunday meetings and are carried out and completed by their respective teams over the next week. A team leader obviously does not have to do all of that work by him/herself and is instead in charge of delegating the work to his/her team in the most effective manner to get things done. Throughout the week our project manager is keeping up and helping teams accomplish their set goals, by ensuring meetings are set and tasks are assigned. If a team is unable to meet its weekly goals, it is then the project manager's task to get the team back on track or notify faculty if a team leader is incapable of effectively fulfilling their position.

The team manager's responsibilities also include organizing and communicating with outside assets and advisors that are linked to the BAJA SAE project. This includes sponsors and faculty.

There are a few key areas that should be improved in order to achieve a higher degree of success on future Baja projects. The first thing I would suggest is to place a greater degree of responsibility on the team seeing all goals through together. Often times throughout our senior design, people would feel like they didn't need to contribute because they saw other people doing the task at hand or they felt like they had already done enough work on other areas of the project. It needs to be made clear from the beginning, that the project at hand is a group endeavor and requires fully engaged cooperation from all team members in order to proceed smoothly. Unfortunately, the suggestions I have for fostering this kind of environment won't work for every group and thus it is important for a team to set forth or discuss some form of strategy to foster this kind of environment. The second most important suggestion goes hand in hand with the first. Complete your tasks by their assigned deadlines. This is important for you as a team since you will confidently be able to say that that part of your project is finished. Failing to set and then attain these goals can lead to disorganization and lack of motivation later on in the project.

3 | Subsystem: Suspension

3.1 | Customer needs, system level requirements(intro to role/requirements)

As mentioned earlier, the suspension of an off road vehicle is one of the most important aspects of the design. The off road capabilities of a suspension are determined by how well the vehicle handles over rough terrain and, therefore, a vehicle's suspension should be tailored to the specific land that it will be traversing. There is no such thing as a generic off road suspension that performs to the level desired for this project. A market survey conducted through a questionnaire to potential customers of a Baja Buggy provided results showing that there is, in fact, a demand for an off road vehicle that is designated for desert use. The results of the survey can be seen in Appendix E.

The desert use designation is beneficial to this project, since the buggy plans to compete in the California SAE Baja competition. A desert race suspension is therefore necessary, which requires a low slung vehicle with just enough ground clearance to avoid frame contact with the ground, and enough wheel travel to absorb the impact generated from jumps and obstacles.

3.2 | System Sketch

The front and rear suspension will employ a double wishbone design that can be seen in Figure 4.

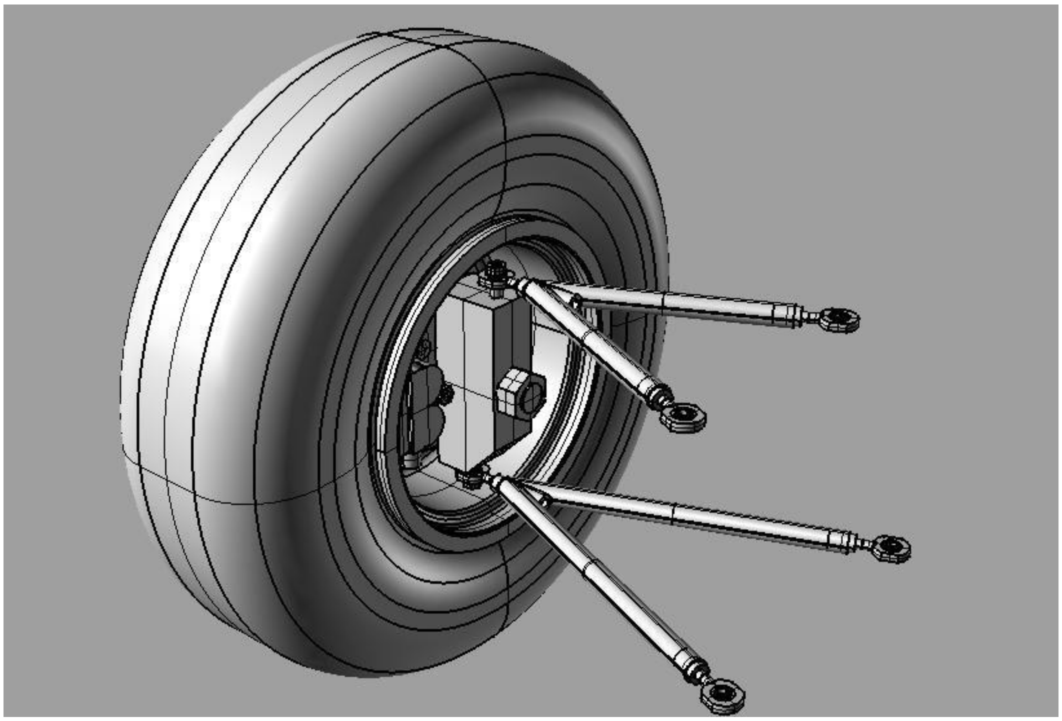


Figure 4: Front Double Wishbone Suspension [7]

3.3 | Benchmarking Results

Unlike the countless variations of frame designs incorporated by past Baja teams, there appears to be a common agreement among teams for using an independent double A-arm design for the front suspension system. This configuration makes the system easily adjustable, while also allowing for maximum suspension travel and improved traction. On the other hand, the rear suspension system has seen a few different designs: trailing arms, semi-trailing arms, and a solid axle. Our design incorporates a double wishbone configuration for front suspension, and a semi-trailing arm design for the rear; furthermore, this report seeks to highlight the use of these suspension configurations by previous Mini Baja teams.

The 2013 Old Dominion team used double wishbones in the front, and a semi-trailing arm in the rear for their design [4]. Their goal was to make their suspension system as structurally sound as possible. For this they used 4130 chromoly steel with 1-inch outside diameter, .065 wall thickness, and a yield strength of 69 ksi. Also, they designed their rear trailing-arm such that it extends and mates to the toe-link receptacle on the rear wheel hub. After modeling and testing, the maximum possible applicable loads before failure were found to be 500 lbf on the lower A-arm and a 745 lbf on the rear trailing arm.

Auburn's 2010 Mini Baja team used a double wishbone design in the front, as well as a semi-trailing arm in the back [8]. Their goal was to design a suspension system which would experience camber gain in roll while minimizing bump steer. Minimizing bump steer is important for ensuring that the car won't jerk sideways due to small bumps, and also so that the tie-rods won't move laterally after releasing from compression after going over a jump. They used the Shark Modeling System to model and test their suspension system design. Testing revealed that the maximum stresses within the front system were experienced within the steering spindles. In addition to the spindles themselves, the bolts for the steering arm were experiencing high stresses due to their location, and to the thickness of the mounting tabs.

3.4 | Key System Level Issues

From the start, it was obvious that the project would be a rear wheel drive vehicle for the sake of simplicity due to time constraints and limited budget. The added complexity of a 4 wheel drive system outweighed the benefits of added traction and crawling capability. Additionally, there was essentially no question that the front suspension would be any other design besides a double wishbone setup, due to the camber gain through the range of motion of a double wishbone design being ideal for the project. Other possible front suspensions, like a solid axle or a twin I-Beam design, only provide the desired camber gain at one wheel because the opposing wheel experiences a gain in camber angle opposite to what is desired.

3.5 | Layout of System-Level Design

The layout of the suspension was broken down into two parts, the front and rear. The front and rear suspensions were designed independently in stages, but considerations for the other were taken into account when working on one to make sure that the overall suspension system would work harmoniously.

3.6 | Designs Considerations / Trade Offs

Of the designs we considered, the twin beam design seen in Figure 5 below is pretty common in high speed desert racing applications.

Figure 5: Twin Beam Suspension Example [Speednik, 9]

This type of suspension works similar to the double wishbone setup, but the suspension pivot points on the frame extend to the opposite sides of each other. This provides more travel, but the extra leverage of the added length creates higher stresses and requires a lot more material. That's also why upon closer inspection these systems look like heavy duty beams rather than light weight tubular control arms.

Another problem is, because of the way the hub is fixed to the beam, we get unwanted camber changes. This can create less than ideal handling characteristics, and when landing after big jumps, the buggy puts a lot of stress on parts near the wheels—parts like the bearings, spindles, and naturally the hubs themselves, because the buggy doesn't land flat on the wheels.

Decision matrices were created from the overall requirements of the suspension. A corresponding description and respective weight was assigned to each requirement. The results are tabulated below:

Table 2: Suspension Requirements

Requirements	Description	Weight
Cost/Manufacturability	The suspension design should be affordable in terms of machining and assembly	0.3
Handling Performance/Travel	High maneuverability and impact absorption	0.3
Lightweight	Design optimized to reduce weight	0.2
Strength	Must withstand maximum loads SF3	0.2

Cost and Manufacturability received a weight of 0.3 because the project had such a limited budget and timeline. Handling Performance and Suspension Travel also received a weight of 0.3 because the intent of the project was to create a vehicle that could be competitive off road. Lightweight and Strength received a weight of 0.2 because they went hand in hand, and it was not much of a concern to add a little weight even if it meant the control arms would hold up to more severe loading—especially when applying a safety factor of 3. Weighing the different suspension design scores against each other, the Double A-Arm was the clear winner, and was consequently what we chose for this project. The results are tabulated below:

Table 3: Suspension comparison with assigned weighting factored in

Design	Cost/ Manufacturability	Handling Performance	Lightweight	Strength	Total
Double A-Arm	5	5	5	3	4.6
Swing Arm	4	3	2	4	3.3
Twin Beam	3	2	3	3	2.7
Semi-Trailing Arm	4	4	4	4	4
Solid Axle	2	1	1	5	2.1

3.7 | Design approach

Using a combination of suspension simulators, VSusp and Racing Aspirations [10,11], we were able observe the kinematics of various geometries to come up with our designs for the front and rear suspension. We began with certain parameters that we knew we wanted to have. For example, in the front we wanted a pretty steep caster and negative camber gains through the suspension cycle. We were able to meet our desired specification of 5 degrees positive caster for better handling and self-centering steering. This was done through manipulation of the frame design and positioning of control arms. Figure 6(a,b,c) are screenshots depicting the suspension geometry at various points in its travel cycle, and Figure 7 is the final outcome we fabricated to match those specifications.

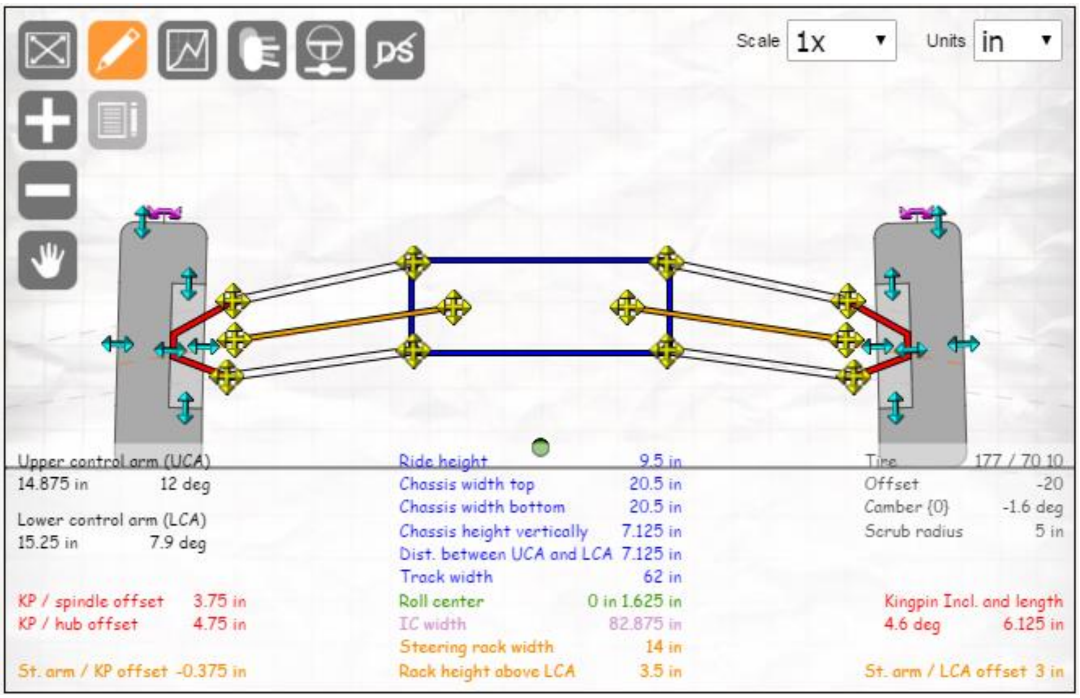


Figure 6a: Racing Aspirations Suspension Dimensions [10]

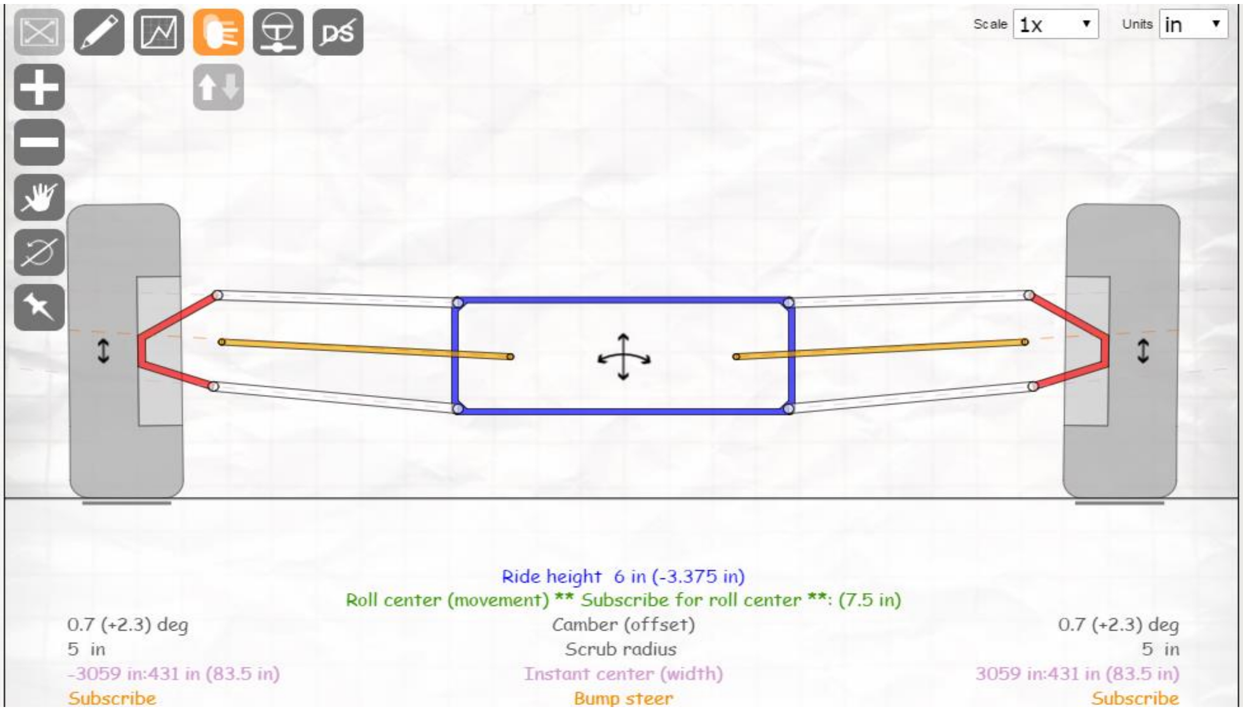


Figure 6b: Racing Aspirations Suspension Geometry at 6in. Ground Clearance [10]

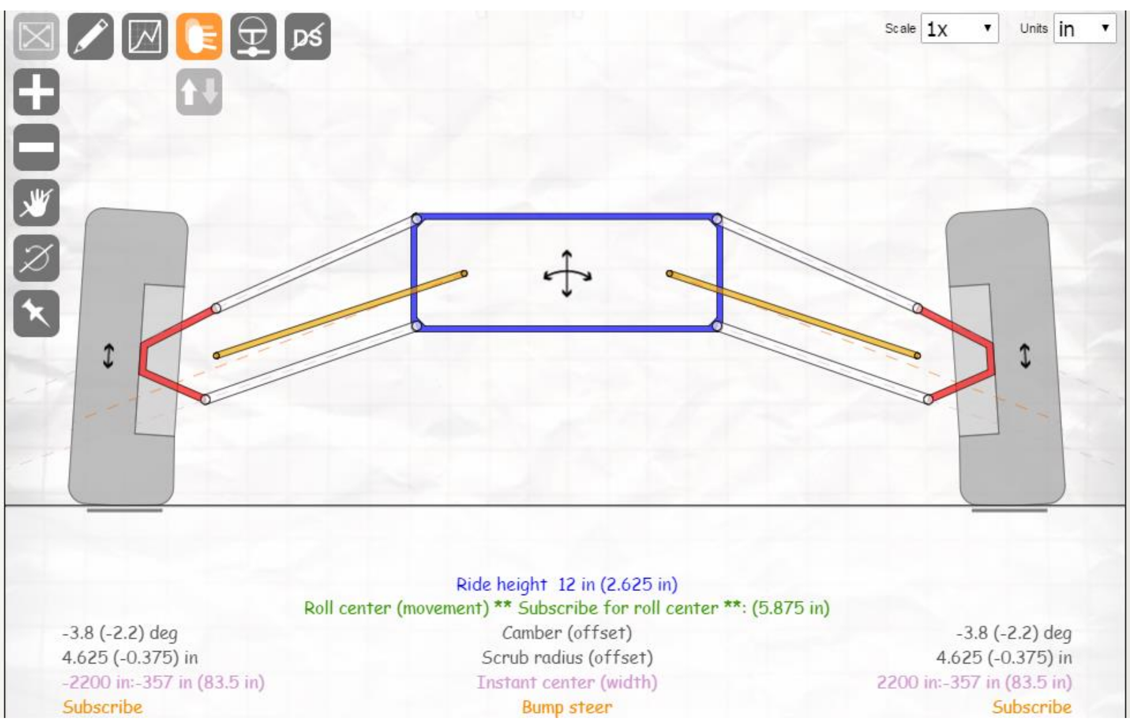


Figure 6c: Racing Aspirations Suspension Geometry at 12in. Ground Clearance [10]

Figure 7: Image of the SCU Baja Buggy Front Suspension Control Arm Assembly

The frame also has 10 degrees of rake built into the front; in essence, this converts some of the lateral force applied by obstacles into an upward force that the shocks can help absorb. Working closely in conjunction with the frame team we had to keep making changes to our control arm mounting points to accommodate spacing around the driver's feet to make sure there was enough space for the foot controls and steering rack. These constraints meant that we could not achieve our desired specification of zero bump steer. Although we could not fully eliminate bump steer, we were able to limit it to less than 90 thousandths of an inch for the 4 inches of travel where the vehicle suspension will spend most of its life, i.e., the range between 6 and 10 inches of frame ground clearance. Over the entire 10 inches of suspension travel we did see approximately 125 thousandths of bump steer, but this was deemed acceptable within the constraints.

4 | Subsystem Level Chapter: Frame

4.1 | Customer needs, system level requirements(intro to role/requirements)

It was determined, based on customer reviews seen in Appendix E, that the buggy had to be focused on performance, simplicity, and durability. In order to satisfy these requirements, the frame had to be lightweight, yet designed with the ability to withstand repeated loading. These loads consisted of both bending and torsion of the beam members in the frame, for both steady state loading conditions and impact loading conditions. As such, the design process focused on minimizing redundant members by applying three different Finite Element Analysis approaches to develop the most efficient geometry, while operating within the stress limits for the design. A systems engineering approach was used in order to iteratively alter the dimension of the frame, within the restrictions imposed by SAE regulations, along with restrictions due to requirements for the suspension, engine and drivetrain.

In order to satisfy the SAE specific regulations, it was necessary to reference the SAE BAJA Buggy 2017 Rule book, Section B8. Not all regulations will be listed, as section B8 comprises 10 pages of rules, but the rules pertaining to the Lateral Members (LC) seen in Figure 8, are shown as an example. The other SAE Rules that were considered can be found as a checklist in the Appendix.

B8.3.2 Lateral Cross Member Requirements

Lateral cross members cannot be less than 203.5 mm (8 in) long. They cannot have a bend; however, they can be a part of a larger, bent tube system, provided the minimum length is met between bend tangents. The cross members which connect the left and right points A, B, C, D, F and E/G for 'Nose' cars (in which case DLC may be omitted) must be made of primary materials. LCs are denoted by the points they connect (*e.g.* ALC, FLC, etc.).

Figure 8: Baja SAE Rule Pertaining to LC Members [SAE, 12]

The Lower Frame Side Member (LFS) and LC subsections are made up of primary and secondary members, as seen below in Figure 9, which must abide by material restrictions of a circular pipe with at least 18% carbon and a yield strength of 52.93 kpsi. As such, the primary and secondary members chosen properties can be seen further below in Table 4.

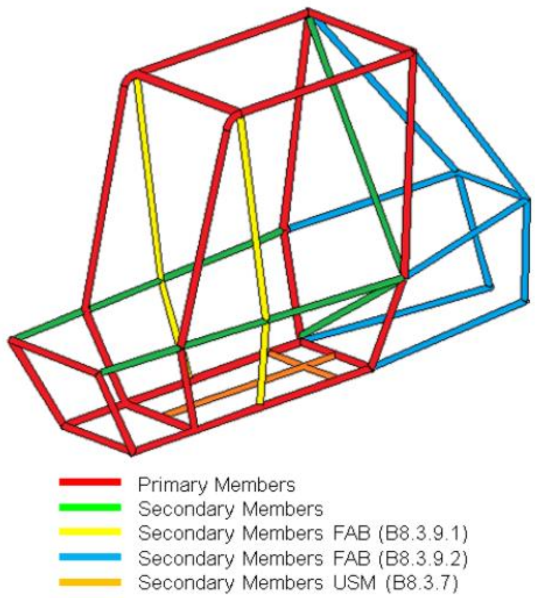


Figure 9: Primary and Secondary Members of the 2017 SAE Baja Buggy [SAE, 12]

Note: The use of FAB and USM refers to Front/Rear Bracing and the Under Seat Members, respectively.

Table 4: Geometric Properties for Primary and Secondary members of the Frame

Primary Members	Secondary Members
Diameter 1 in, Thickness .120in, 1018 Steel	Diameter 1 in, Thickness .035 in, 1018 Steel

In addition to the material restrictions, no single beam member can exceed a length of 40 inches, between two named points. Furthermore, no beam member can have a bend that is greater than 30 degrees without external bracing.

For the attachment of the seat, a lateral or horizontal member must be used that either connects the two LFS members on the left and right side or connects the ALC to the QLC. To help clarify what is meant by A and Q in LC, a reference image has been provided below.

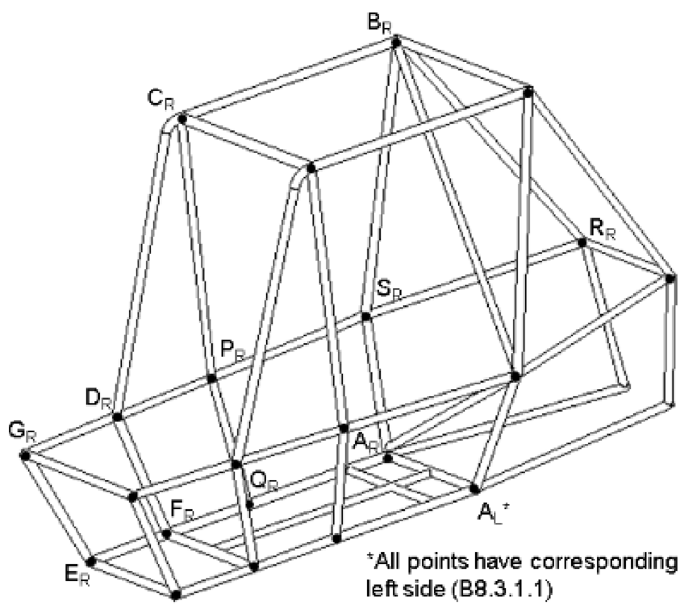


Figure 10: Roll Cage Points of an SAE Baja Buggy [SAE,12]

Note::A, B, C, D, F, S, (E and/or G for ‘Nose’ cars) and P, Q, and R as applicable for FAB systems. All named points have a Left and Right hand side, denoted by subscript L or R (e.g. □□ and □□) as shown in Figure 10. See 2017 Baja Rules [12], Section B8, for more details.

These members must have 2 in welds, and if drilled through, must have an internal support inserted. The width of the ALC must accommodate a seat that can hold the waist of a male in the 95th percentile, with a waist diameter of 15.9in, and allow for a minimum of a 3in clearance between the driver's body and the frame. The seat mount position, connected to the QLC, must allow the 95th percentile of men and 5th percentile of women comfortable access to the steering wheel and the gas/brake pedals. Table 5 and Figure 11 shown below illustrate these necessary dimensions, and it is important to note that only the Imperial Unit columns of Table 4 were considered.

Dimension #	Dimension	Measurements			
		95th Percentile Male		5 th Percentile Female	
		Metric	Imperial	Metric	Imperial
	Weight	102 kgs	225 #	49 kgs	108 #
1	Standing Height	186.5 cms	73.4 ins	151.5 cms	59.6 ins
5	Hip Height	100.0 cms	39.4 ins	74.0 cms	29.1 ins
8	Erect Sitting Height	97.0 cms	38.2 ins	79.5 cms	31.3 ins
10	Sitting Shoulder Height	64.5 cms	25.4 ins	50.5 cms	19.9 ins
17	Sitting Shoulder Width	50.5 cms	19.9 ins	37.5 cms	14.8 ins
19	Hip Width	40.5 cms	15.9 ins	31.0 cms	12.2 ins
25	Shoulder Grip Length	71.5 cms	28.1 ins	55.5 cms	21.9 ins
30	Foot Length - bare	28.5 cms	11.2 ins	22.0 cms	8.7 ins
31	Foot Width - bare	11.0 cms	4.3 ins	8.5 cms	3.3 ins

Table 5: Seat Mount Dimensions for Males and Females [13]

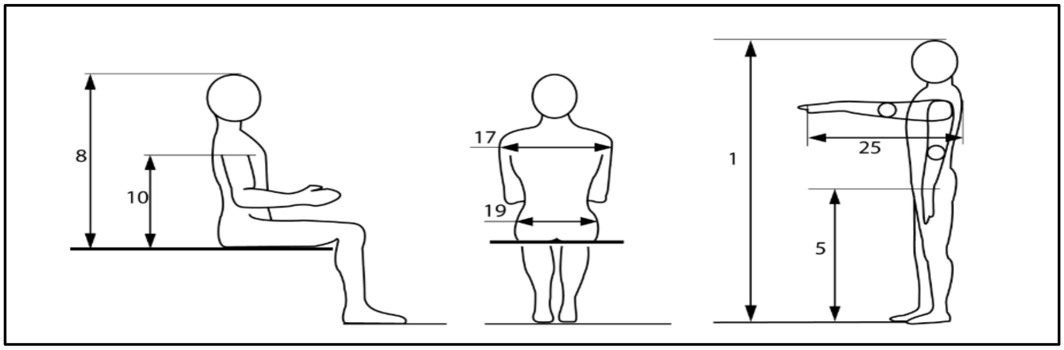


Figure 11: Anthropometric Reference Fixtures [Formula SAE, 13]

Note: The numbers in Figure 11 refer to the “Dimension #” in the left hand column of Table 5, shown above.

Although, most other subsystems of the frame, especially suspension and drivetrain connecting points, required interdisciplinary restrictions on the design. The design of the QLC and LFS were more simplistic, and only relied on the material and spatial restriction of SAE rules.

4.2 | System Sketch

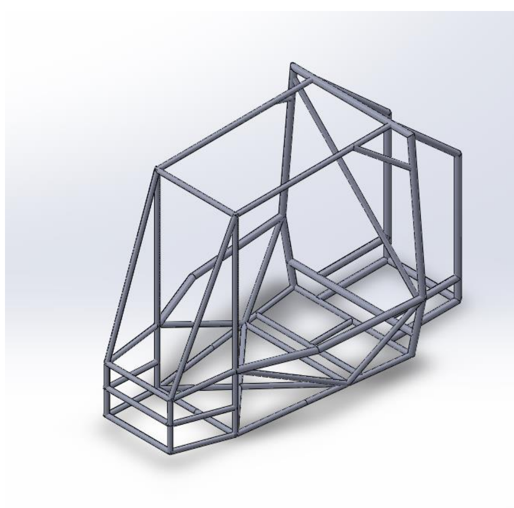


Figure 12: Isometric View of Final Frame Design

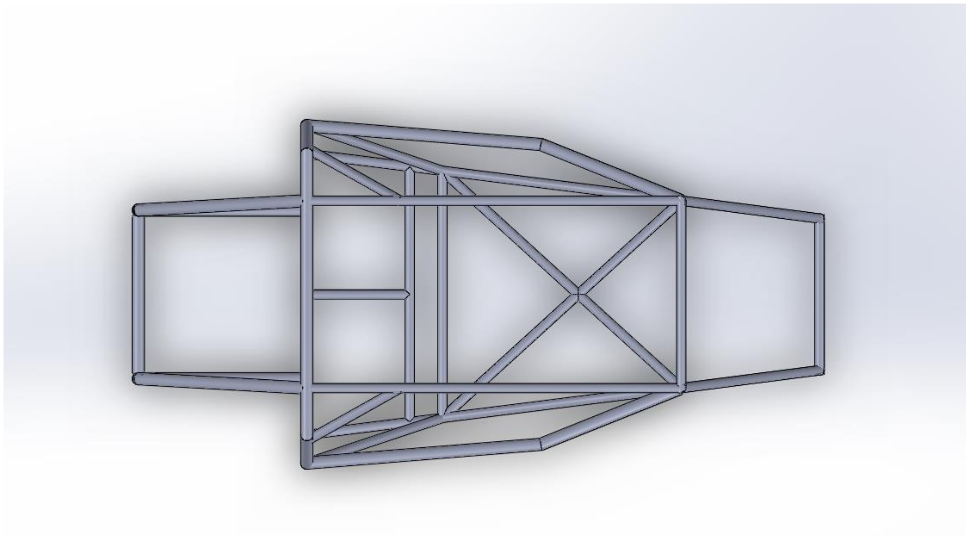


Figure 13: Top-Down View of Final Frame Design

The frame was designed to be used by any driver that steps into the buggy in order to ensure collision safety. Figure 12 highlights the vehicle's roll cage design, which consists of a steel frame used to safeguard the driver in case of rollover, whereas Figure 13 illustrates same design, but with a top view instead.

4.3 | Benchmarking results

There are countless frame designs that have been used by past Mini Baja teams, but this report seeks to highlight three of those designs. The first can be seen in Figure 14 shown.

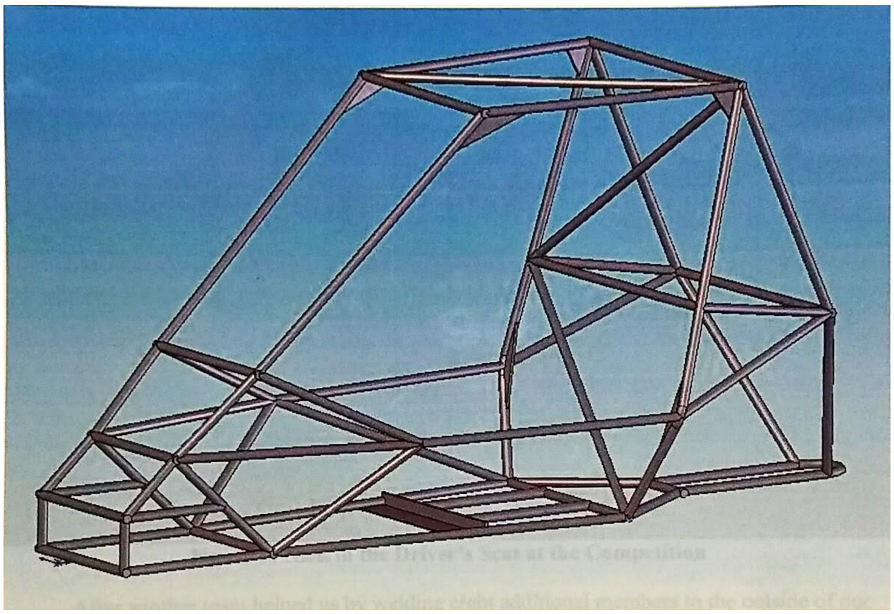


Figure 14: Frame Design for the 2007 SCU Mini Baja Team [14]

The SCU team in 2007 employed a frame design that sought to maximize strength in bending along the width and length of the vehicle. In order to do this, the team used 4130 chromoly steel tubing due to its high strength-to-weight ratio, and tried to keep members spanning the width of the vehicle relatively short.

The second frame that was considered was designed by the Auburn University Mini Baja team, and can be seen in Figure 15 below.

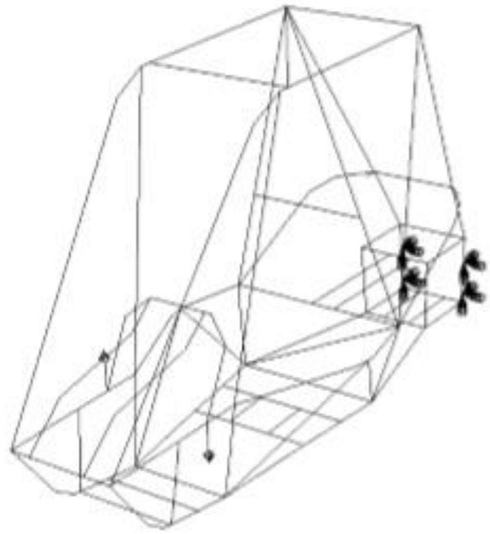


Figure 15: Frame Design for the 2006 Auburn University Mini Baja Team [8]

This team focused on designing the best frame under dynamic loading with an emphasis on the force placed on the front shocks and the seat. This was done by using FEA analysis on the frame in Figure 15 and by plotting the response for varying modes of loading. The team chose the design that responded the best to their loading conditions.

The NAU team, on the other hand, focused on static loading conditions through the use of SolidWorks. Through several renditions, and after subjecting the frame to loads of up to 600 lbs, the team chose their final design, which is shown in Figure 16 below. This team also optimized their design by making sure that it was easily manufactured. As a result, various bends and turn in the frame were eliminated from early renditions.

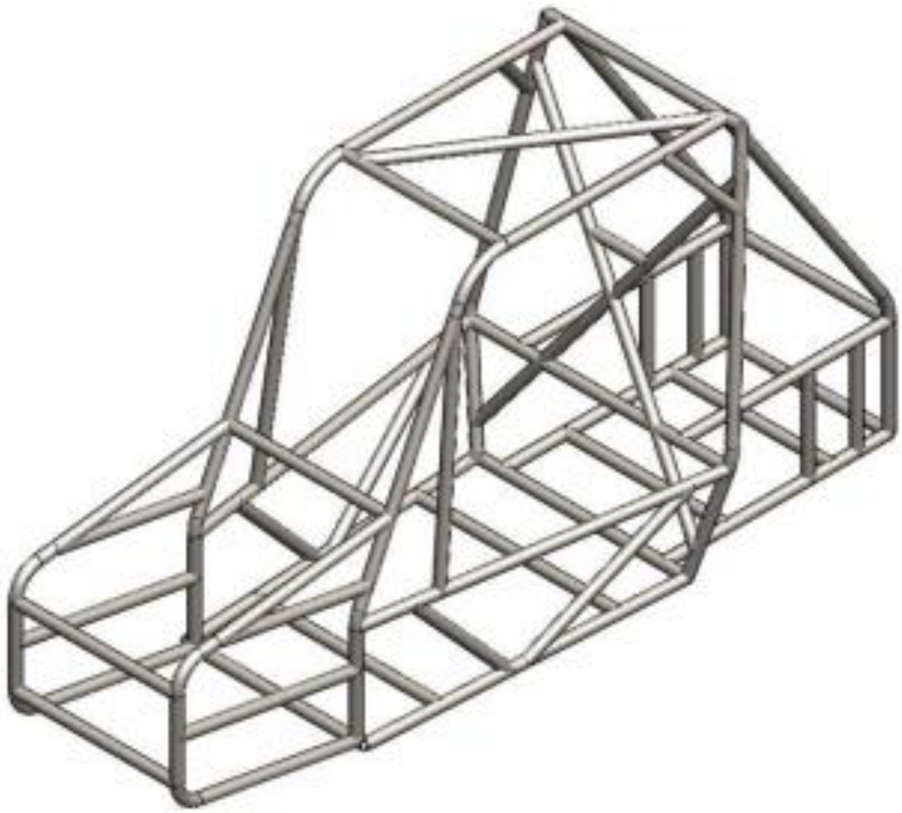


Figure 16: Frame Design for the 2013 N. Arizona University Mini Baja Team [Zane, 15]

These three frame designs were considered and influenced our design by giving us a set of pros and cons that we chose to work with. For instance, one of the "cons" we considered not doing was the idea of using only SolidWorks, like the above Northern Arizona University team chose to do. Instead, a "pro" that we chose to implement was the use of FEA analysis, like the Auburn University team chose to do.

4.4 | Key System Level Issues

When designing the frame, in order to reduce its weight while maintaining its structural integrity, a variety of Finite Element Analysis (FEA) models were used. These models were used to iteratively determine/highlight modifications needed in our final frame design; alterations were to be made until our desired criteria for the vehicle frame was satisfied. Two different tests were used to analyze our final, chosen frame design. It is noted that an additional design for the frame (separate from our final, chosen frame design) was planned to be analyzed using these same FEA models if project time constraints were not an issue; however, the final, chosen frame design was our primary focus.

FEA Model 1 looked to develop the optimal geometry for the subdivided sections of the frame. The LFS and QLS design process incorporated FEA Method 1. It is noted that the actual loading conditions seen on each of the various subsystems were far too complex to model in FEA, and FEA Method 1 involved considerable simplifications. The difference between the actual loading configurations and the loading configurations employed in FEA Method 1 is emphasized.

In the design of the primary and secondary members that make up the LFS and the QLC, loads were applied, in various configurations, to all four corners of this cube in order to create torsion and bending. This was done in order to observe how stress propagates throughout the frame, and to compare the maximum stress experienced between different geometric configurations. This would allow for better understanding of what geometry works best, for the already restricted combination of possibilities that exist for each subsystem and give rise to a supported decision for the best geometric configuration of the LFS and QLC. The system was modeled as beam members in 2D bending since only the deflection in the xy plane was of interest for this study. Two iterations of this configuration are shown below, in Figure 17.

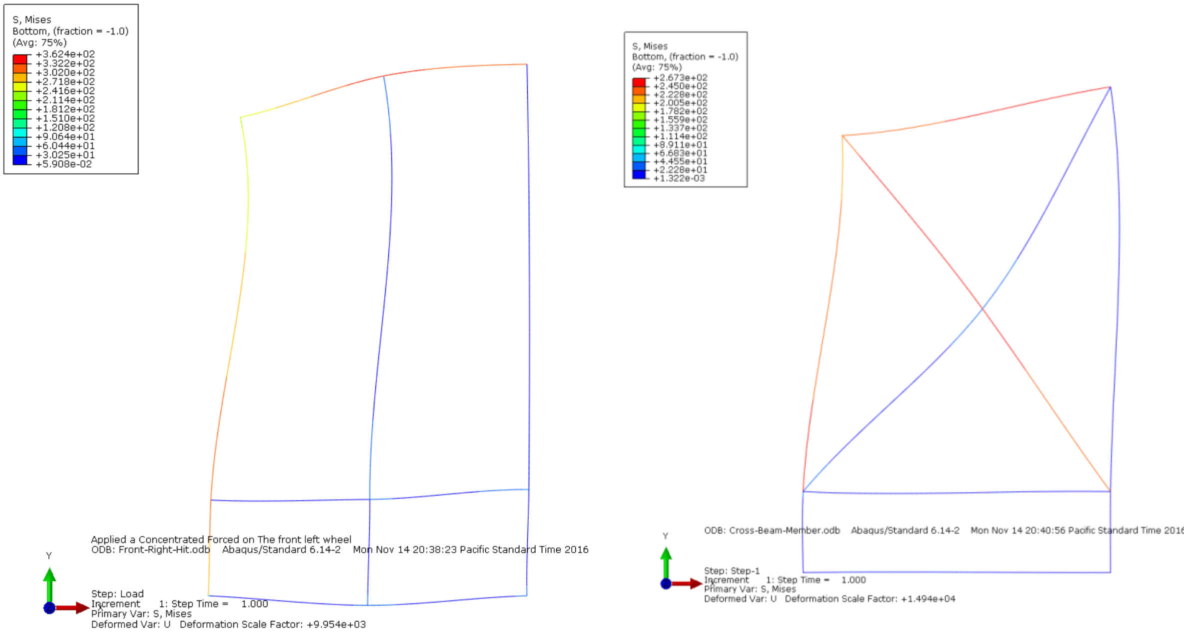


Figure 17: Abaqus von Mises Stress for Design 1 and Design 2 Respectively, in Order to Determine Which Design Dissipates the Concentrated Force Best. Red coloring indicates locations of higher stress while blue showed regions of less stress

As can be seen in Figure 17, Design 2 resulted in a lower stress of 2.675(e2) psi compared to Design 1 which had a maximum stress of 3.624(e2) psi. Since the tensile strength of 1018 steel is 53,700 psi, both models are well within the necessary stress range. The consideration of steel deflections was not included in this process. Although both models were well within the necessary stress range, Design 2 uses the most efficient design. This process was completed for all subsystems of the frame.

Method 2 of this analysis considered the propagation of stresses and strains induced by bending and torsion loads. Due to large bending and torsion loads subjected by the vehicle, an analysis on the propagation of the corresponding stress and strain was key to determine if the vehicle would plastically deform. This analysis was conducted using a Finite Element Analysis (FEA) Approach, with the use of the software package Abaqus.

The vehicle was created as a 3D sketch in SolidWorks and then imported into Abaqus, were it was modeled with the use of beam members. These beam members were assigned a pipe profile correlating with the primary members of the frame. These members were composed of 1020 Low Carbon steel and were meshed using quadratic elements and a beam type specification.

This system was then subjected to six tests, where loads were applied to various regions of the vehicle to simulate different crash scenarios and, as such, test its structural integrity. These tests were simulated statically with applied loads that would simulate a dynamic crash scenario, similar to a drop test. These tests were done with a safety factor of 3, which is typical for crash tests that would endanger human life. For these tests, the following assumptions were made:

<u>Assumptions</u>

- Frame can be modeled as Beam members.
    - Although Beam members are seen more often in static simulations.
    - Beam assumption due to limitation of Student Abaqus’ 250,000 Elements.
- Frame Impact can be modeled as Static, with applied loads.
    - This is done due to the complicated nature of beam to surface interaction specifications in Abaqus, which results in errors
- Beams meet at fixed points.
- Frame is a homogenous part, with no breaks in geometry.
- Weld geometry and material are not considered.
- Loads are applied instantaneously.
- Homogeneous material and consistent material properties.

- No Plastic Material Properties for 1020 Low Carbon steel.

After this approach was used to test a variety of different frame iterations, the final frame design was finalized; the different frame iterations were with respect to the ones shown in Table 5 below, and the finding for all tests can be seen in Appendix B.1. Once the fame was finalized, it was verified that it would not fail.

Table 6: Location of applied loads and reason for why loads were applied in that location

Test #	Location of Applied Loads	Reason
1	Front suspension points of connection	Front wheel impact
2	Rear suspension points of connection	Rear wheel impact
3	Top of the vehicle points of connection	Scenario in which vehicle flips over
4	Side members points of connection	Scenario in which vehicle falls sideways
5	Front of the vehicle points of connection	Crash impact on front part of vehicle
6	All Suspension points of connection	Normal/standard vehicle loading conditions

Table 7: Material properties used for beam members on the vehicle frame

Material	Yield Strength (psi)	Strain at Yield	Ultimate Tensile Strength (psi)	Modulus of Elasticity (psi)	Poisson's Ratio
1020 Low Carbon Steel	42748	0.0015	57249	29000000	0.29

As an example of this type of analysis, we now direct our attention to Test 5 in Table 6, where the frame is seen to simulate a head-on collision. For this test, the fame was constrained and had applied loads of 300 lbs applied as follows:

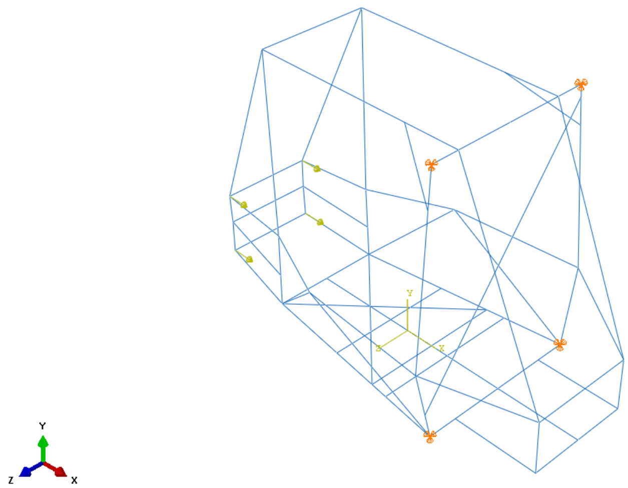


Figure 18: Constrained Frame(olive points) with Applied Loads(orange points)

After analysis, the following principle stress diagram was created, and is shown below..

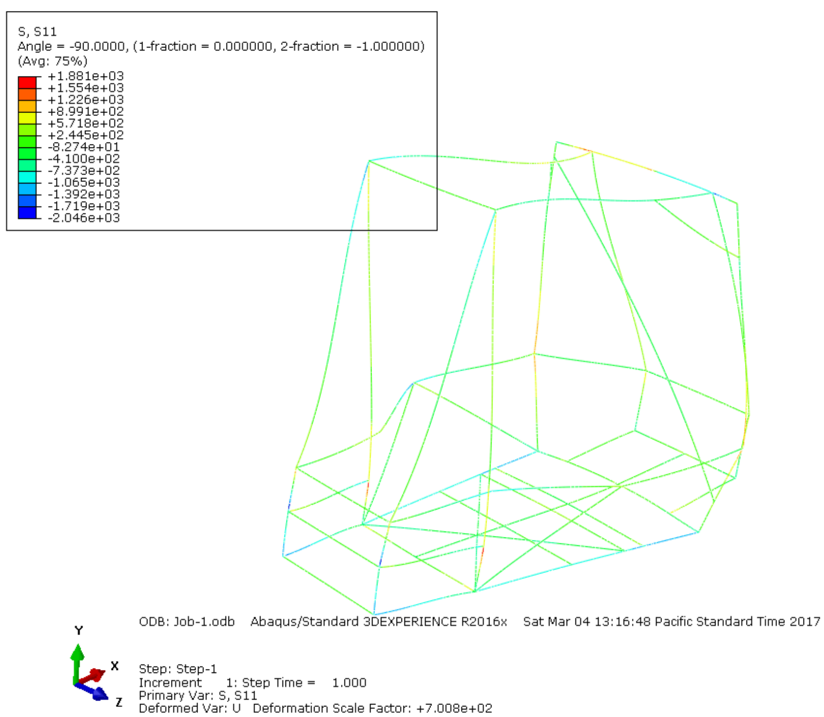


Figure 19: FEA Results for Front Impact of Frame Areas trending red were experiencing higher forces while those trending blue experienced lesser forces

By then comparing the maximum stress of 1.88e+03 psi to the yield stress of 1020 low carbon steel of 42748 psi, one can see that the frame would not fail due to this collision. The results of the other 5 tests, for the finalized frame, can be seen below.

Table 8: Final Stress and Strain Analysis for Frame

Test	Maximum S11 Stress (lb/in^2)	Maximum S12 Stress (lb/in^2)	Stress Mises (lb/in^2)	Maximum Displacement (in)	Strain Max. Prinicple
Front Right Force	1038	77.7687	2039	0.00245	0.00002522
Rear Right Force	6592	431.507	6592	0.00752	NA
Front Applied Force	1880	327.769	2220	0.01091	0.00006492
Side Applied Force	2340	270.318	2570	0.01494	0.00008190
Top Applied Force	1910	234.589	2130	0.00705	0.00006838
Rgular Weighted	2190	237.054	2560	0.01279	0.00007624

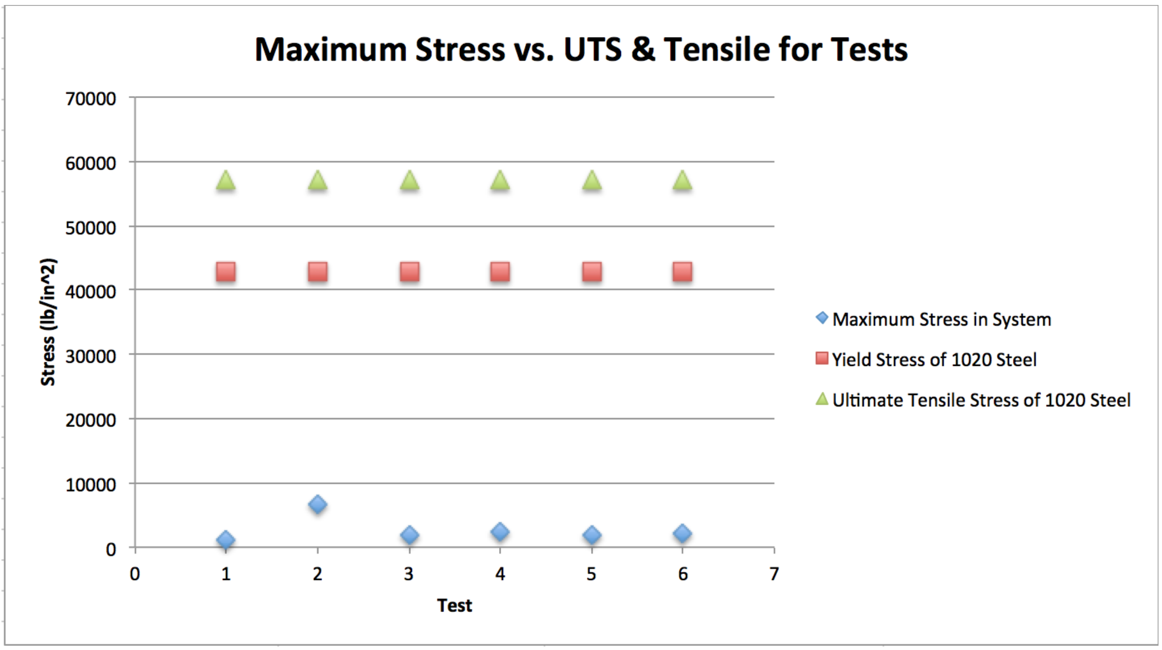


Figure 20: Stress Variation Results on the Final Frame Design for the 6 Tests in Table 8

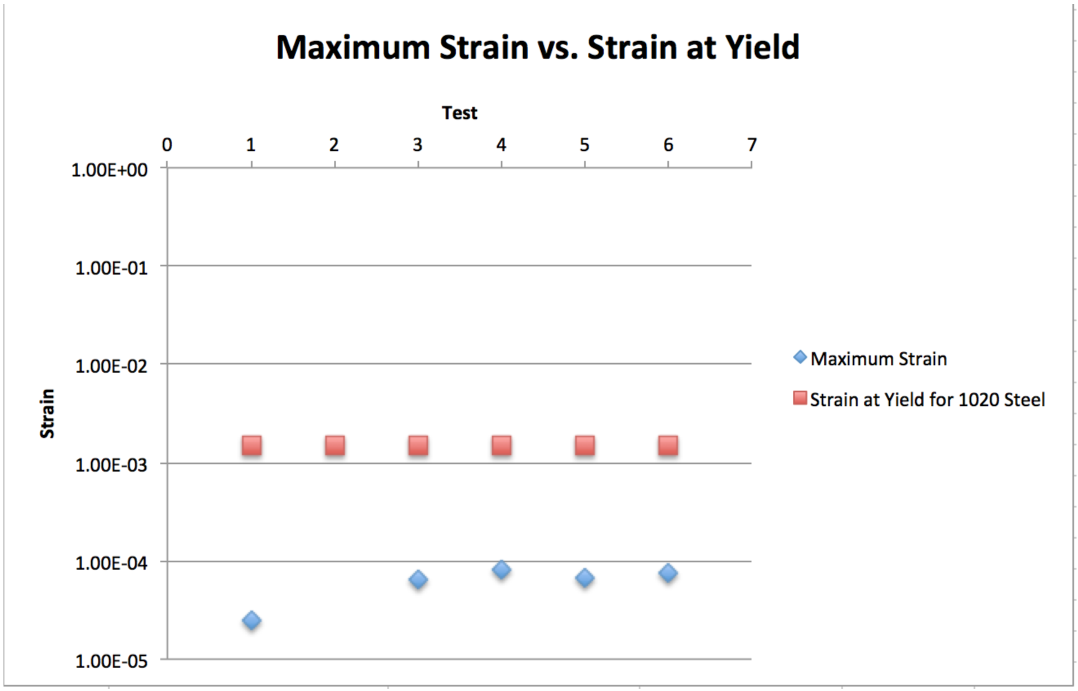


Figure 21: Strain Variation Results on the Final Frame Design for the 6 Tests in Table 8

The most obvious conclusion that can be taken from these tests is that the final frame design for our vehicle will not fail due to stress or strain propagations, experienced under the tested loading conditions. However, in order to develop the final frame design a number of iterations had to be done, After taking the 3D CAD model that was generated from Method 1, the LFS and RRH design had to be altered as the theoretical strain was past the failing point With regard to the attachments of the front and rear suspension initial tests showed that horizontal bracing members, QLC, had to be added to reduce the bending in the frame. This iterative process, where members were added and removed due to the variation in stress propagation required a number of tests, however images from these test were not saved. This is because during this process the frame design was changed so frequently that keeping each iteration would have been unnecessary and irrelevant. The final design, along with its supporting FEA analysis can be found below in appendix B.1.

However these findings should not be taken at face value. There were many assumptions made when conducting this static analysis, such as the strength of the welds and the assumption that these loads were statically applied. In a real life crash situation forces are applied dynamically and as such the response of our vehicle will most likely be different than that of our statically loaded model. Regardless, these results are valuable for us as a team to have. They give us a rough idea of what we can expect should our buggy ever encounter any of these scenarios. Even if our buggy was subjected to forces two to three times as large as those that we tested, it would still not fail due to stress or strain.

The final analysis approach, Method 3, looked to break the forces applied to the frame into inertial forces based on their location in the frame, and model the various components in the fame as lumped masses, as can be seen below.

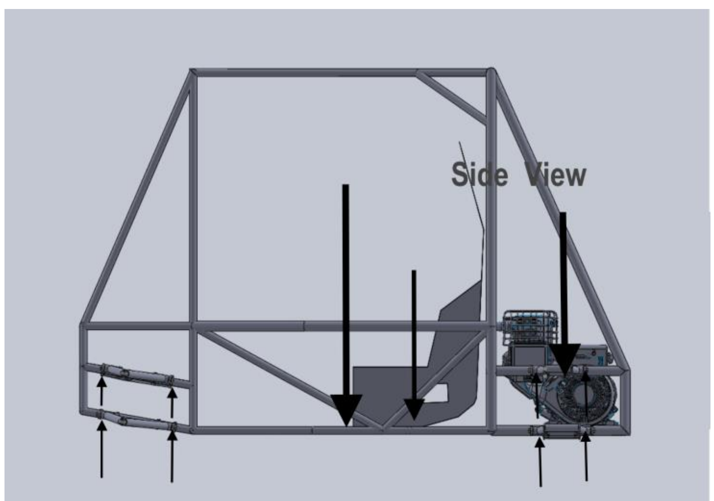


Figure 22: Frame Loading for Method 3 of FEA Analysis

This approach would consider a dynamic situation, in which the frequency of the shocks of 5 Hz, as such a time duration of .1 seconds would dictated the time application of the forces on the system. The applied forces to the system would take into account the maximum force output of Fox Float 3, which is 1750 lb’s as can be seen in Figure 23.

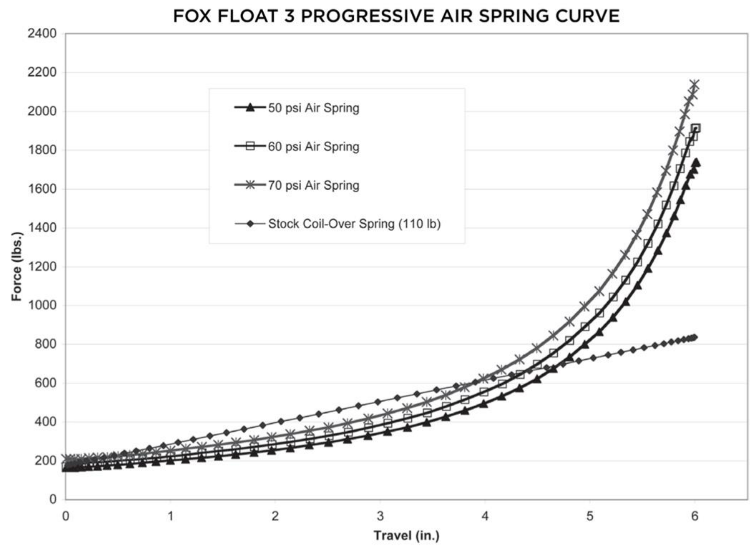


Figure 23: Fox Float 3 Used to Evaluate the Maximum Force Applied by the Air Spring

This analysis would have allowed for a more accurate representation of the forces on the buggy in order to refine the members used even more, however it was not needed.

4.5 | Design Process

In order to compete in the SAE BAJA buggy competition, the buggy's design must adhere to a variety of restrictions. Failure to follow these rules would prevent a team from passing the Frame Pre-Check and from competing. As such, it was first necessary to review, in detail, the rules and regulations that pertain to the frame. With the fundamental principles down, and a checklist made, it was then possible to begin considering a design.

Since this is the first SAE Buggy our team has built, it was necessary to familiarize ourselves with previous design processes. This was done by reading through past senior theses from SCU and other schools to gain an understanding of their approach. It was determined that the build for the frame should be a bottom up one, where we would design the lower members, i.e., the LFS and (F,Q,A) LC sections first. To gain a better idea of what an ideal frame would look like, we looked at winning buggies from previous competitions. This led to an inspiration for the designs above.

It was determined that our time should be spent developing a design that focused on minimizing the weight while keeping a low center of gravity. Although, it was initially believed that a more complex design would reduce drag, it was deemed a less critical issue due to the low speed the car would experience and small margin for improvement that could be made. Considering the minimal amount of time that was allotted for the development of the buggy, effort was allocated to areas that would achieve larger performance gains.

However, it was too soon to start developing a finished frame design, as the suspension, drivetrain and other major subsystems were still in their preliminary stages of development. Without the imposed restrictions, based off of each of those subsystems needs for the frame, it would be impossible to develop a final frame design. As such, a preliminary frame design, that was oversized, was developed that focused on meeting all of the SAE specific frame regulations, while considering overestimates for the required space for other subsystem attachment points. With a preliminary 3D sketch, a model was created in SolidWorks that could be slowly reduced in order to meet the goals of a lightweight and structurally safe frame design.

With the goal of developing a minimalist frame design, while still maintaining the structural strength of a larger and heavier buggy, the 3D sketched frame was broken up into subsections, one of which was the LFS and QLS cube that housed the driver, discussed earlier. With each of these subsystems the first FEA approach, seen above, was used in order to test different subsystem geometries. The goal was to develop a frame geometry, for each of the frame subsystems, that would reduce stress concentrations in the members and allow for even load distribution. This allowed for the reduction of much of the redundancy in the frame; that had been

3D sketched. At this point, most of the connection points to the frame for the larger buggy subsystem had been finalized, so it was then possible to refine the buggy to fit all external subsystems without excessive space.

With the frame roughly designed, in the sense that all connections points, along with SAE regulations and ideal geometry were meet, it was possible to look at the frame using the FEA Method 2. This method looked at the frame as a whole in order to verify that bending and torsion on the frame, given a variety of different loading conditions, wouldn't result in failure. In these tests, realistic loading situation were applied to the frame and the stress and strain propagation was looked at. This allowed for a finer tuning of the frame, and further reduction of redundant members, making sure that the frame wouldn't experience plastic deformation. This method allowed for a finalized design of the frame, that would meet the criteria of lightweight and structurally sound.

The final analytical approach, that was desired but not completed, was to look at the frame under actual running situation, seen by FEA Method 3. This approach would allow for a further refinement of the frame, but was not a needed test to verify the safety of the frame.

With the frame designed completed it was then necessary to fabricate the frame. This was done by first cutting and bending all the members to length, based on the finalized 3D design drawings. The members were then notched and tack welded together. A professional welder was then hired who completed the welds, abiding by the the necessary wield thickness and welding material for SAE standards. Metal tabs were then fabricated, and attached to the frame, which were used in order to attach the suspension, seat, engine, body panels, etc.

The final step to the frame design was testing the fabricated frame, to make sure, under typical loading, the frame would not fail. The main concern was not the bending of the frame, but the weld joints that connected the separate frame members together. This is because, if the joint was not properly wielded, the frame would fail there. This test was not completed, but would be possible by developing an apparatus that would fix the motion of the frame. By then applying sandbags, or other weights, in the positions of maximum bending and torsion, the frame's actual structural integrity could be verified.

4.6 | Cost Analysis for Frame

Table 9: Cost report for materials needed and manufactured to build the frame

Frame Subsystem											
Item	**Category**	**Description**	**Purchased**	**Fabricated**	**Vendor**	**Quantity**	**Material Cost**	**Labor Cost**	**Extended Material Cost**	**Extended Labor Cost**	**Extended Total**
1	Complete Roll Cage	1020 Steel DOM		X	Donghoonsp CO. LTD	1	$279.49	$0.00	$279.49	$0.00	$279.49
2	Body mounts	General Purpose Low Carbon Steel		X	McMaster-Carr	2	$35.38	$0.00	$70.76	$0.00	$70.76
3	Brake mounts	Master Cyclinder Attachment		X	McMaster-Carr	1	$35.38	$0.00	$35.38	$0.00	$35.38
4	Firewall	Corrosion-Resistant 1100 Aluminum Soft Sheet		X	McMaster-Carr	0	$56.04	$0.00	$0.00	$0.00	$0.00
5	Gussets	1020 Steel DOM		X	Donghoonsp CO. LTD	1	$279.49	$0.00	$279.49	$0.00	$279.49
6	Hitch	1.125 Diamater Low Carbon Steel, Rear Hitch		X	McMaster-Carr	0	$35.38	$0.00	$0.00	$0.00	$0.00
7	Seat	Summit Racing® Poly Performance Seats SUM-G1100	X		Summit Racing	0	$34.97	$0.00	$0.00	$0.00	$0.00
8	Seat Mounts	Summit Racing® Universal Sliding Seat Brackets SUM-G1153	X		Summit Racing	0	$33.97	$0.00	$0.00	$0.00	$0.00
9	Steering mounts	ididit Steering Column Floor Mounts 2401300010	X		Summit Racing	0	$29.76	$0.00	$0.00	$0.00	$0.00
10	Suspension mounts	General Purpose Low Carbon Steel		X	McMaster-Carr	2	$35.38	$0.00	$70.76	$0.00	$70.76
11	Transmission mounts	General Purpose Low Carbon Steel		X	McMaster-Carr	0	$35.38	$0.00	$0.00	$0.00	$0.00
12	Tube caps	High-Visibility Cap 10 pack	X		McMaster-Carr	1	$5.00	$0.00	$5.00	$0.00	$5.00
13	Other	Increased-Penetration Fast-Deposit Stick Electrodes for Steel	X		McMaster-Carr	1	$9.44	$0.00	$9.44	$0.00	$9.44
14	Other	Engine Connection Plate 4 holes .120 General Purpose Low Carbon Steel		X	McMaster-Carr	1	$35.38	$0.00	$35.38	$0.00	$35.38
15											
16											
17											
18											
19											
20											
21											
22											
23											
24											
25											
		Subsystem Assembly Time (min)		300	Subsystem Assy Cost					$175.00	$175.00
		Totals							$785.70	$175.00	$785.70
									Total:		**$960.70**

Building the frame required the purchase of various parts and materials. Table 9 highlights all of these parts and materials such as seat mounts, tube caps, 1020 steel tubes, etc. As can be seen in Table 9, the total cost including manufacturing of the frame came out to be about $960. It is important to note that a lot of the manufacturing cost, such as cutting tubes and welding, were avoided by donations. In addition, companies such as the one the team went to for bending the tubes offered their service for a discounted price which helped decrease the overall manufacturing cost.

5 | Subsystem Level Chapter: Drivetrain

5.1 | Intro to Role/Requirements of Drivetrain

For the SAE competition, all teams were issued the same Briggs & Stratton engine. This engine is a four stroke 10 HP engine specifically designed for the BAJA SAE competition. Teams were not allowed to modify the engine in any way, as such the only way to alter vehicular speed and acceleration was through careful manipulation of the drivetrain. Our primary focus was always on manipulating gear ratios and providing ourselves with enough gears to effectively operate the buggy through the various environments that it would encounter.

5.2 | Summary of Options and Trades

There exists many different options for the drivetrain of a buggy. Drivetrains off of similar sized go-karts offered a possible solution. The similarity between these two systems sparked a great amount of interest within our team. By incorporating the entire drivetrain assembly off of a pre-existing go-kart, design and manufacturing would have essential been cut out. Similarly, our team also looked at axles, transmissions, chain, sprockets, bearings, etc. from other off-road recreational vehicles. For the most part, parts off of full sized quads were found to function as possible solutions to our drivetrain assembly.

The idea of going with an existing drivetrain assembly quickly went out of consideration. Instead, our team looked forward to the challenge of constructing our own assembly.

5.3 | Systems Sketch

The diagram below outlines the system:

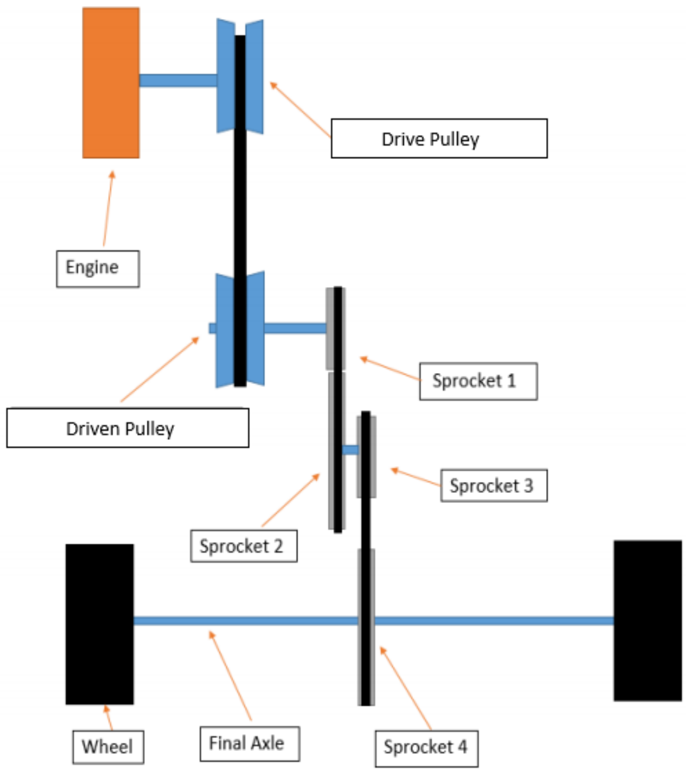


Figure 24: Mating of the Transmission

Diagram explanation:

a. The orange block (the engine) provides power to the drive pulley of the CVT which then via a belt powers the driven pulley of the CVT.

b. That pulley is on a jackshaft that transmits the power to sprocket 1

c. Which then uses roller chain to power the next sprocket (Sprocket 2)

d. Sprocket 2 is on another jackshaft that spins sprocket 3

e. The same chain drive is repeated from sprockets 3 to 4

f. Sprocket 4 powers the final drive axle or shaft

Figure 25 below shows a CAD model of the actual setup:

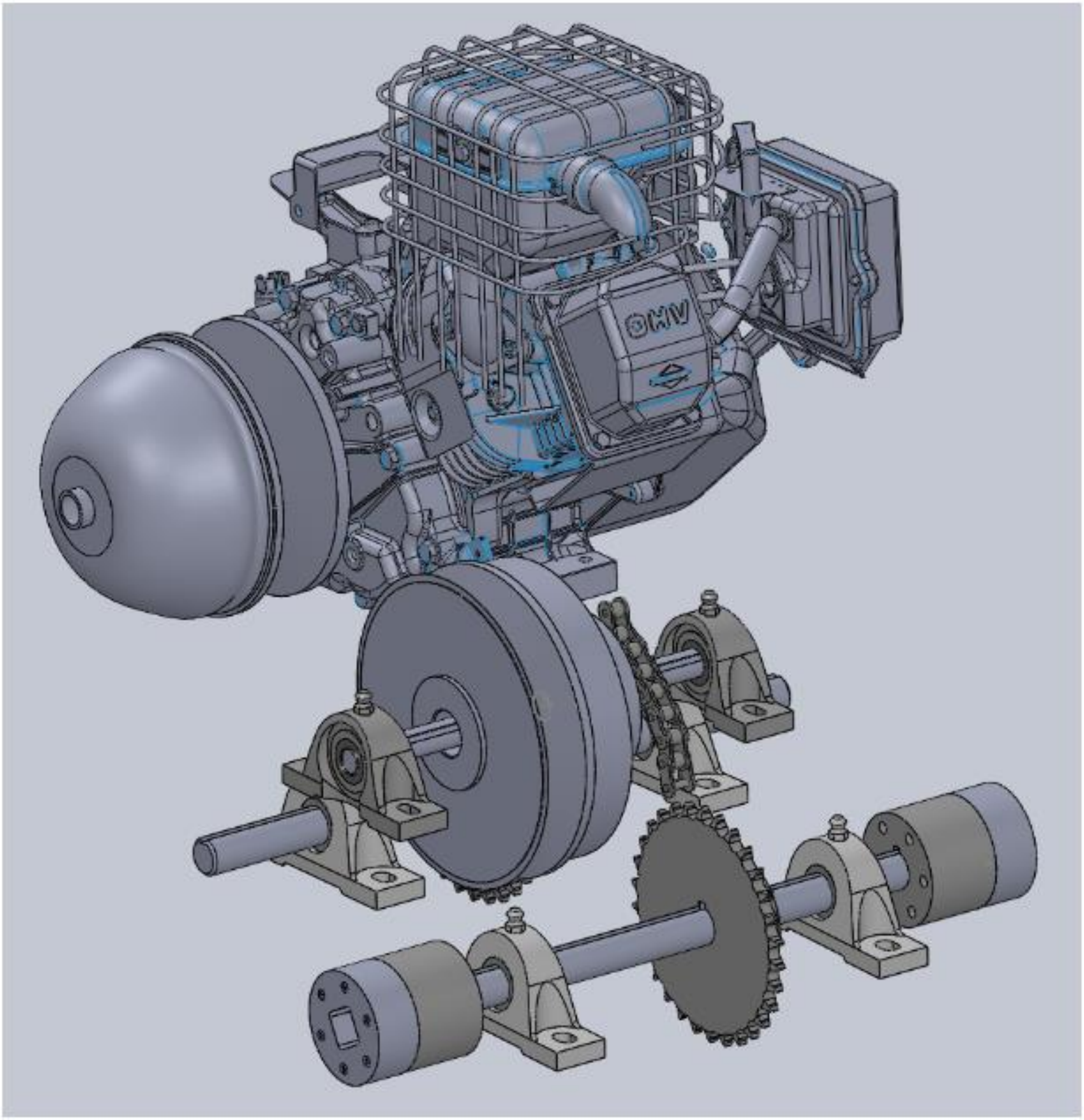


Figure 25:CAD Model of Drivetrain

5.4 | Benchmarking Results

Most teams seemed to favor a continuously variable transmission or CVT. This kind of transmission allows for a wide range of gear ratios that are intrinsically tied to the RPM range of the engine. The NAU Baja team saw some benefits to using a CVT as well as some drawbacks [7]. The high (.45:1) and low (3.1:1) end ratios provided by their CVT were not ideal for the goals that they had in mind [6]. From the CVT output, they decided to connect a 2 stage sprocket assembly in order to achieve the final output ratios that they desired. West Virginia's 2015 team also decided to go with a CVT into a gear reduction assembly in order to achieve their desired final ratio of 19:1 on the low end [5]. The benefits of the CVT were clear in that it allowed for a large range of gear ratios. The only concern was finding the correct gearbox assembly to couple with the CVT in order to obtain the desired high and low end performance.

5.5 | Key System Level Issues

Initially, our team had interest in solely using a CVT but we also had issues with its desired effects at very low speeds. The reason this was seen as an issue is because these kinds of off-road vehicles are meant to navigate on hill climbs and log jumps, which require most of the engine's torque at a low rpm range. A CVT is continuously variable so it is really hard to hold it in a specific torque range effectively.

5.6 | Design Process

Like NAU and West Virginia's team, our design ultimately settled on a compromise of the CVT and traditional geared transmission. Through the transmission comparison matrix below we were able to arrive at this decision.

Table 10: Transmission Requirements Matrix

	User Friendly (0.2)	Manufacturability (0.3)	Cost (0.3)	Efficiency (0.2)	Total
Manual Gearbox	1	2	2	3	2
Continuously Variable	2	3	3	2	2.6
Combination	3	3	2	3	2.7

The plan in mind with the CVT was that it would allow for gear ratio variability. The fixed gearbox would then be used to ensure that there would be adequate low range capacity. Our vision was to have a 4:1 high end ratio and 27:1 low end ratio. These values were obtained from ratios used by previous teams and assumptions made on what the terrain and obstacles at the competition would be like. Even though we didn't compete, a CVT, jack shafts, sprockets, axles, pillow block bearings, and chain was purchased.

6 | Business Plan

6.1 | Overview

The Society of Automotive Engineers clarifies the market for our mini baja vehicle in the 2017 rulebook, which states that “the vehicle is to be a prototype for a reliable, maintainable, ergonomic, and economic production vehicle which serves a recreational user market, sized at approximately 4000 units per year” [5]. It also mentions that the vehicle should strive to have “market-leading performance in terms of speed, handling, ride, and ruggedness over rough terrain and off-road conditions” [5]. In other words, the vehicle must be easy to manufacture/replicate due to the large demand, but without sacrificing quality in its driving performance.

On top of performance, the SCU Mini Baja team aspired to follow all other constraints and criteria listed in the rulebook while using good engineering practices. The team focused on creating a vehicle that was low in cost, but also overly safe. Aiming to create a very durable and safe vehicle limits the risk of lawsuits from injuries, and would thus save the fictitious firm money and maintain a reliable reputation. The later subsections describe the team’s business plan for the Mini Baja buggy.

The Mini Baja buggy itself is a single-driver all-terrain vehicle. It is a front wheel drive vehicle that is capable of crossing any and all obstacles that it is met with. The frame is extremely durable, built for speed and with the highest protection of the driver in mind. Customers for this Mini Baja buggy are for example, park rangers and adrenaline seekers. Disaster relief is an excellent use for this model because it is capable of reaching the most unreachable destinations. Its agile and small in size make it ideal for getting through tight spaces. It is also for those seeking adventures. The fast acceleration and high top speed are exhilarating. In addition, the suspension makes it capable of going off jumps. This Mini Baja buggy helps those in need of immediate medical attention and those seeking fun.

6.2 | Cost

Based off of the cost analysis for this buggy, which is stated in the budget portion of this report, the cost of materials for this project is approximately $10,000/unit. The cost of fixed/variable labor is approximately $8,000/unit. However, since the majority of the labor cost for this project was out of house, the actual labor cost for the company would be cheaper by hiring employees and buying equipment to do almost everything in house. Also, since materials will be purchased in greater bulk, the total cost of materials will be much lower. The business is assumed to have cost percentages of roughly 25% overhead, 65% materials, and 10% labor. Based on the percentages, the overhead cost would be around $650,000/month for a business producing 4,000 units per year when supposing a new material cost of $5,000/unit and a new labor cost of $800/unit. The breakeven price per unit would be around $6000 (overhead/# of units + materials + labor). In order to turn a decent profit, the price would be estimated at around $10,000/unit. In attempts to earn more money, the company could look into other similar vehicle types to be sold, such as offering multiple-person vehicles and two-wheel bikes. Expanding on a variety of inventory would bring in a variety of customers, and hence more profit.

6.3 | Gaining Customers

Customers will learn about the business through advertisements such as TV ads and billboards, as well as online searches. The company will invest in SEO, or Search Engine Optimization, which will allow it to be the first result when keywords for the product are searched online. The company will encourage referrals by offering a discount, such as 5% off, if you refer another customer. This will help spread the word and foster a loyal customer base.

The company could be a useful sponsor in all-terrain races such as Motocross and the SAE Mini Baja competition. Sponsoring a vehicle can get the logo out to target customers. Social media campaigns and using celebrity endorsements are also ways in which the company can engage potential and current customers. Overall, having strong customer service is important to keep this customer base prosperous.

6.4 | Success

The company will know its success when their target number of customers and annual net income is growing consistently. The benefits must outweigh the costs in order to properly measure out to success. Once the company is running with this positive income and clientele, it will know its success.

7 | Engineering Standards and Realistic Constraints

7.1 | Economic

While designing the buggy, the team had to make several engineering decisions that affected the cost of the project. One of these decisions was made in the interest of saving time and money. The team decided to make the entire frame of the buggy and suspension control arms out of primary steel members with a 0.120 in. wall thickness. In doing this, the team could minimize the variance in material and was able to buy steel tubing in bulk. The bulk price the team payed turned out to be $279.49 instead of $592.44 for different diameter and wall thickness tubes [16]. As a result, the team was able to save $312.95, which was used to buy other necessary parts. However, if the team wanted to make improvements to the buggy in terms of weight and speed, investing in the secondary members could make it more attractive to consumers. The lighter frame would also increase fuel economy which can be seen as another reason to improve the design.

7.2 | Environmental Impact

In the design of the Mini Baja buggy, there are important environmental impacts that we as engineers need to acknowledge. The most significant are the steel tubes used to construct the frame of the buggy because they entail considerable risks to the environment. In essence, steel is iron nearly fully deplete of carbon, and 98% of the iron ore that is mined in the United States is used to make steel, including the steel we used for our project [17]. What is often overlooked is that the iron ore impacts the environment because it is extracted and is then converted into a variety of iron types through manufacturing processes, the most common being using blast furnaces to produce pig iron. Upon deep reflection along the lines of environmental impact, a great factor is the energy usage required to process, manufacture, and transport the steel which can be seen in the bar graph provided in the appendix [18,19]. With the energy used for manufacturing steel comes gas emissions such as CO2. Also, waste material that detrimentally impacts the environment also need to be acknowledged, such as the molten slag by-product. Optimizing the recycling process is necessary to mitigate environmental damage; fortunately, the molten slag by-product is often reused to make concrete.

7.3 | Manufacturability

Manufacturability is a critical aspect of the Mini Baja project. SAE's rulebook states that teams should approach the project as if the vehicle they are designing will serve a market sized at approximately 4000 units annually. The single prototype constructed for the competition has taken nearly a year by itself, so in order to scale production by 4000 times it is necessary to explore more efficient manufacturing techniques. The current manufacturing process has been handled almost entirely by students and has yielded a handmade vehicle. Expediting the manufacturing and assembly of the vehicle could be done in many ways.

One method would be to continue the handmade process as it is now but expand the production by hiring more skilled employees to build multiple vehicles at once. This option is a viable choice since 4000 annual units is a quantity that could definitely be handled by a large number of skilled employees. The drawback to this is that a large skilled workforce would demand a large payroll expense. The large bi-monthly expense would be siphoning money away from a growing business and it could be detrimental.

Another option is to seek automation through machinery that could produce the same results quickly and consistently. The obstacle standing in front of this option is that it requires enough upfront capital to invest in expensive automated machinery.

Another possible choice would be to manufacture using a combination of skilled labor and automation; for example having a CNC bend and notch the frame tubes prior to sending them to a human welder. This would mean the frame joints fit perfect every time so the welder does not have to do any fitting and trimming by hand, they could just come in at that point and weld the frame together. A small skilled labor force would not place drastic payroll demand and humans could replace certain expensive machines that are not deemed absolute necessities to meet production goals.

In order to meet the annual goal of 4000 units, running a production facility 5 days a week, means that at least 16 vehicles have to be manufactured per day. The vehicle was designed to use mostly off the shelf parts for serviceability but this also aids in manufacturing. With the exception of the tubular space frame, suspension control arms, and a few custom parts for the drivetrain, the entire vehicle is constructed of mass produced parts from other manufacturers that have absolutely no problem meeting demand. The entire manufacturing performed in house would be limited to the frame, control arms, and drivetrain components; the rest of the production process would essentially be assembly.

7.4 | Sustainability

Sustainability is defined as the ability of something to last and function properly over a long period of time, by use of methods that do not completely use up or destroy natural resources. One of the main goals of our team's platform was to be able to pass down this project to the future seniors of Santa Clara University. To move forward with this goal, our team has planned to start SCU's first ever Baja Club — a club designed for engineers (preferably Mechanical), with a passion for manufacturing and design, and an interest in our SCU Baja Buggy Senior Design Project.

By starting an on campus club, our senior design team is ensuring that this will be an ongoing project over the next few years at Santa Clara University. We plan on giving future seniors the option of using the existing buggy that our team has produced over the course of our senior year, and improving upon our current designs. While there are certain parts of our buggy that can obviously be replaced, such as the engine and transmission, there are many resources that uphold the definition of what we have deemed sustainable, such as our team's frame and the suspension, which we expect future seniors to keep and develop.

Therefore, by choosing not to dispose of our buggy, and instead offering to pass down our designs and resources that we have acquired and machined, future seniors of SCU will have the opportunity to remanufacture our existing parts. Remanufacturing conserves the energy embodied in a product, and, compared to traditional manufacturing, requires minimal additional energy usage. Our team strives to instill these ideas and values in the Baja Club and hope that the future design teams will uphold our vision of sustainability for years to come.

7.5 | Health and Safety

This vehicle was designed for the SAE International Competition, and therefore strict requirements and rules specified by the SAE organization needed to be met. Some of the requirements focused on frame design, construction process, driver restraints, fire protection, fuel isolation, etc. The design of the buggy was created in a way to provide a safe ride for the driver while being able to enjoy the thrill of the rough terrain at the same time. While many of the safety restrictions demanded by SAE laid the foundation for a preliminary frame design, there still existed some room to incorporate some ingenuity and creativity into the final product. The frame design was created in such a way that it could withstand the harsh loads generated on the vehicle as it traverses rough terrain, jumps, and the high impacts associated with a crash. The final design of the frame was heavily dependent on conclusions drawn from finite element simulations in ABAQUS. Besides overall construction of the frame, there were also specific instructions for placement of items like the fire extinguisher mounts, driver restraint mounts and kill switches on the frame.

SAE's rulebook also dictated driver safety items that are out of the hands of the vehicle manufacturer when this product is introduced to market [20]. As a designer and manufacturer of the vehicle we are responsible for meeting all of the vehicle safety requirements, but once the vehicle is in the possession of others it is their responsibility to follow safety guidelines. For example drivers must take all the necessary precautions such as wearing a helmet, firesuit, and buckling their seatbelts.

7.6 | Arts Requirement

Table 11: Parts and Assembly Drawings

Team Member	Description	Location (page #)
Westley Tusa	FBM Low (F001)	91
Westley Tusa	FBM Up (F002)	92
Westley Tusa	LFS Member (F003)	93
Westley Tusa	FAB Upper (F004)	94
Westley Tusa	FAB Mid (F005)	95
Matthew Nagy	FAB Low (F006)	96
Matthew Nagy	SIM (F007)	97
Westley Tusa	SIM Brace 1 (F008)	98
Christian Hellmers	SIM Brace 2 (F009)	99
Westley Tusa	Suspension Bar (F010)	100
Westley Tusa	Rear Roll Hoop RRH (F011)	101
Chad Russick	RRH Bracing Member (F012)	102
Westley Tusa	Gusset (F013)	103
Angel Robles	Support Beam (F014)	104
Westley Tusa	ALC Support (F018)	105
Christian Ruiz	USM 1 (F019)	106
Matthew Nagy	USM 2 (F020)	107
Christian Ruiz	USM 3 (F021)	108
Anmol Jones	LFS Support (F022)	109
Angel Robles	Tube Adaptor (S016)	110
Ruben Contreras	Plastic Ends (S020)	111
Mauricio Jimenez	Chassis Tabs (S021)	112

Mauricio Jimenez	Control Arm Bushing (S022)	113
Mauricio Jimenez	CV Coupler Outboard (S023)	114
Matthew Nagy	Font Lower C.A. (2024)	115
Angel Robles	Front Upper C.A. (S025)	116
Christian Ruiz	Front Lower C.A. Assembly (A001)	117
Christian Ruiz	Front Upper C.A. Assembly (A002)	118
Christian Ruiz	Rear Lower C. A.	119
Christian Ruiz	Reap Upper C.A.	120
Christian Ruiz	Rear Lower C.A.A. (A003)	121
Christina Ruiz	Rear Upper C.A. Assembly (A004)	122
Christian Ruiz	Buggy Assembly (A005)	123

8 | Summary and Conclusion

8.1 | Conclusion

Though our design was never fully assembled and manufactured it is still possible to evaluate its overall design qualities and shortcomings. Our vehicles strongest qualities were its overall strength, low cost, and ease of manufacturability. The entire frame was made out of primary one inch steel tubing members, compared to buggies that may utilize smaller secondary members to reduce weight, this greatly improved its overall survivability. In addition to this, our CV couplers were purposely oversized giving them a safety factor of 8 to ensure that any rotational forces that they experienced would be easily handled by the couplers. In addition our Baja team designed or vehicle to be primarily fabricated from off the shelf parts and hardware that could easily be sourced. In addition to this, our frame was designed in such a way that their would only be straight members butting up against each other or meeting at joints; there would be no curved members in our buggy to keep assembly and manufacturing costs down. The only downside to this tradeoff is that we potentially added more weight to the vehicles by not employing innovative curved weight saving members. By having low manufacturing costs, we also ensured that our manufacturing process would also be easier since lower cost manufacturing processes are obviously faster and easier to perform.

It must be noted that our design was fairly standard among Baja vehicles. It employed no new novel design techniques or parts. It must be noted though, that our A-Arm assemblies, and CV axle Couplers were designed and fabricated by our team. Our vehicle also employed a Continuously variable transmission manufactured by CV tech in Canada that was used by winning teams in the past three years in the competition. In addition to this our frame and suspension designs were based on previous successful Baja vehicles that were semi reverse engineered to suit our buggies needs.

We offer some advice for future Santa Clara University teams seeking to participate and compete in the SAE Baja competition. Firstly as pointed out early in this thesis in Section 2.5.3| Risks and Mitigations you will have a time crunch from the get go. If a future Santa Clara team cannot establish themselves in the spring of their Junior quarter then they will be at the same disadvantage as our team was. This is not death knell however, as previous Baja SAE teams with as little as four members have manufactured and competed in the competition within a school year. All being said, time is of utmost importance and it would be wise for future Baja teams to form regular meetings and seek to achieve their laid out goals on time. Otherwise things can quickly get out of hand.

In addition to time being a limiting factor for future teams, so will cost. As of this year, we were only able to secure about a quarter of the financing that a typical SAE Baja team would typically operate on. If a future team is able to secure around 20,000 dollars by the start of winter break, then they could easily expect to have their entire buggy to be fabricated by third party vendors by the end of winter quarter, and would therefore be prepared to race in that coming spring.

Appendices

Appendix A: References

[1] C. David, A C. David, G James al., “Lessons learned from starting an SAE Baja program in a small liberal arts

college,” American Society for Engineering Education., Washington, DC, Rep. 3714, 2012

[2] M. Allen ., “A hybrid transmission for SAE Mini Baja vehicles,” SAE International., Warrendale, PA, Rep. 0045, Sep. 2003

[3] T.O. Taylor , “Structural considerations of a Baja SAE frame,” SAE International., Warrendale, PA, Rep. 3626, Jan. 2006

[4] D’Amico, Dan, Curtis May, Greg Schaffran, Peter Morabito, Michael Paliga, and Brian Ross. SAE BAJA Final Report. Rep. N.p.: n.p.,n.d, Print

[5] Bovard, Kaylah, Wyatt McClead, Farshid Zabihian, Winnie Fu, and Bernhard Bettig. *SAE Baja Multi-Speed Transmission/Transaxle*. Department of Mechanical Engineering West Virginia University Institute of Technology, 2015. Web. 20 Apr. 2017.

[6] Almuflih, Abdulrahman, Andrew Perryman,, Caizhi Ming, Zan Zhu, and Ruoheng Pan. *SAE Mini Baja Drivetrain*. *Engineering Analysis*. Department of Mechanical Engineering Northern Arizona University, Fall 2013. Web. 20 Apr. 2017.

[7] Pires, Hermes. *GrabCAD - CAD library*. N.p., 01 July 2015. Web. 07 June 2017. https://grabcad.com/library/suspensao-dianteira-sae-baja-front-suspension-for-sae-baja-1

[8] Schlereth, Tripp, and Stephen Sparks. *2010 Baja SAE Suspension*. Rep. Auburn University, April & May 2010. Web. Nov. 2016.

[9] *Speednik*. N.p., 2014. Web. http://cdn.speednik.com/files/2014/12/8-mikes-race-photo-i-beam-camber.jpg.

[10] SGC Suspension. N.p.. Web. 6 Dec 2016

[11] "Vsusp: Default Values." *Vsusp.com*. N.p.,Web. 13 Aug. 2015.

[12] "SAE Collegiate Design Series," in SAE International, 2017. [Online]. Available: https://www.bajasae.net/content/2017_BAJA_Rules_11_21_16.pdf.

[13] "Formula SAE Anthropometric Reference Data." *Formula SAE* . N.p., 23 Nov. 2015. Web. https://www.fsaeonline.com/content/FSAE%20Rules95th_2016.pdf.

[14] T. Swarbrick, D. Fernandez, N. Arcelona. "SAE Mini Baja," 2007. Print. Accessed: Nov. 3, 2016

[15] C. Zane , "SAE Mini Baja: suspension and steering., Northern Arizona University., Flagstaff, AZ, 2014

[16] "Metals Depot® Shopping Cart", Metalsdepot.com, 2017. [Online]. Available: http://www.metalsdepot.com/catalog_cart_view.php?msg=removed. [Accessed: 03- May-2017].

[17] 2017. [Online].

http://www.greenspec.co.uk/building-design/steel-products- and-environmental-impact/.

[18] "How much energy does it take (on average) to produce 1 kilogram of the following materials?", LOW-TECH MAGAZINE, 2017. [Online]. Available: http://www.lowtechmagazine.com/what-is-the-embodied-energy-of-materials.html.

[19] CESEduPack. UK: Granta Material Inspiration, 2016.

[20] SAE International, "Baja SAE® Rules", SAE International, 2017.

Appendix B: Subsystem Calculations

Appendix B.1: Frame

<u>Finite Element Analysis for Structural Integrity of Frame</u>

Test 1: (Applied Load to Front wheel**)**

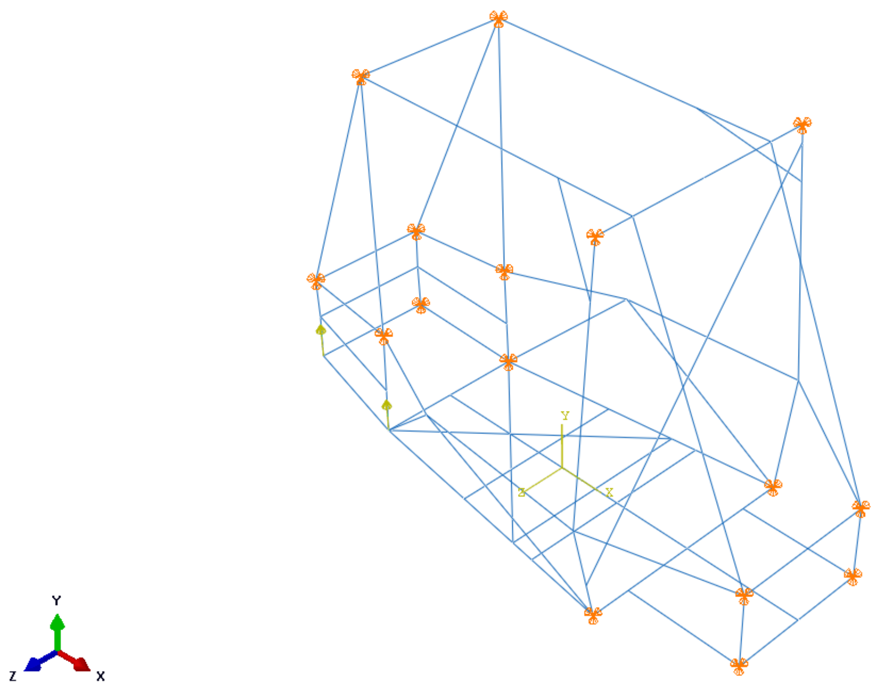


Figure A.1: Constraints used to perform FEA analysis for Load applied to front corner.

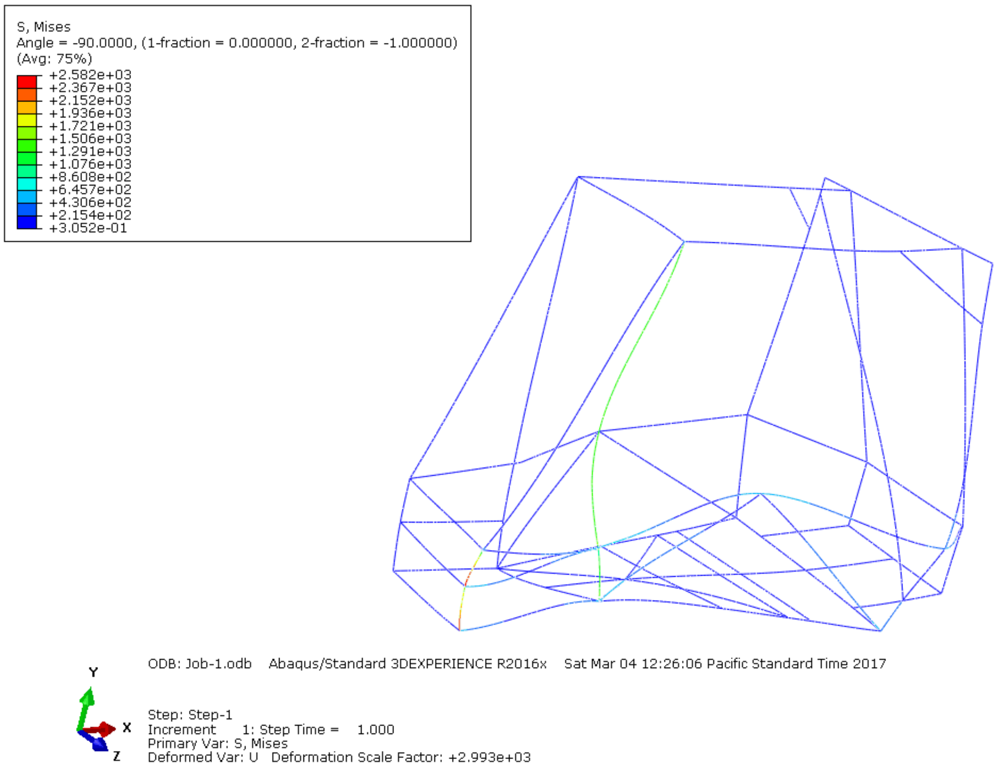


Figure A.2: Stress associated with volumetric change of frame, used to give a representation of the frame distortion due to front impact for final frame design. Scale Factor: 2.59e3

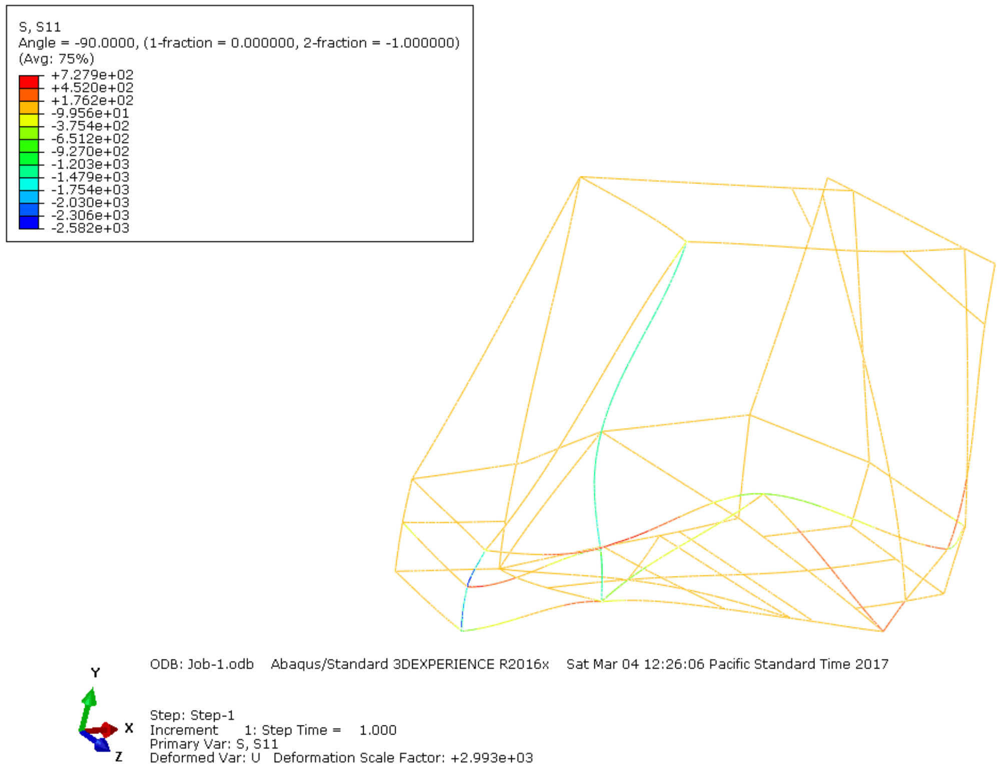


Figure A.3: Stress associated with the xx direction, used to validate the structural integrity of frame with respect to yield of 1020 steel.

Test 2: (Applied Load to Rear wheel**)**

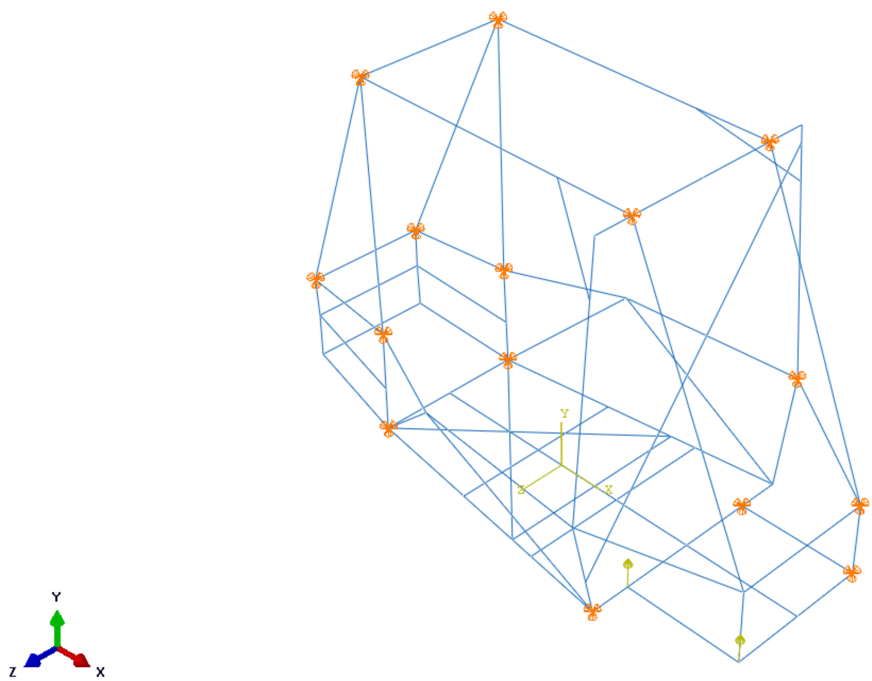


Figure A.4: Constraints used to perform FEA analysis for Load applied to rear corner.

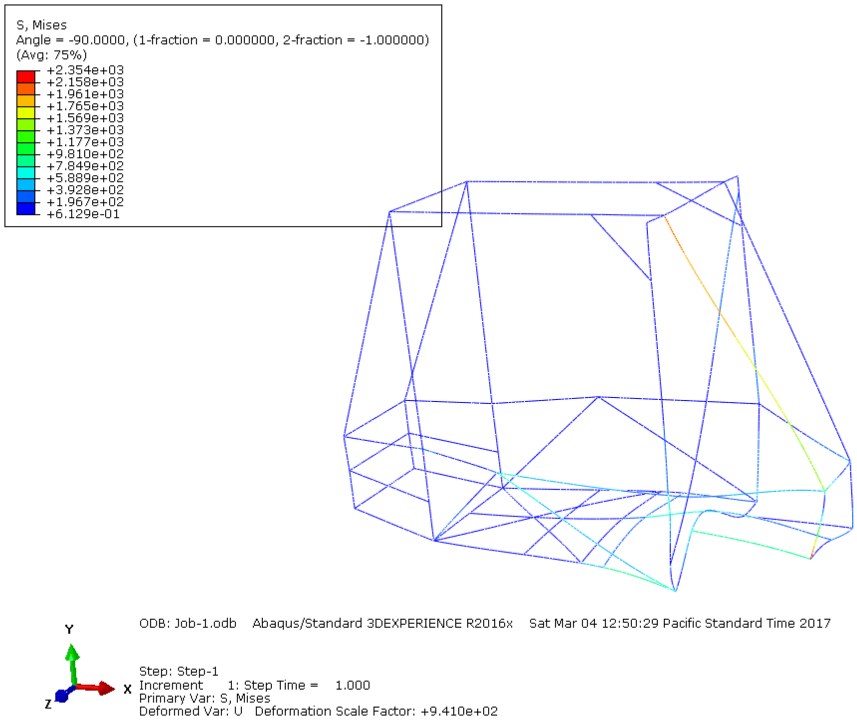


Figure A.5: Stress associated with volumetric change of frame, used to give a representation of the frame distortion due to rear impact for final frame design. Scale Factor: 9,41e02

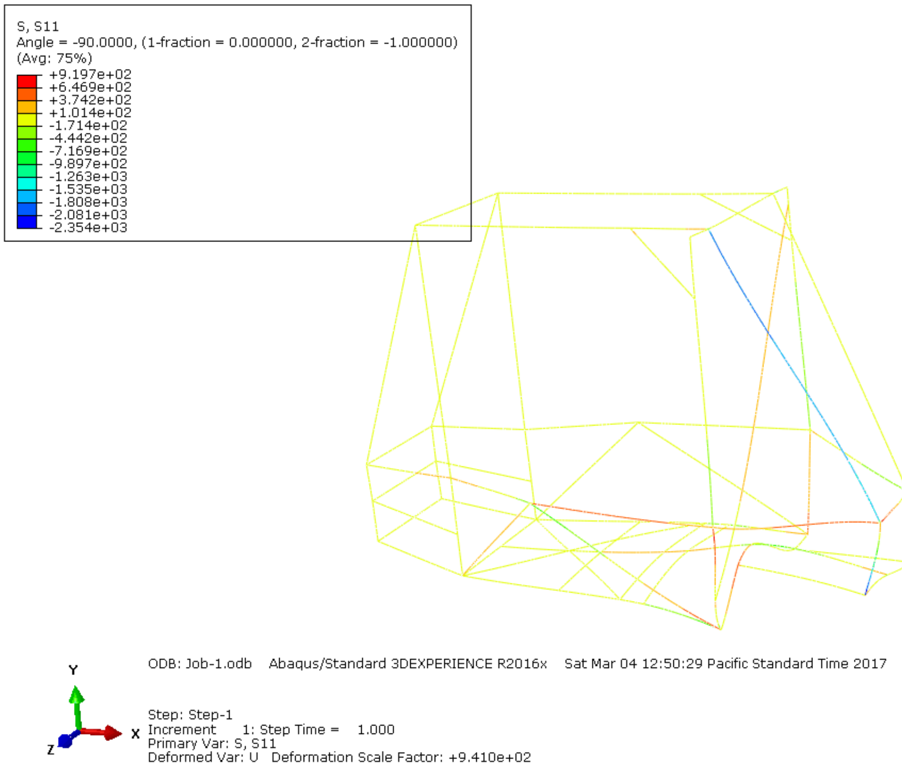


Figure A.6: Stress associated with the xx direction, used to validate the structural integrity of frame with respect to yield of 1020 steel.

Test 3: (Applied loads to top of frame)

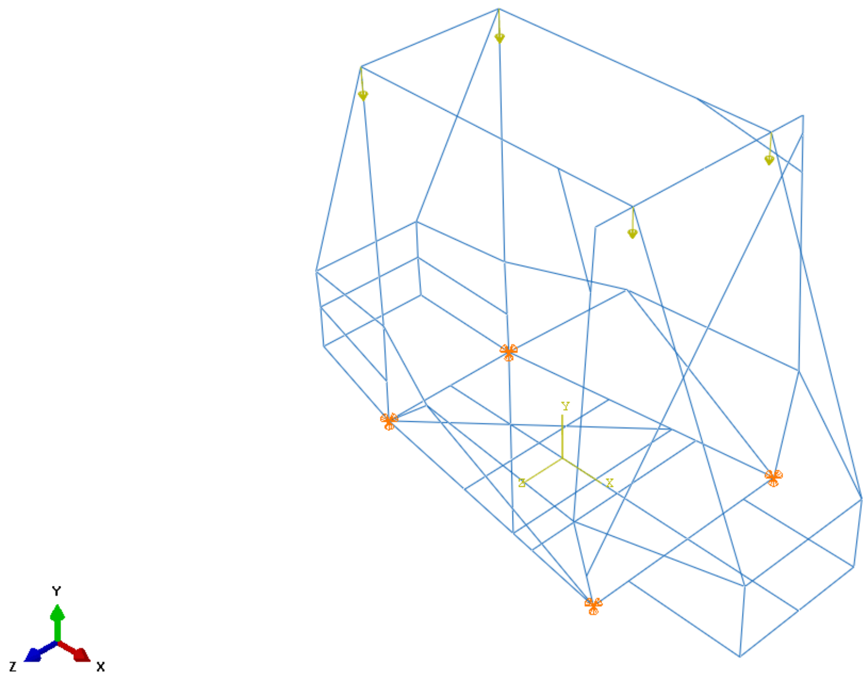


Figure A.7: Constraints used in order to perform FEA analysis for Load applied to top of frame to simulate if the buggy were to flip and land on top.

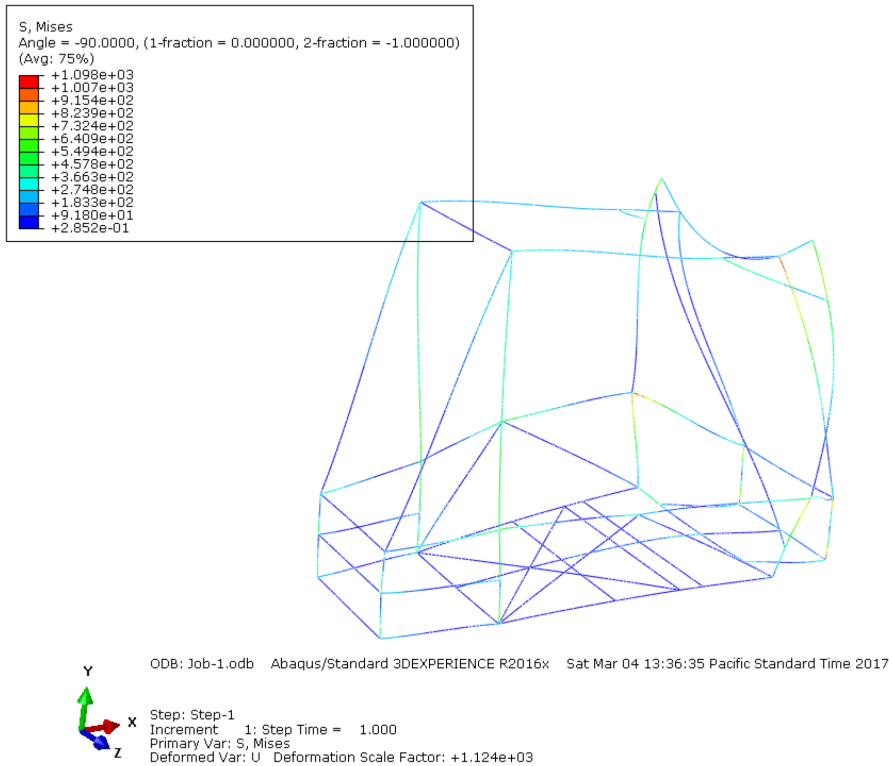


Figure A.8: Stress associated with volumetric change of frame, used to give a representation of the frame distortion due to top impact for final frame design. Scale Factor: 1.12e03

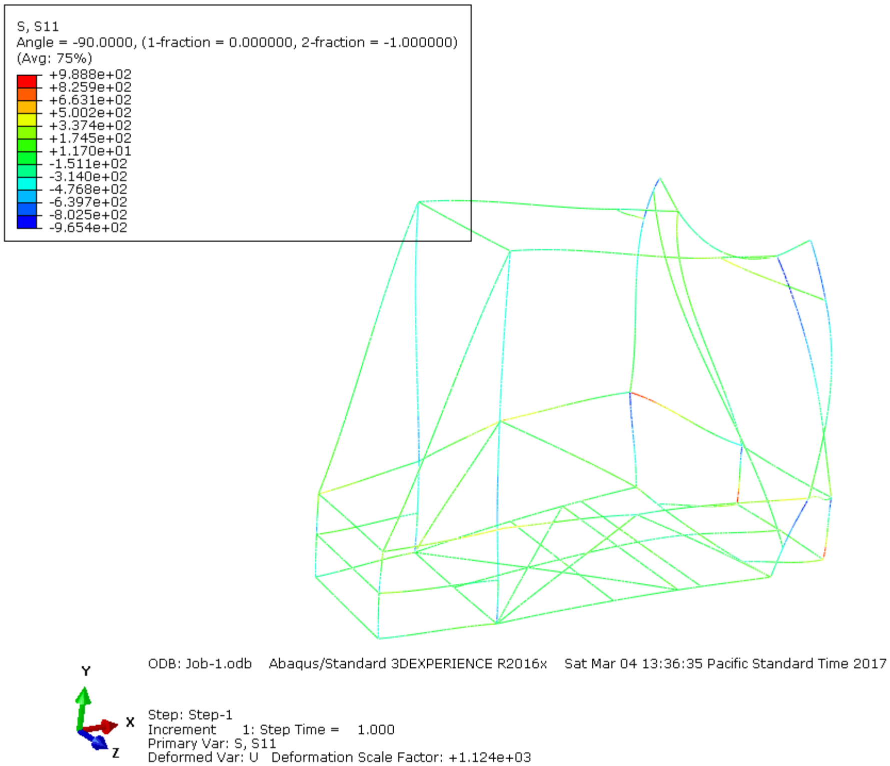


Figure A.9: Stress associated with the xx direction, used to validate the structural integrity of frame with respect to yield of 1020 steel.

Test 4: (Applied load to side of frame, side impact**)**

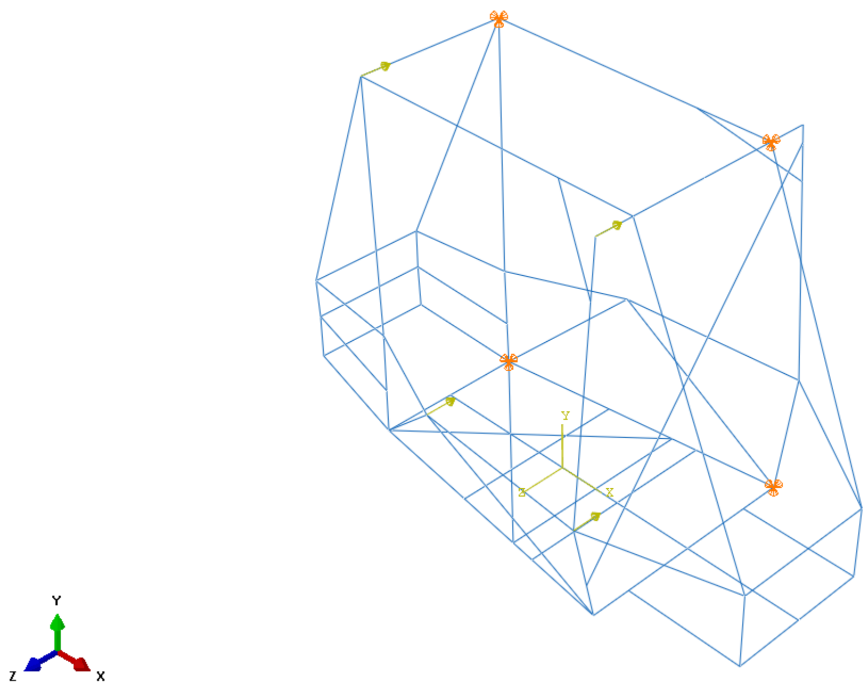


Figure A.10: Constraints used in order to perform FEA analysis for Load applied to side of frame to simulate if the buggy were to collide with objects/cars.

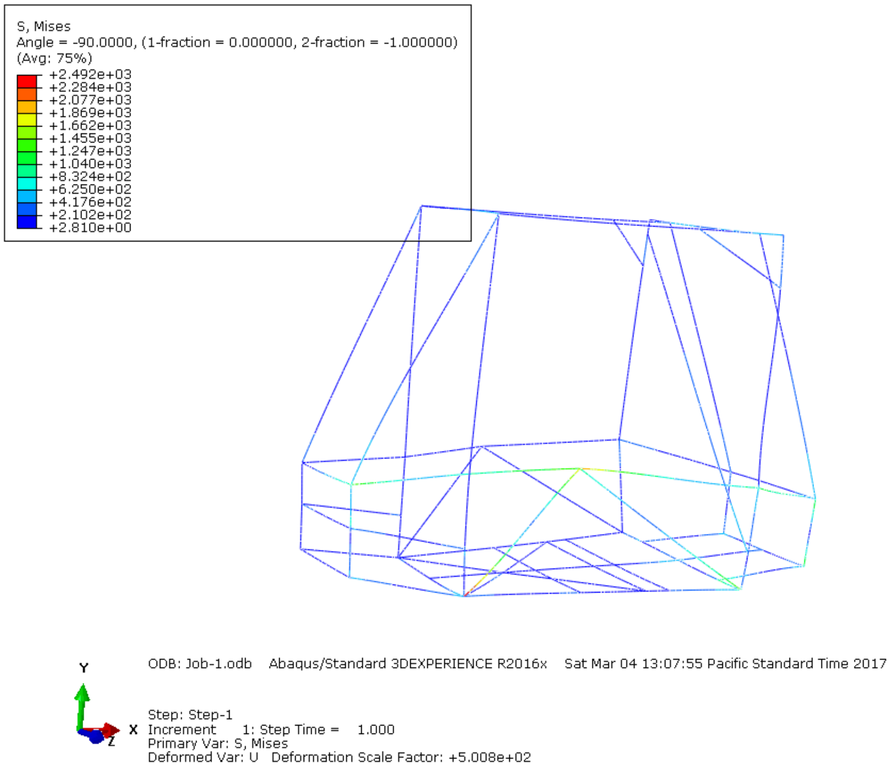


Figure A.11: Stress associated with volumetric change of frame, used to give a representation of the frame distortion due to side impact for final frame design. Scale Factor: 5e02

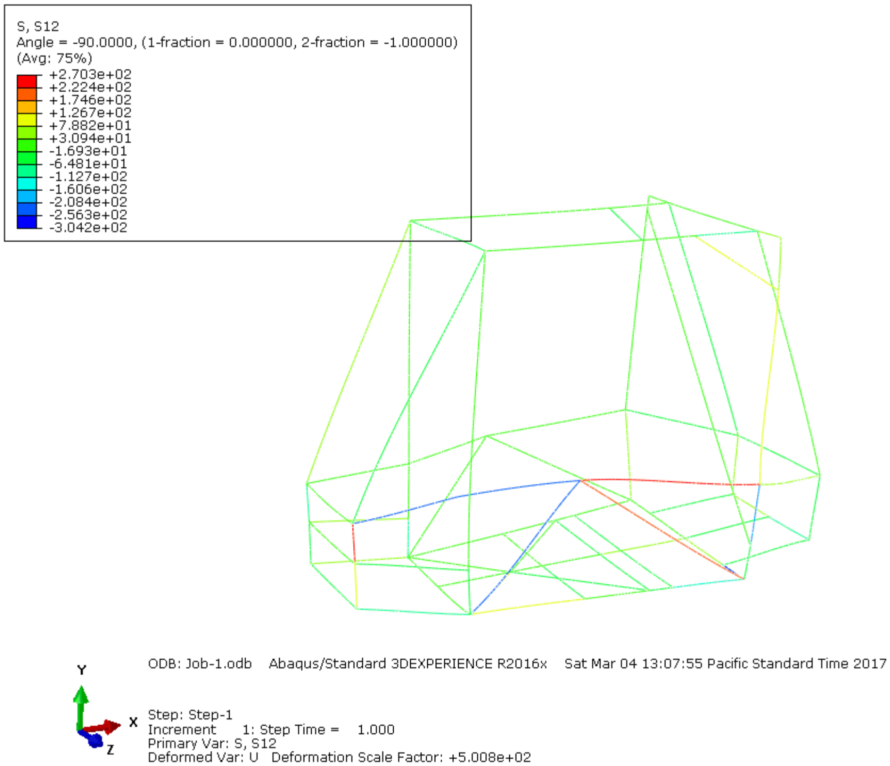


Figure A.12: Stress associated with the xy direction, used to validate the structural integrity of frame with respect to yield of 1020 steel.

Test 5: (Front Impact: Head on Collision**)**

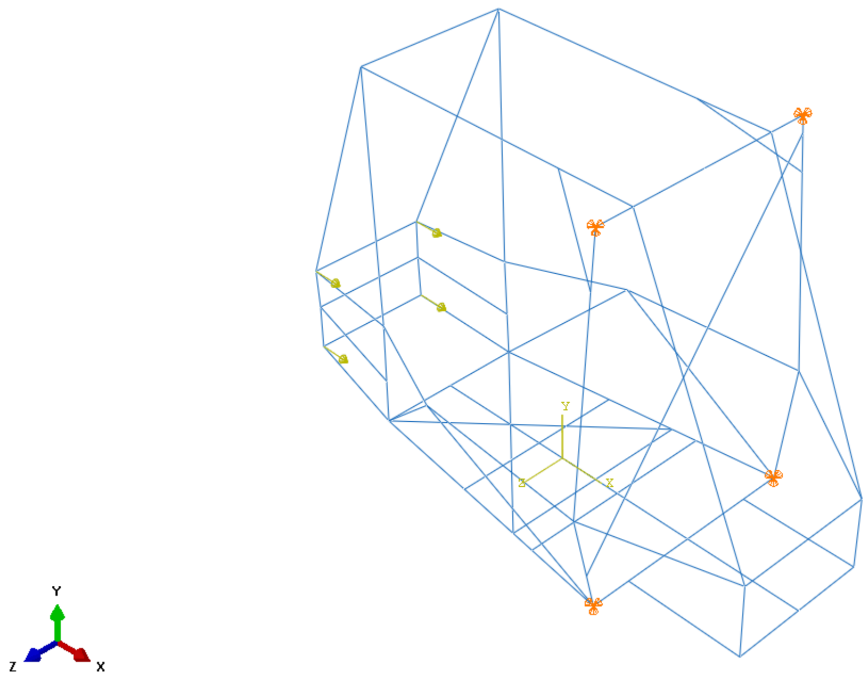


Figure A.13: Constraints used in order to perform FEA analysis to simulate front impact on frame.

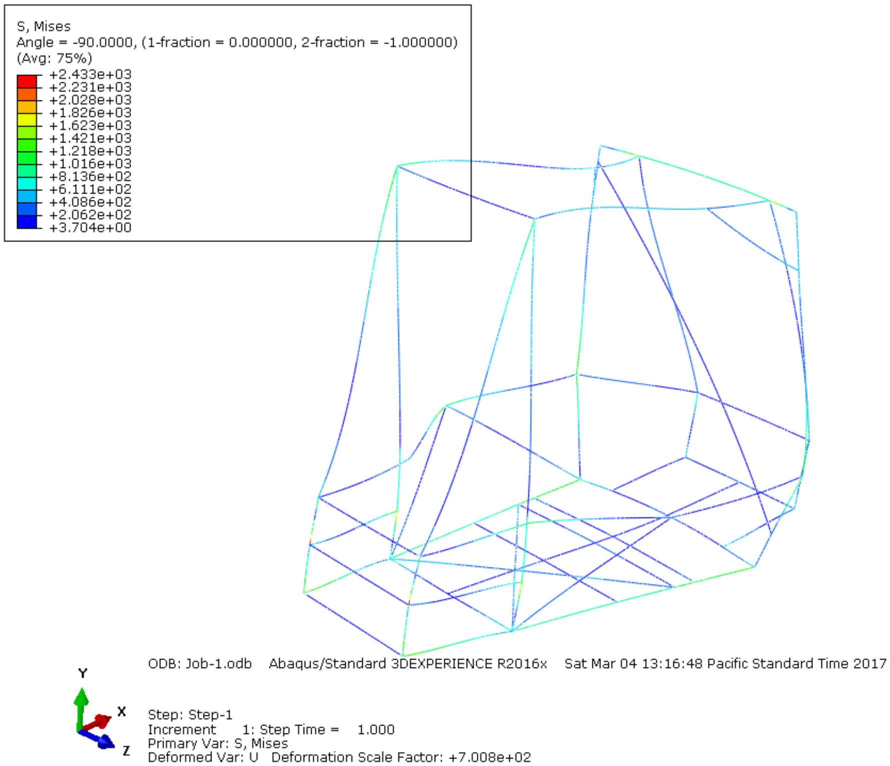


Figure A.14: Stress associated with volumetric change of frame, used to give a representation of the frame distortion due to front impact for final frame design. Scale Factor: 7e02

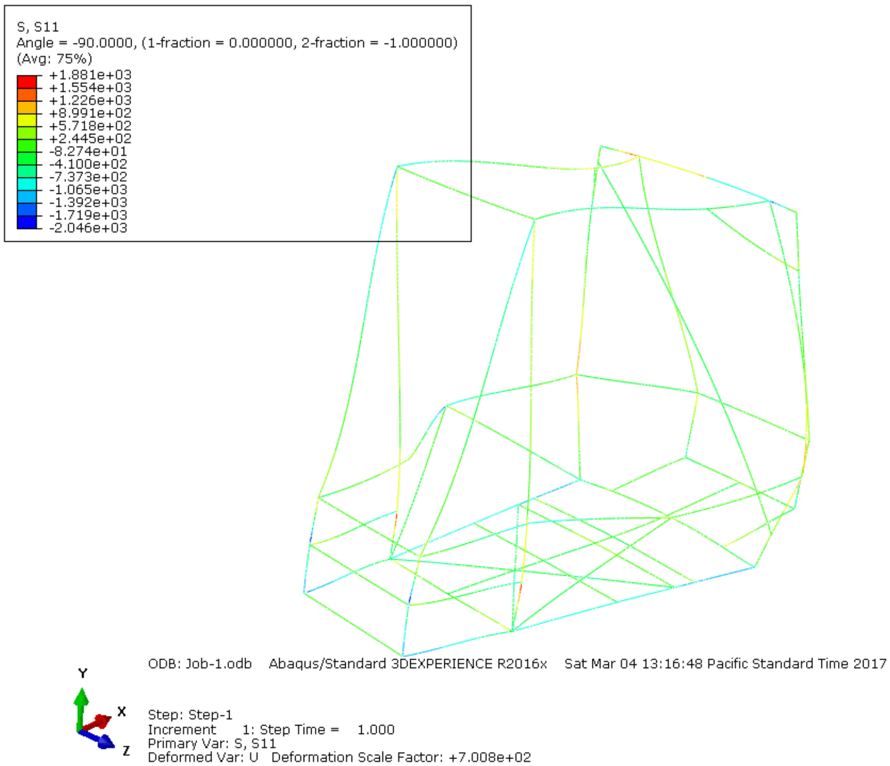


Figure A.15: Stress associated with the xx direction, used to validate the structural integrity of frame with respect to yield of 1020 steel.

Test 6: (Normal Loading Condition**)**

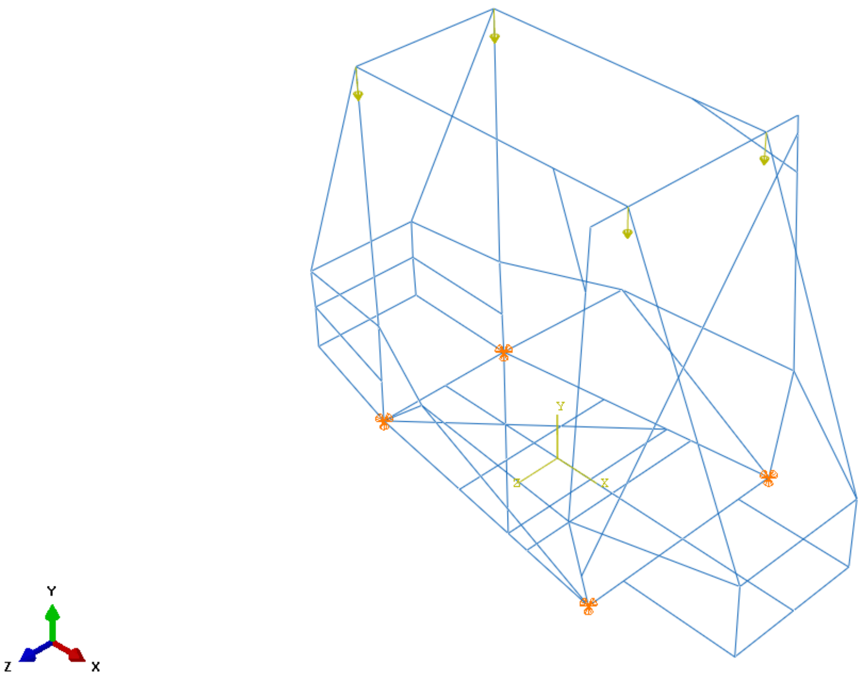


Figure A.16: Constraints used in order to perform FEA analysis to simulate normal loading on frame.

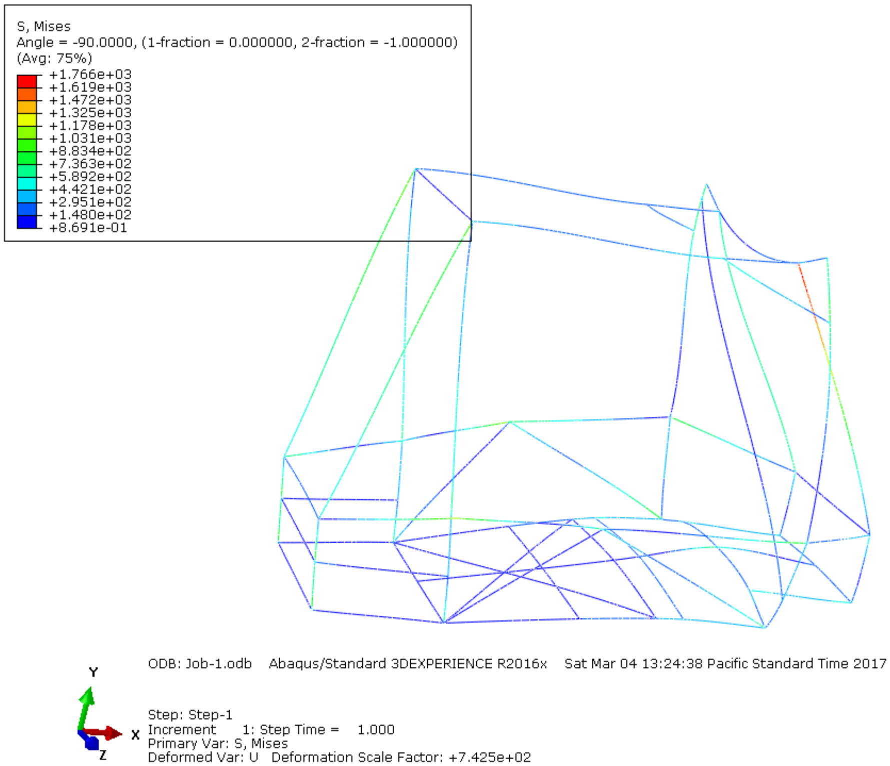


Figure A.17: Stress associated with volumetric change of frame, used to give a representation of the frame distortion due to normal loading for final frame design. Scale Factor: 7.4e02

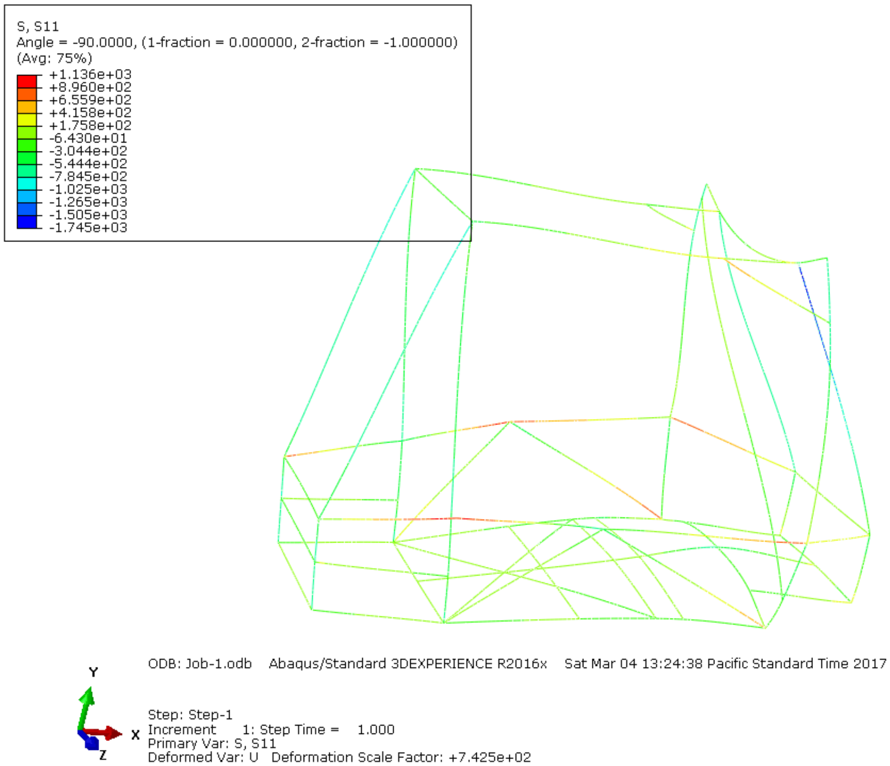


Figure A.18: Stress associated with the xx direction, used to validate the structural integrity of frame with respect to yield of 1020 steel.

Appendix B.2: Transmission

Finite Element Analysis for Structural Integrity of CV Connectors

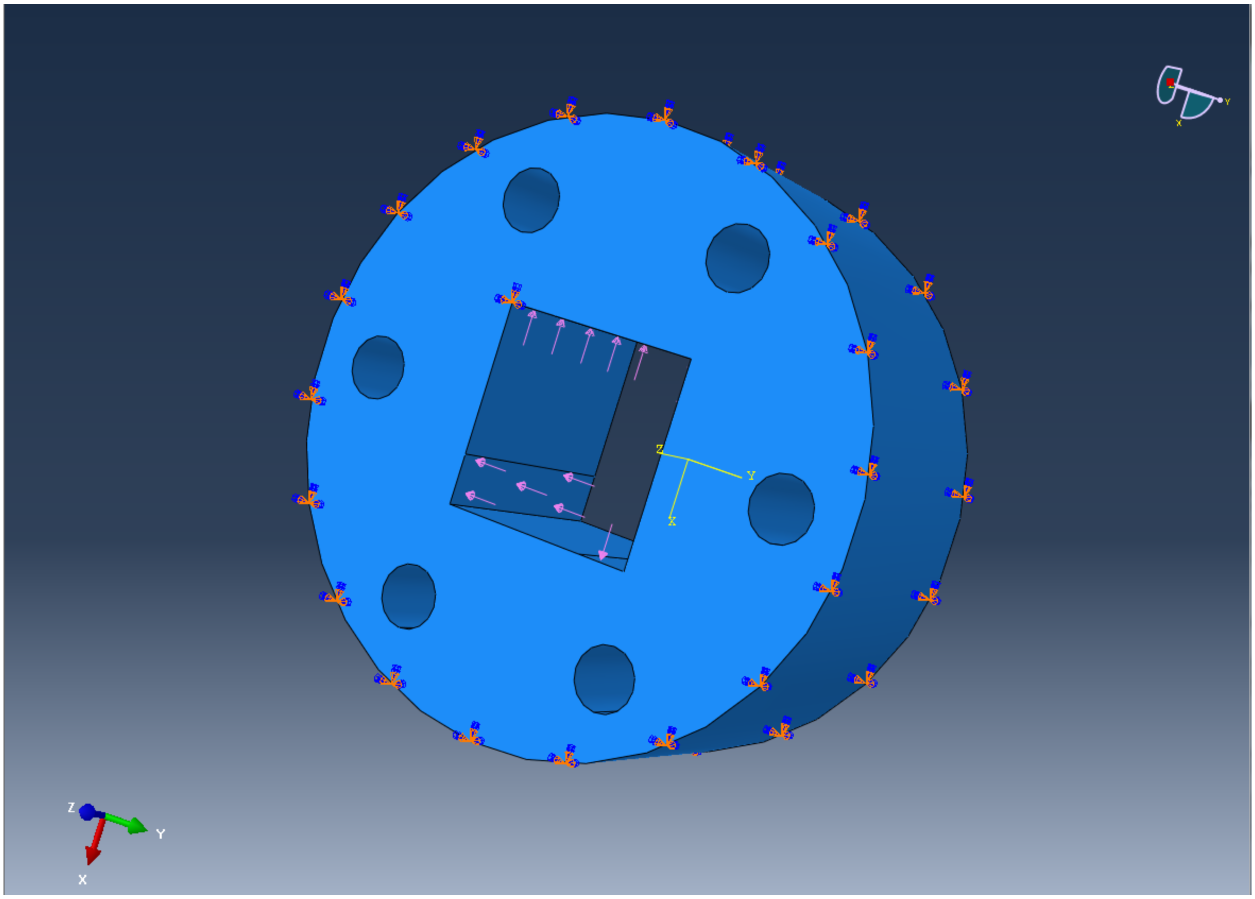


Figure A.19: Constraints used in order to perform FEA analysis to simulate torsional loading on the CV axial connector.

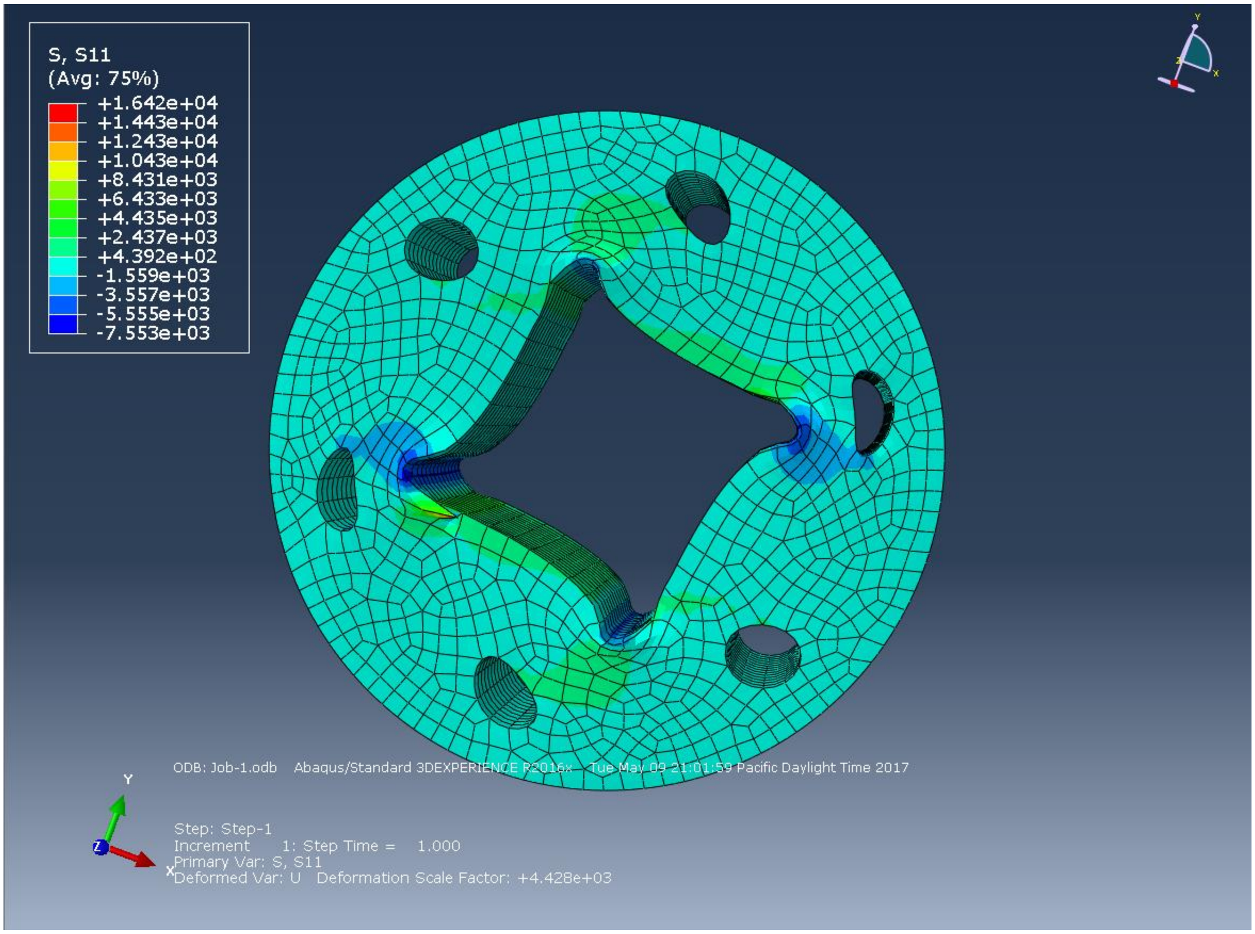


Figure A.20: Principle stress in the xx direction resulting from torsion, used in order to verify the structural integrity of this design.

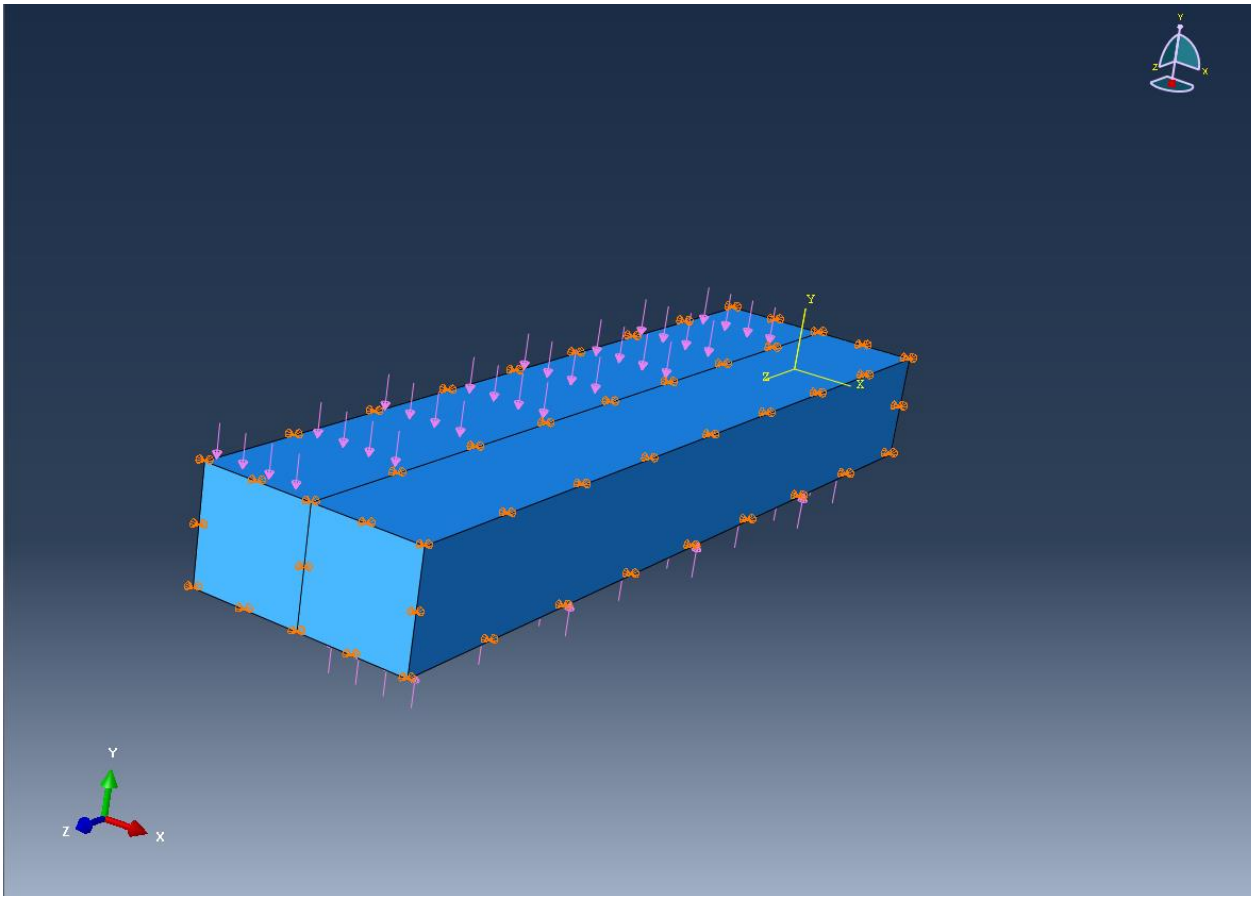


Figure A.21: Constraints used in order to perform FEA analysis to simulate shear on the CV connector with keyway.

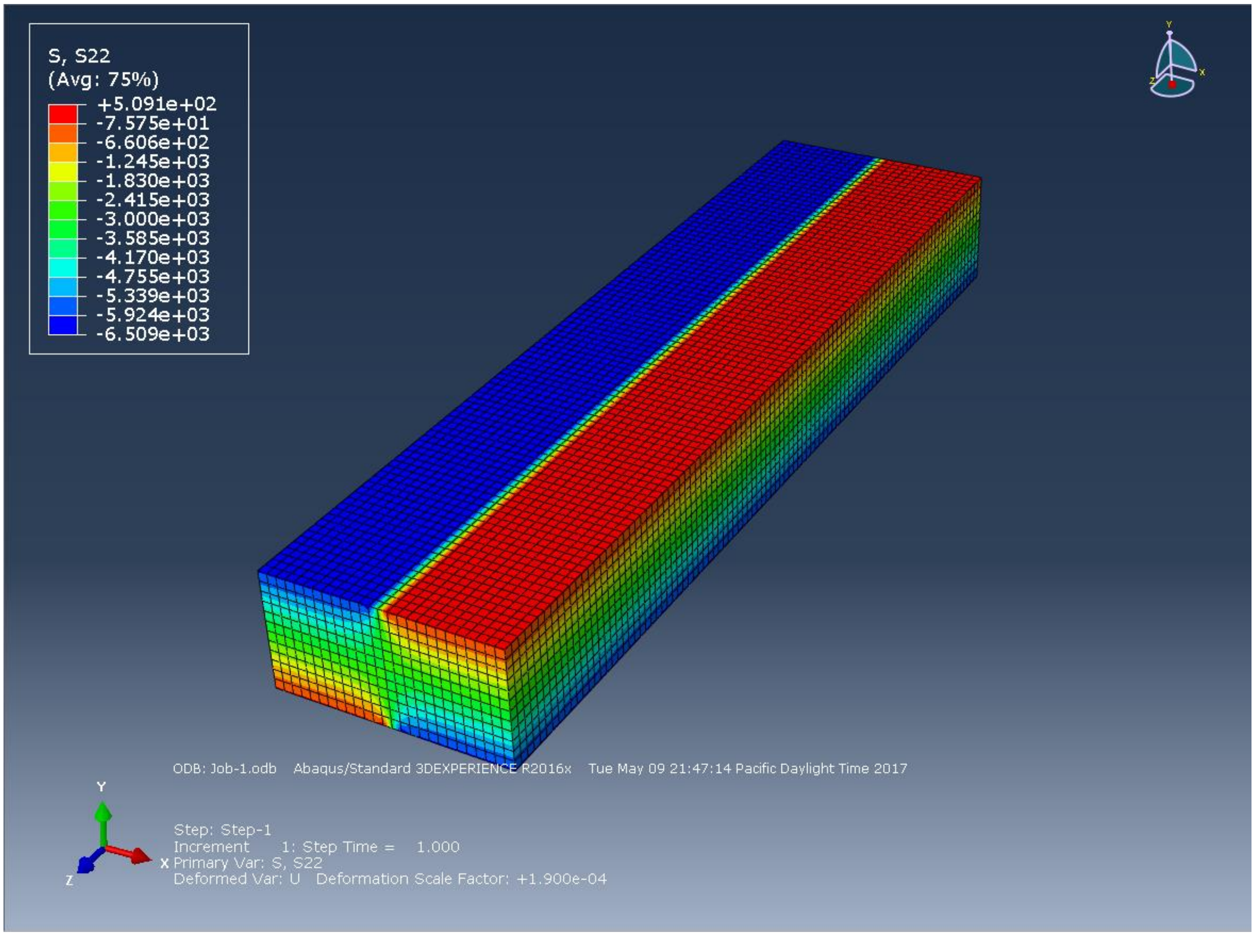


Figure A.22: Principle stress in the yy direction resulting in shear, used in order to verify the structural integrity of the keyway used in CV axial connector.

Appendix C: Detail and Assembly Drawings

Appendix C.1: Frame Part Drawings

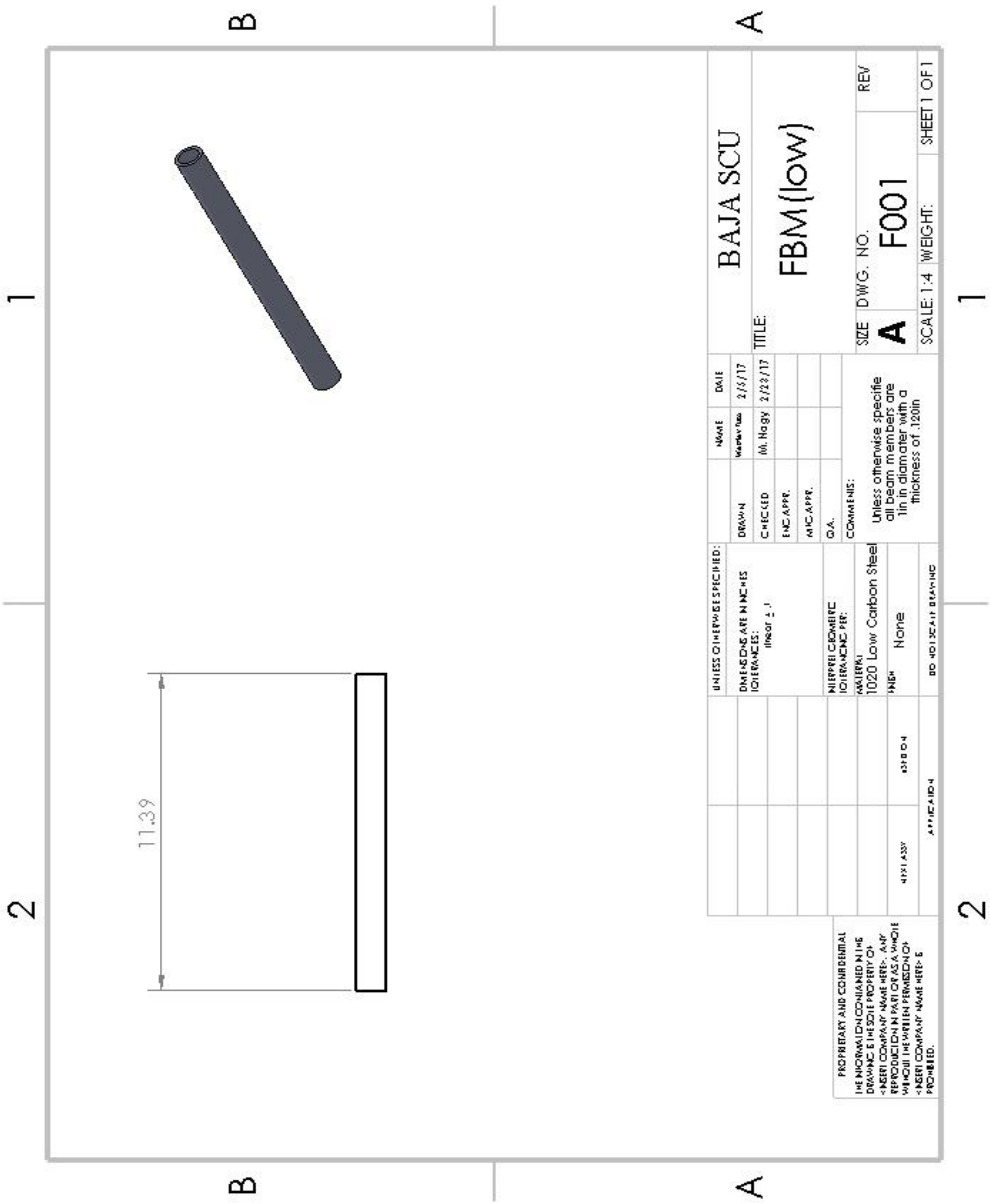


Figure A.23

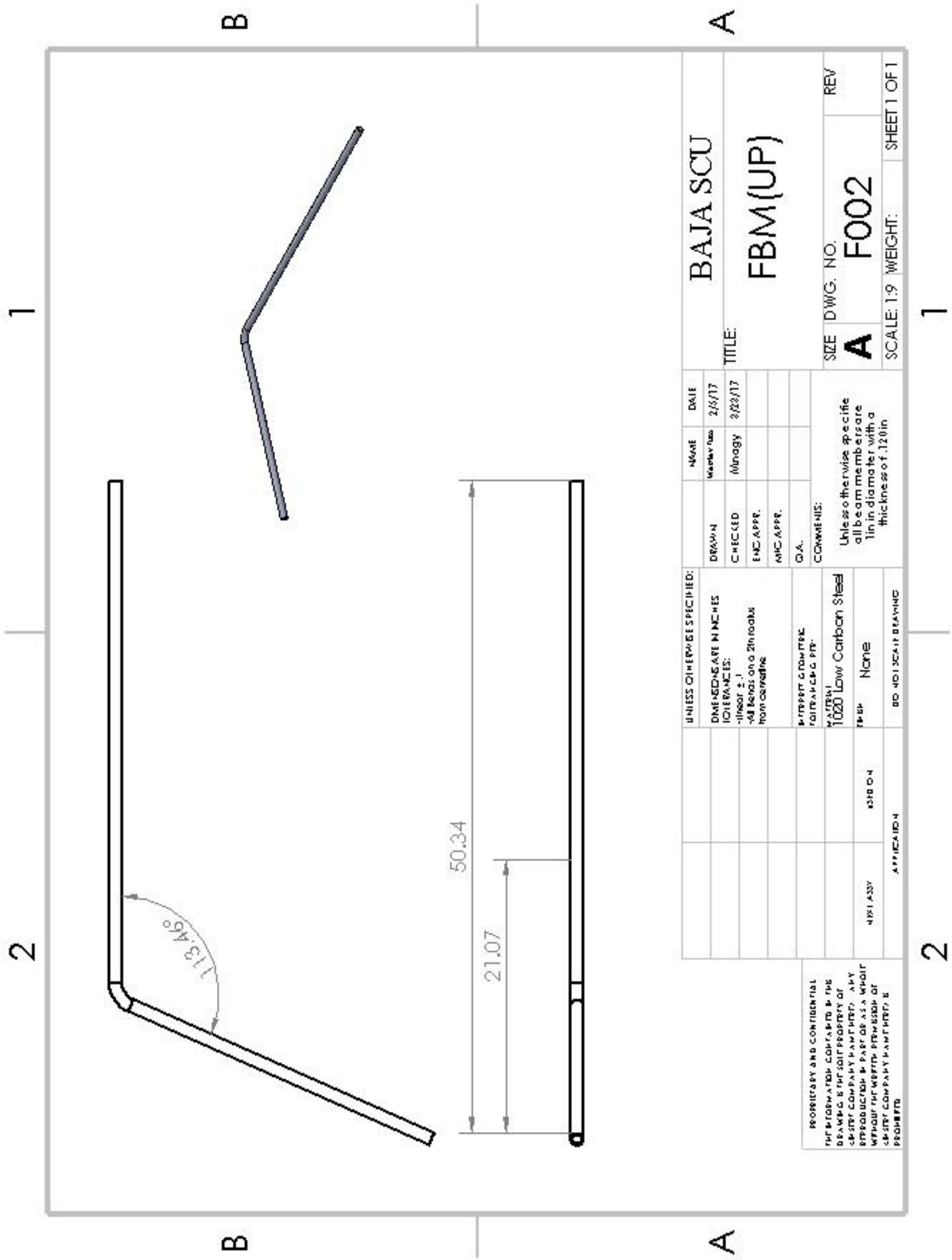
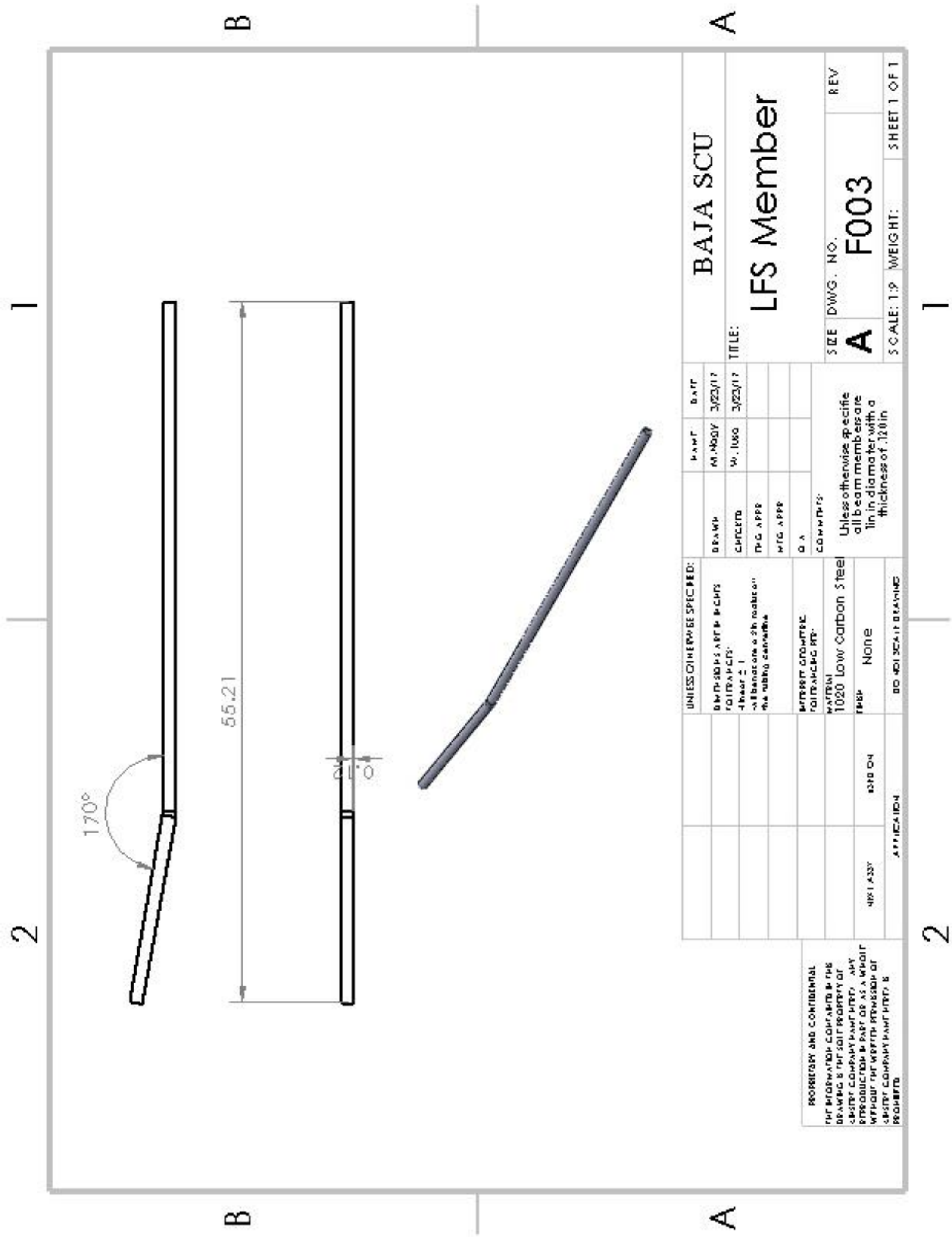

BAJA SCU
TITLE:
FBM(UP)
SIZE
A
DWG. NO.
F002
REV
SCALE: 1:9
WEIGHT:
SHEET 1 OF 1
50.34
21.07
113.46°
DRAWN
CHECKED
2/5/17
Minagy
2/23/17
COMMENTS:
Unless otherwise specifie
all beam members are
1in in diameter with a
thickness of .120in
1020 Low Carbon Steel
None

Figure A.24



170°
55.21
0.12
BAJA SCU
TITLE:
LFS Member
SIZE
A
DWG. NO.
F003
REV
SCALE: 1:9
WEIGHT:
SHEET 1 OF 1
DRAWN
M. Nagy
3/23/17
CHECKED
W. Luo
3/23/17
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Unless otherwise specifie all beam members are 1in in diameter with a thickness of .120in
UNLESS OTHERWISE SPECIFIED:
1020 Low Carbon Steel
None
APPLICATION
PROPRIETARY AND CONFIDENTIAL

Figure A.25

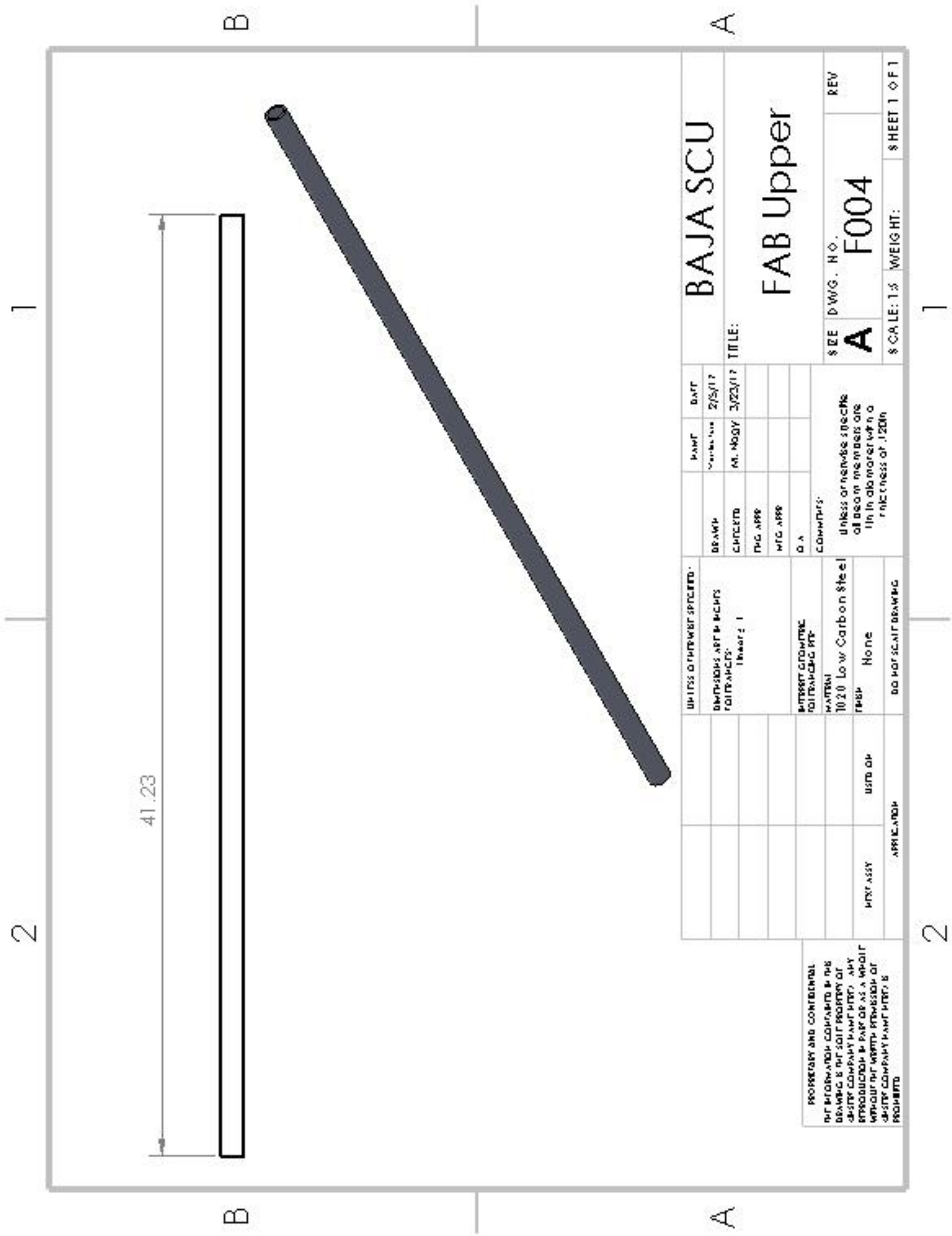
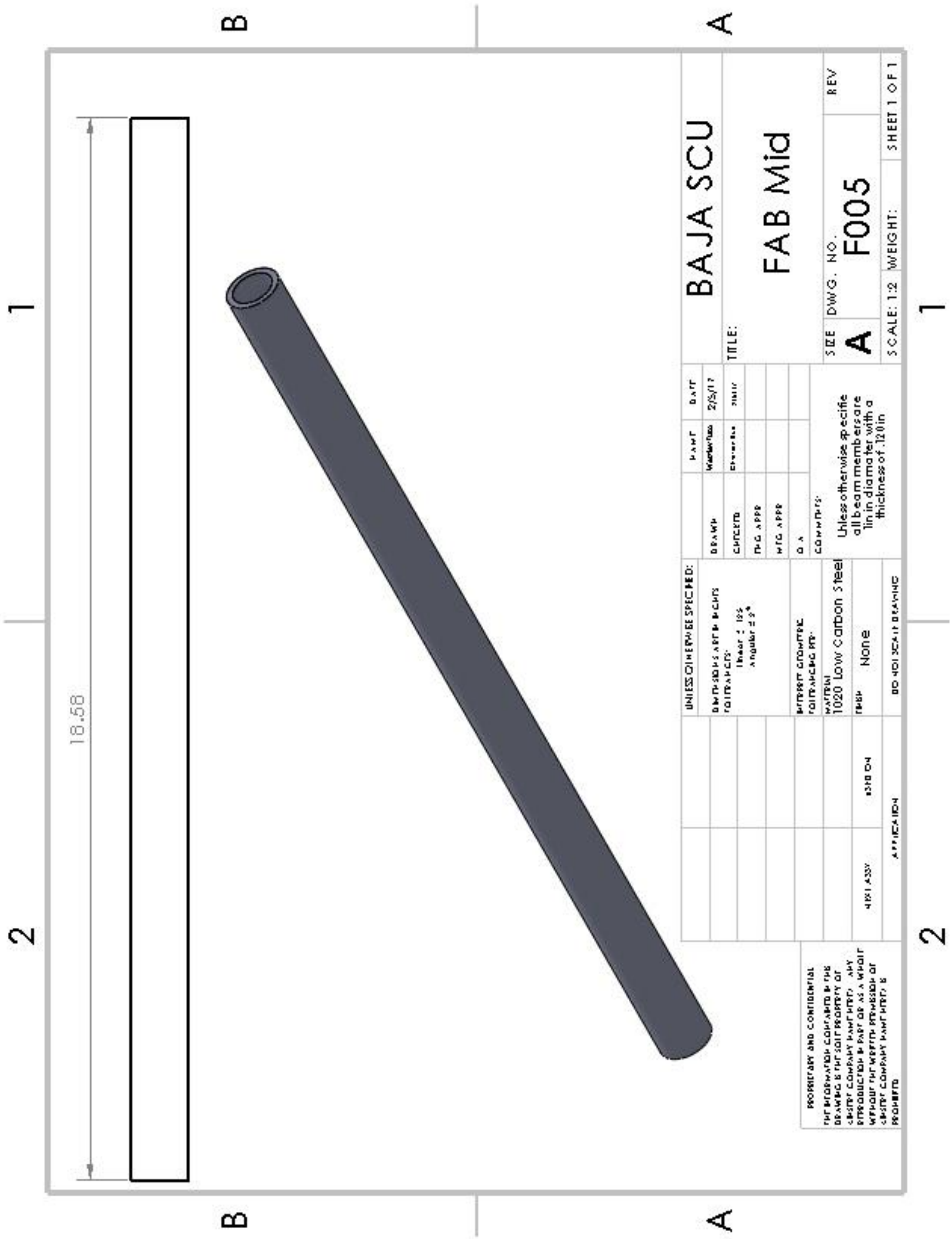
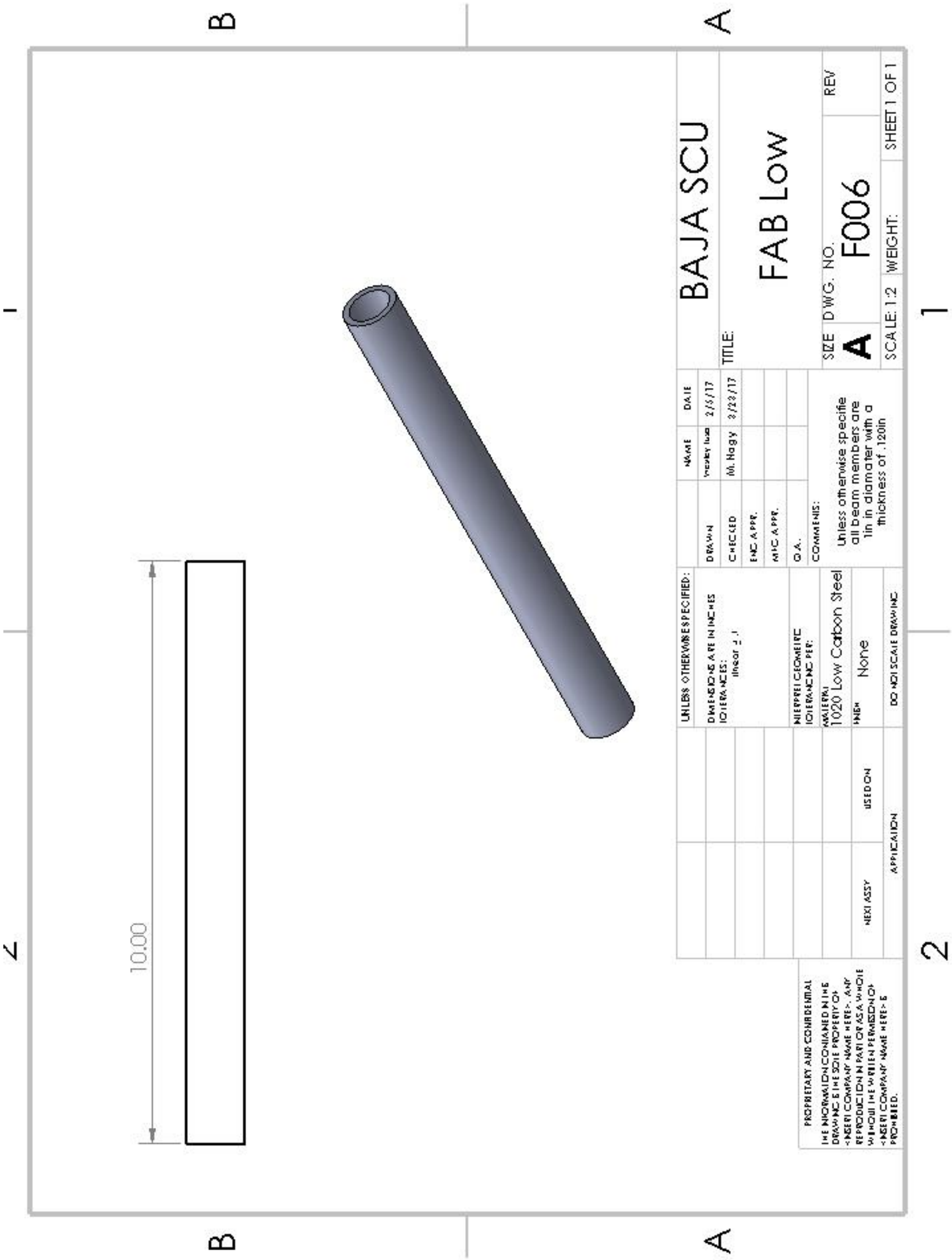

41.23
BAJA SCU
TITLE:
FAB Upper
SIZE
A
DWG. NO.
F004
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
1020 Low Carbon Steel
None

Figure A.26



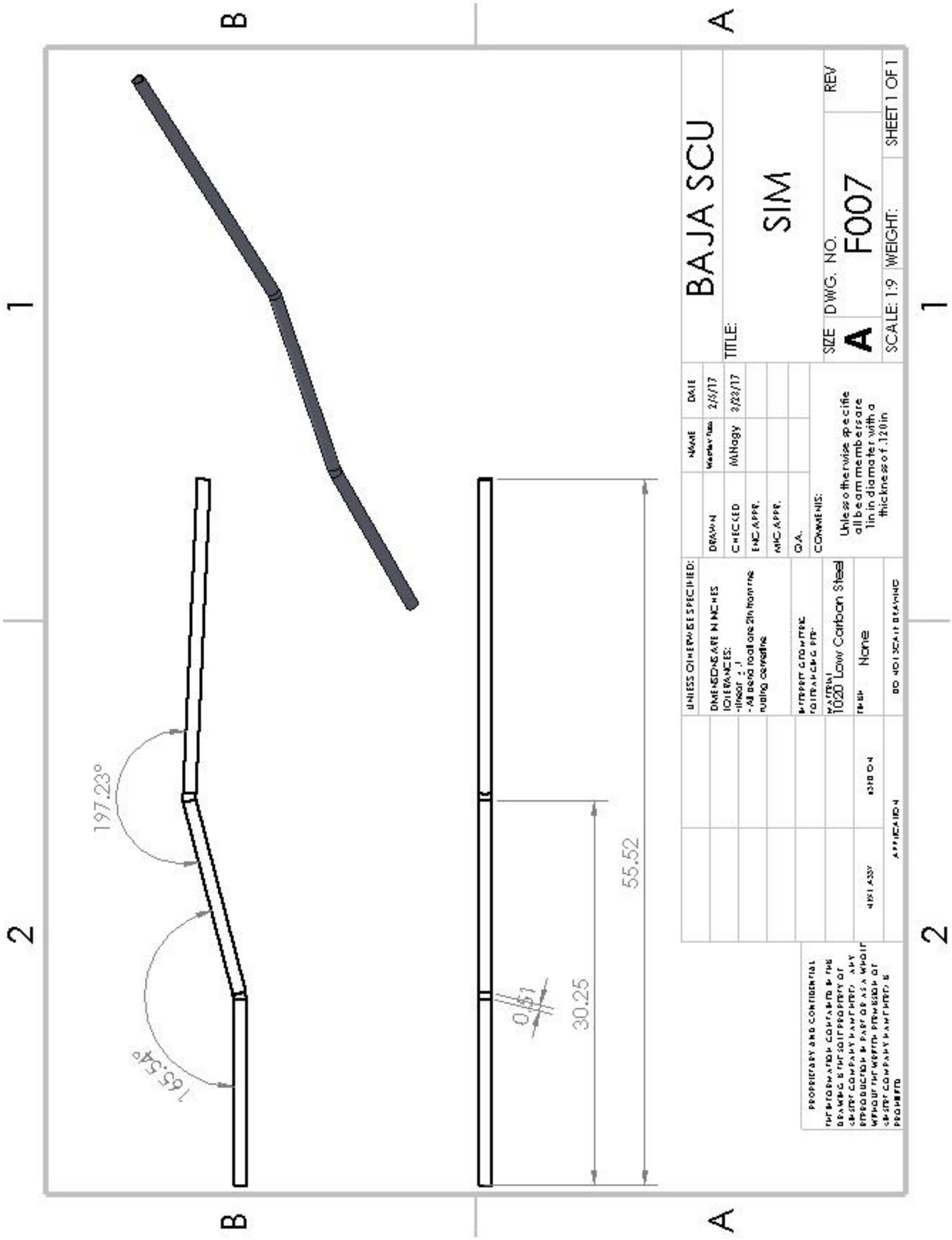
18.58
BAJA SCU
FAB Mid
DWG. NO.
F005
SIZE
A
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
TITLE:
1020 Low Carbon Steel
None
Unless otherwise specife all beam members are 1in in diameter with a thickness of .120in

Figure A.27



10.00
BAJA SCU
TITLE:
FAB Low
SIZE
A
DWG. NO.
F006
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
MATERIAL
1020 Low Carbon Steel
FINISH
None
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
M. Nagy
2/22/17
COMMENTS:
Unless otherwise specifie all beam members are 1in in diamater with a thickness of .120in
PROPRIETARY AND CONFIDENTIAL

Figure A.28



B
A
1
2
197.23°
165.54°
0.51
30.25
55.52
BAJA SCU
TITLE:
SIM
SIZE
A
DWG. NO.
F007
REV
SCALE: 1:9
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
MATERIAL
1020 Low Carbon Steel
FINISH
None
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Unless otherwise specifie all beam members are 1in in diameter with a thickness of .120in
NAME
DATE
2/5/17
MNagy
3/23/17
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL

Figure A.29

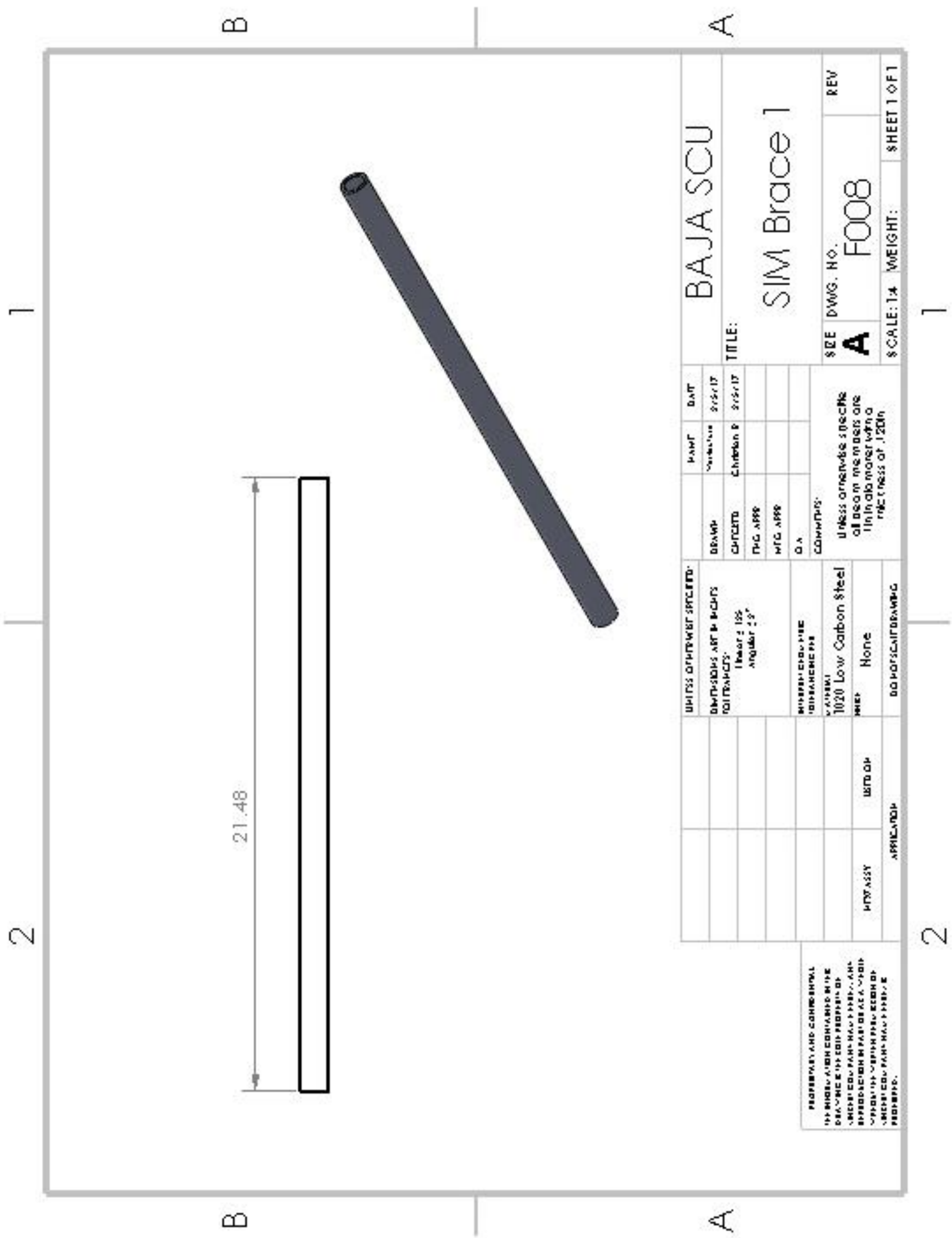

21.48
BAJA SCU
TITLE:
SIM Brace 1
SIZE
A
DWG. NO.
F008
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
1020 Low Carbon Steel
None

Figure A.30

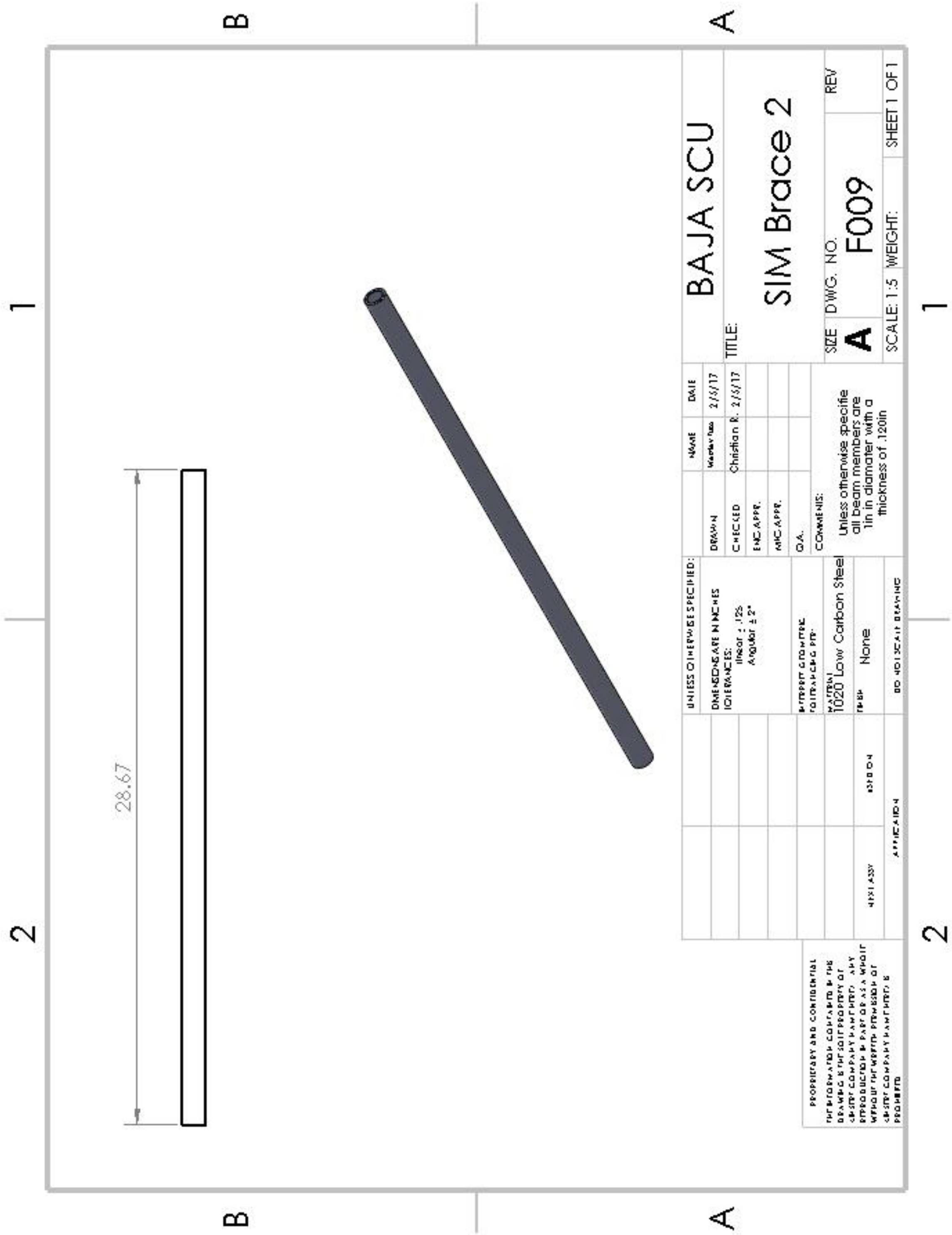
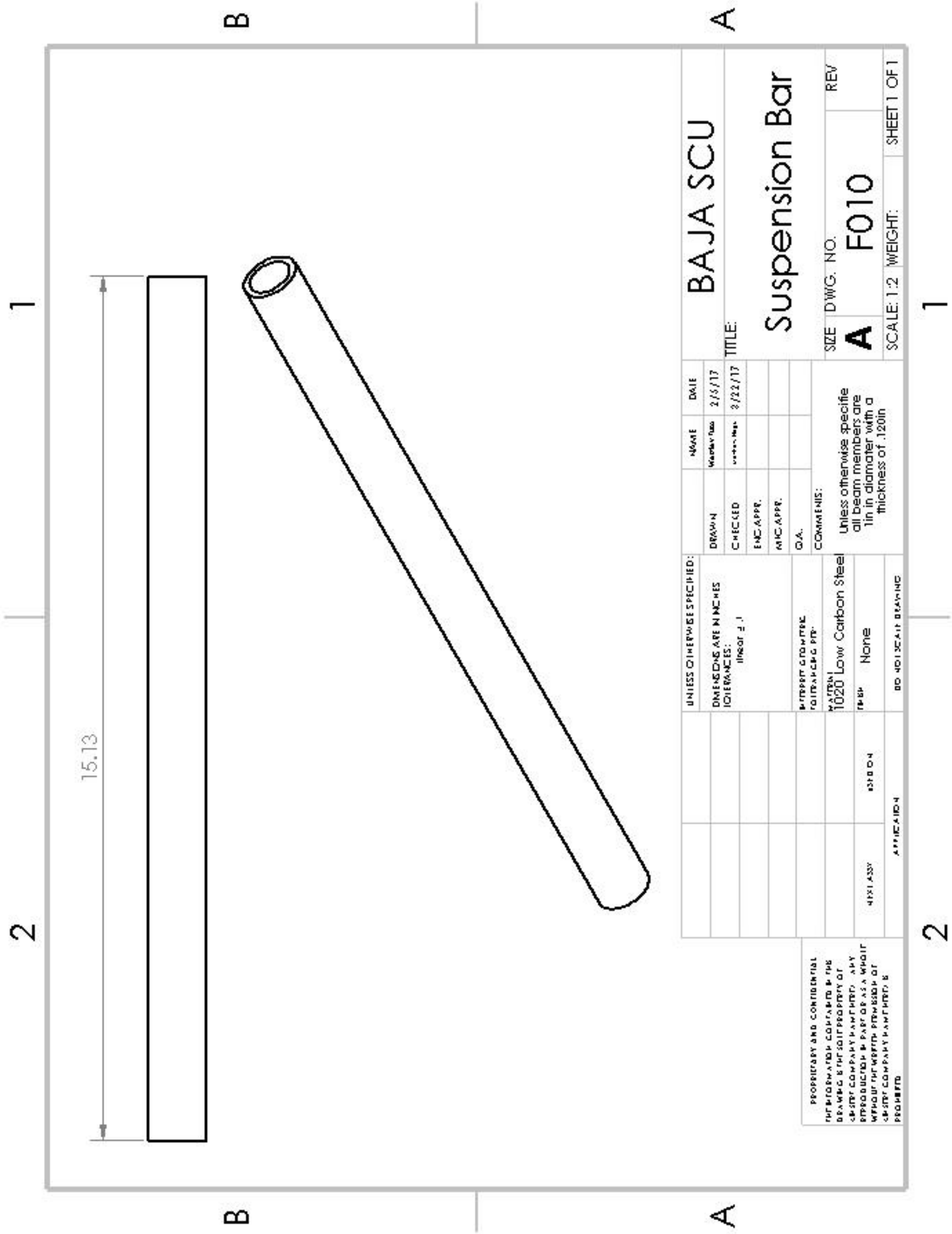

28.67
BAJA SCU
TITLE:
SIM Brace 2
SIZE
A
DWG. NO.
F009
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN
2/5/17
CHECKED
Christian R.
2/5/17
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Unless otherwise specifie
all beam members are
1in in diamater with a
thickness of .120in
1020 Low Carbon Steel
None
1
2
A
B

Figure A.31



15.13
BAJA SCU
TITLE:
Suspension Bar
SIZE
A
DWG. NO.
F010
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Unless otherwise specifie all beam members are 1in in diamater with a thickness of .120in
NAME
DATE
2/5/17
2/22/17
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MATERIAL
1020 Low Carbon Steel
FINISH
None
DO NOT SCALE DRAWING
APPLICATION
NEXT ASSY
USED ON
PROPRIETARY AND CONFIDENTIAL

Figure A.32

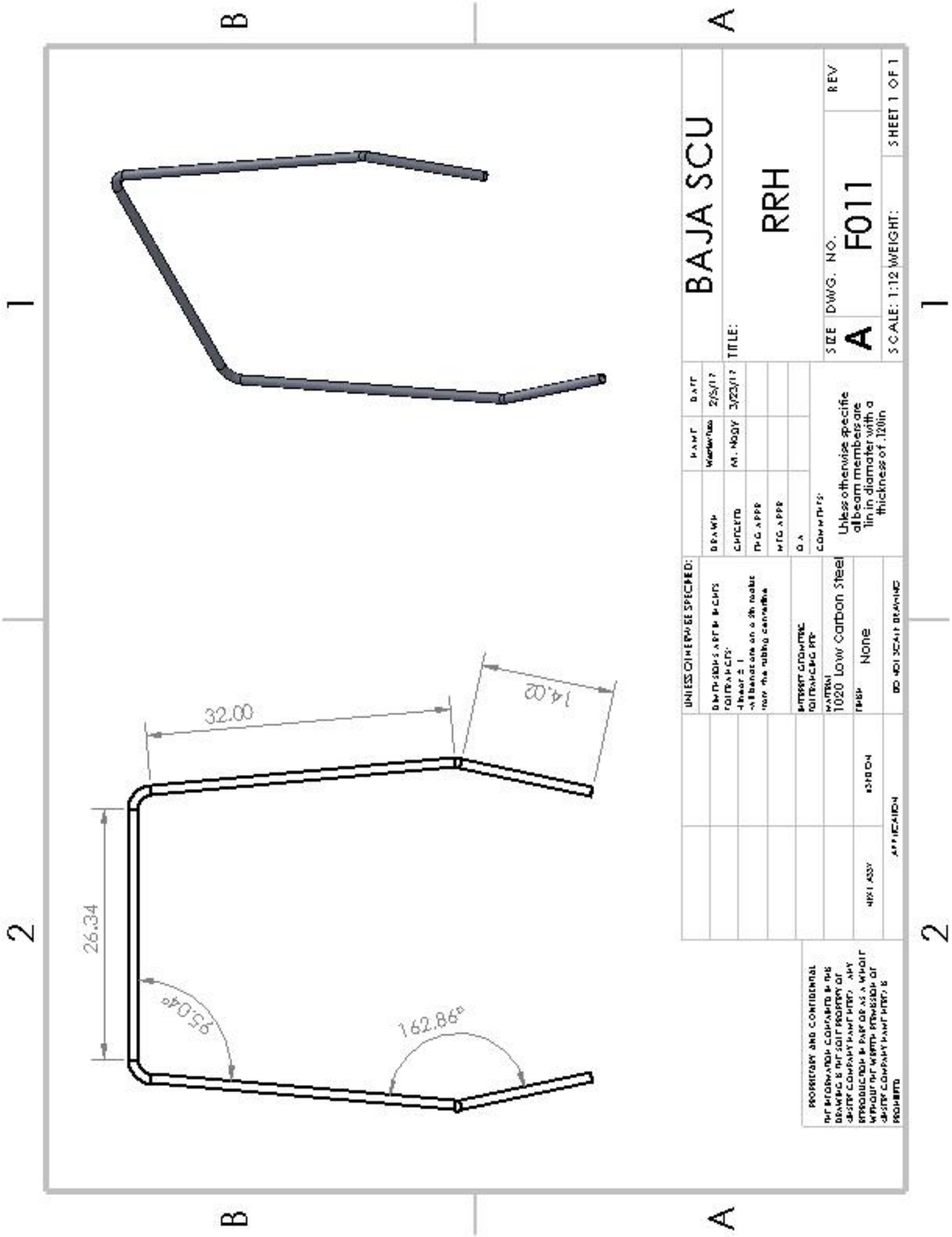
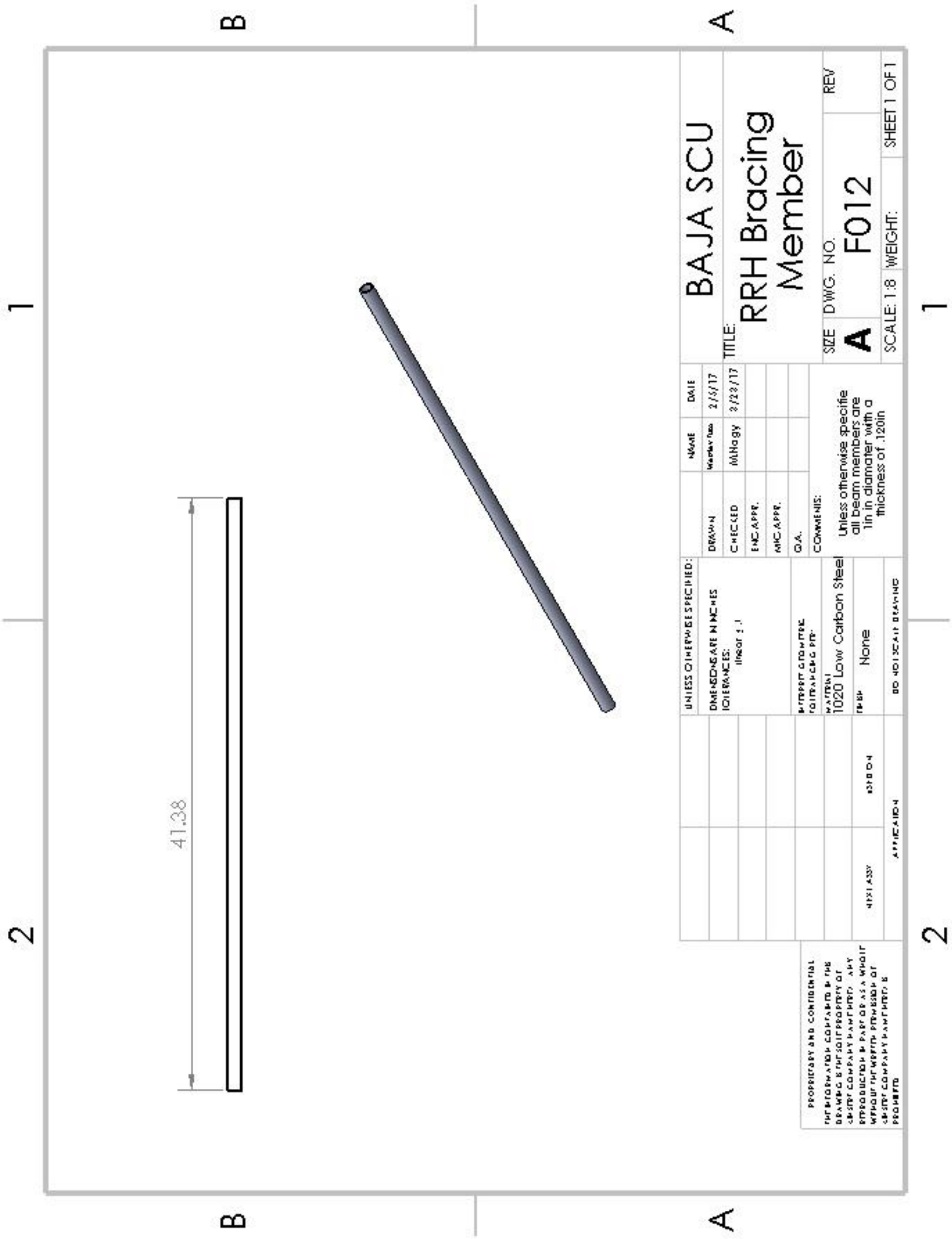
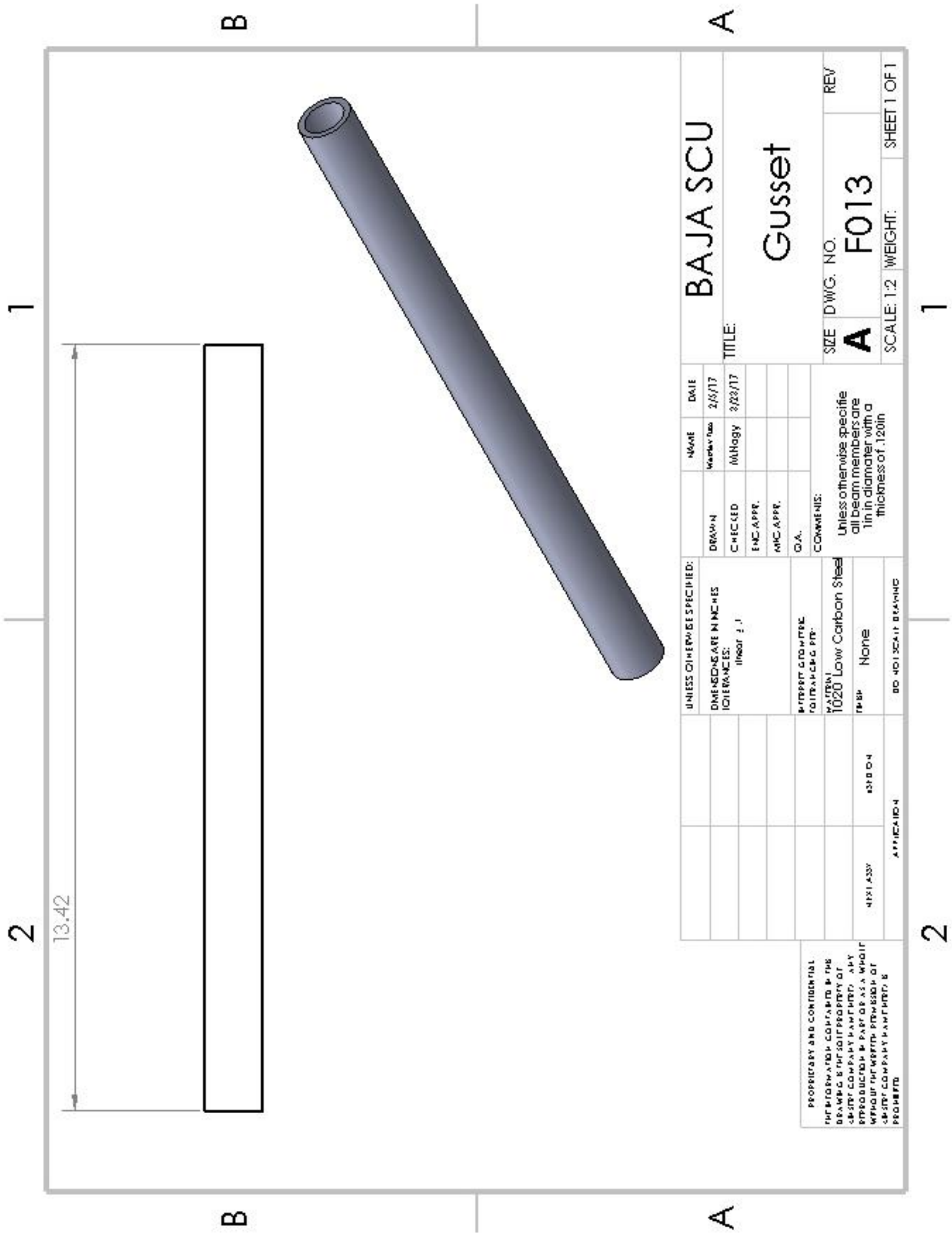

BAJA SCU
TITLE:
RRH
SIZE
A
DWG. NO.
F011
REV
SCALE: 1:12
WEIGHT:
SHEET 1 OF 1
32.00
14.02
26.34
95.04°
162.86°
1020 Low Carbon Steel
None
M. Nagy
3/23/17
2/5/17
Unless otherwise specifie
all beam members are
1in in diamater with a
thickness of .120in

Figure A.33

Figure A.34



BAJA SCU
TITLE:
RRH Bracing Member
SIZE
A
DWG. NO.
F012
REV
SCALE: 1:8
WEIGHT:
SHEET 1 OF 1
41.38
DRAWN
CHECKED
MMagy
2/22/17
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Unless otherwise specifie all beam members are 1in in diamater with a thickness of .120in
MATERIAL
1020 Low Carbon Steel
FINISH
None
NAME
DATE
2/5/17
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL



13.42
BAJA SCU
TITLE:
Gusset
SIZE
A
DWG. NO.
F013
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
DRAWN
CHECKED
MJNagy
2/5/17
2/23/17
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Unless otherwise specifie all beam members are 1in in diamater with a thickness of .120in
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
1020 Low Carbon Steel
None

Figure A.35

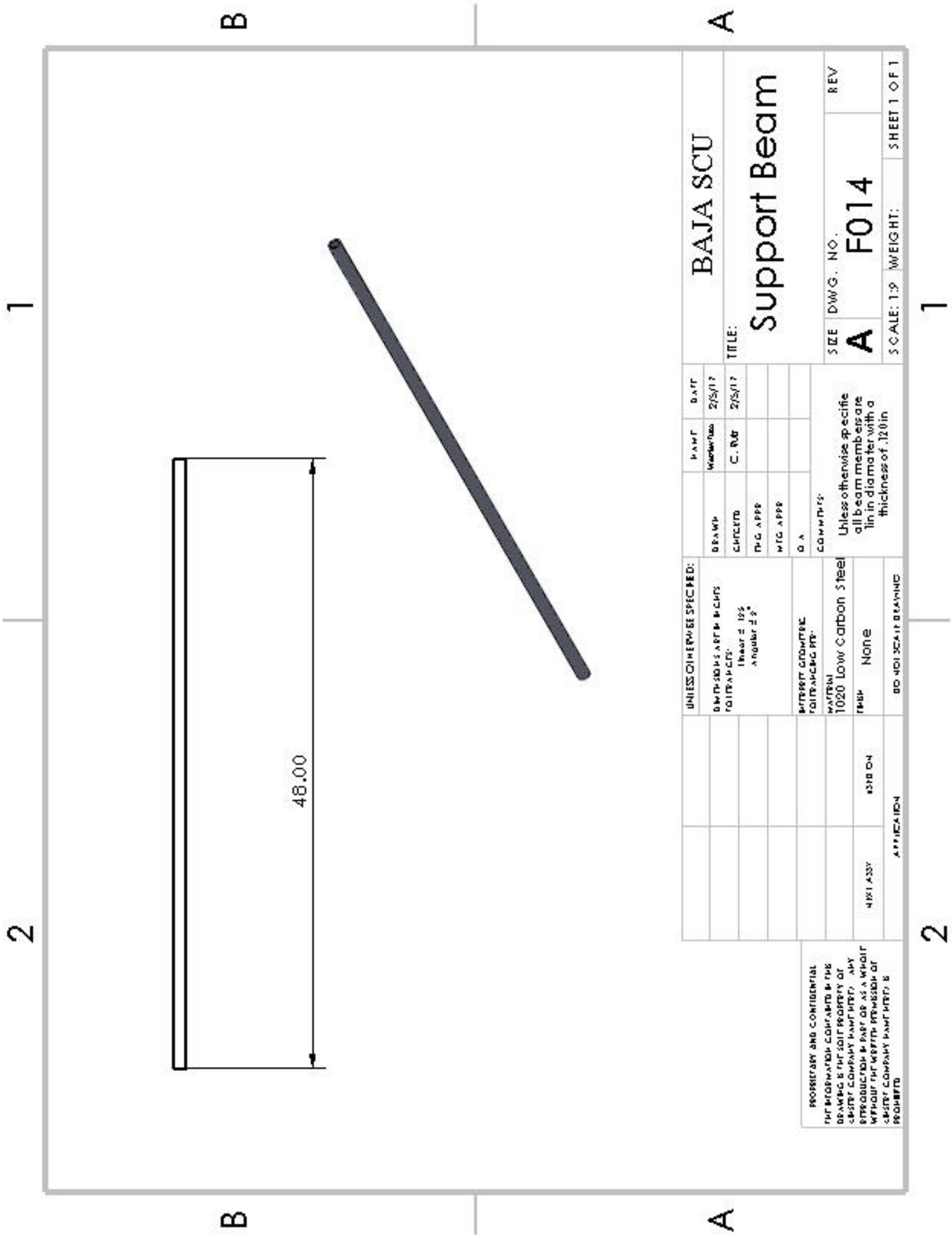


Figure A.36

Note: DLC (F015), QLC (F016), ALC(F018) were removed through FEA Analysis

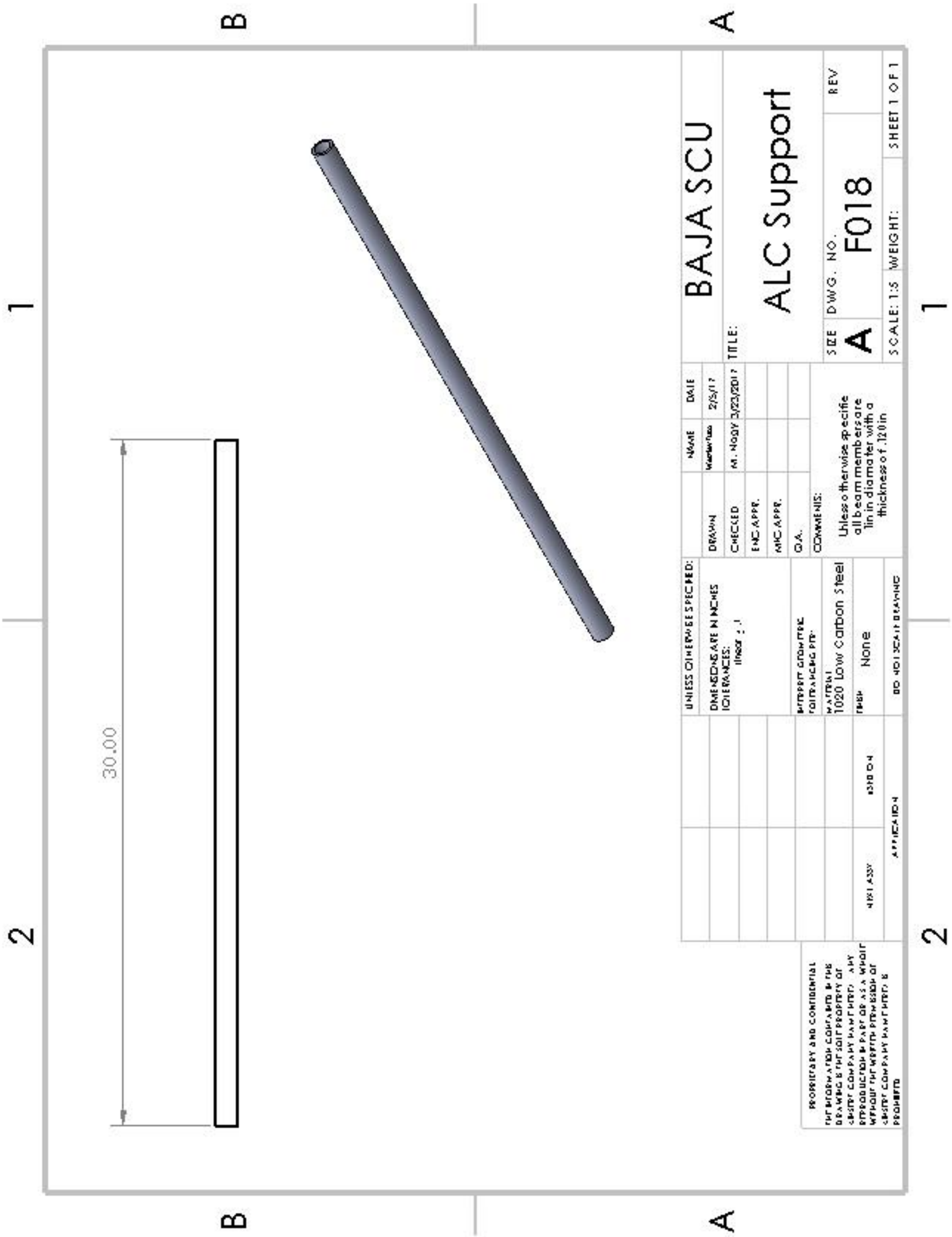
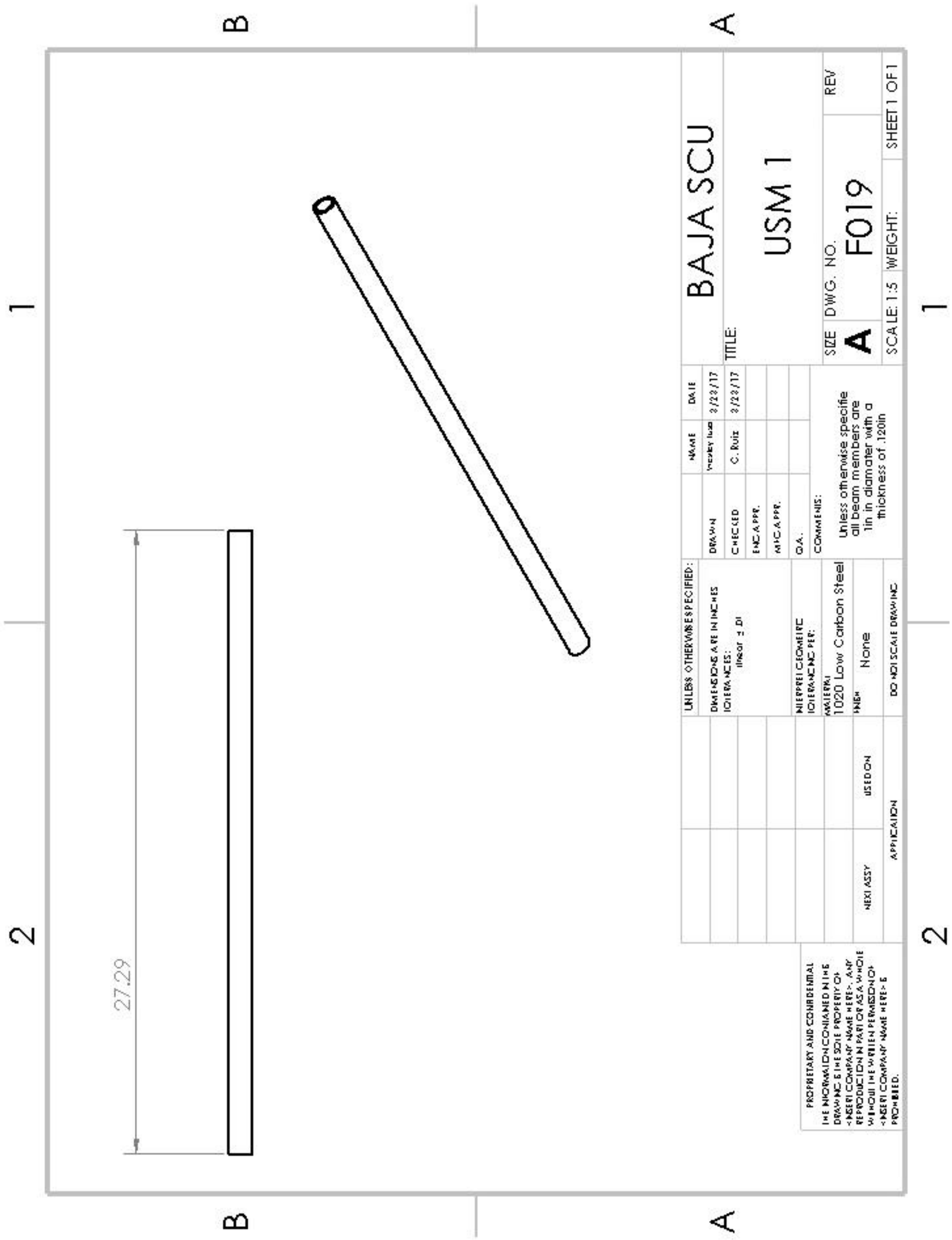

30.00
BAJA SCU
TITLE:
ALC Support
SIZE
A
DWG. NO.
F018
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DRAWN
CHECKED
M. Nagy 3/23/2017
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Unless otherwise specifie all beam members are 1in in diameter with a thickness of .120in
MATERIAL
1020 Low Carbon Steel
FINISH
None
DO NOT SCALE DRAWING
NAME
DATE
2/5/17

Figure A.37

Figure A.38



BAJA SCU
TITLE:
USM 1
SIZE
A
DWG. NO.
F019
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
27.29
DRAWN
CHECKED
C. Ruiz
2/22/17
COMMENTS:
Unless otherwise specifie all beam members are 1in in diamater with a thickness of .120in
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
1020 Low Carbon Steel
None
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL

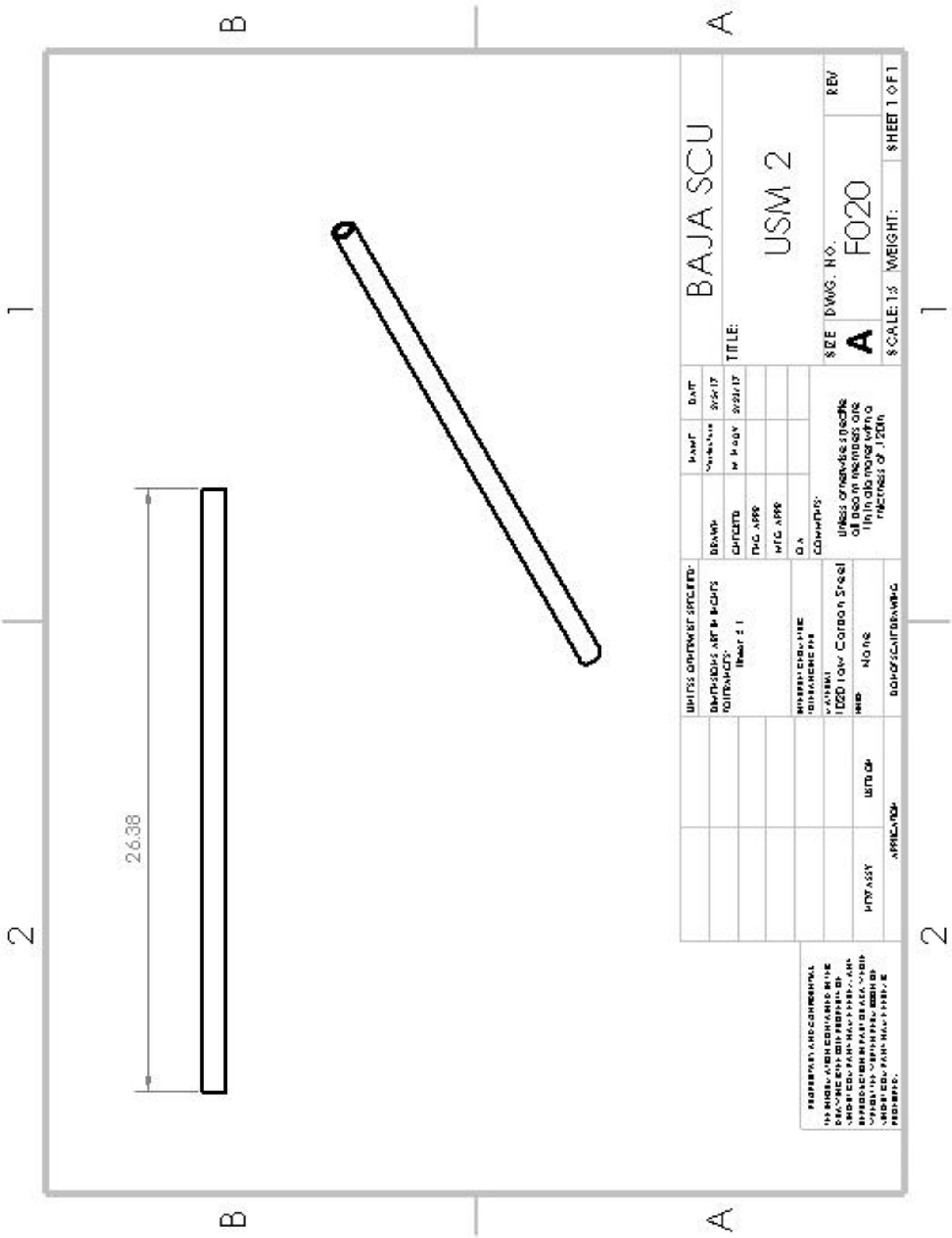

BAJA SCU
TITLE:
USM 2
SIZE
A
DWG. NO.
F020
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
26.38
1020 Low Carbon Steel
None
Unless otherwise specified all beam members are 1 in diameter with a thickness of .120in

Figure A.39

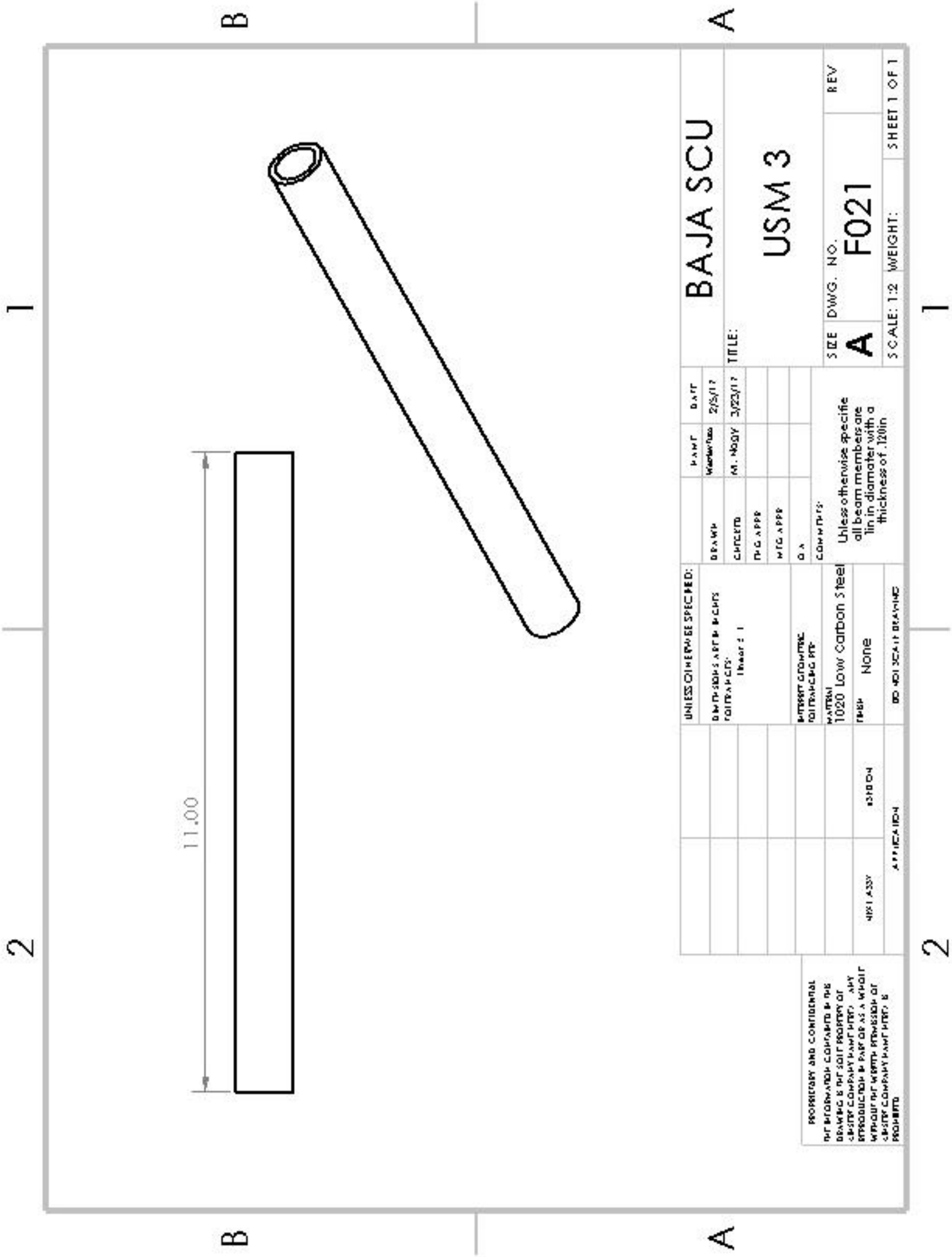

11.00
BAJA SCU
TITLE:
USM 3
SIZE
A
DWG. NO.
F021
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
1020 Low Carbon Steel
None
Unless otherwise specifie
all beam members are
1in in diamater with a
thickness of .120in
2/5/17
3/23/17
B
A
1
2

Figure A.40

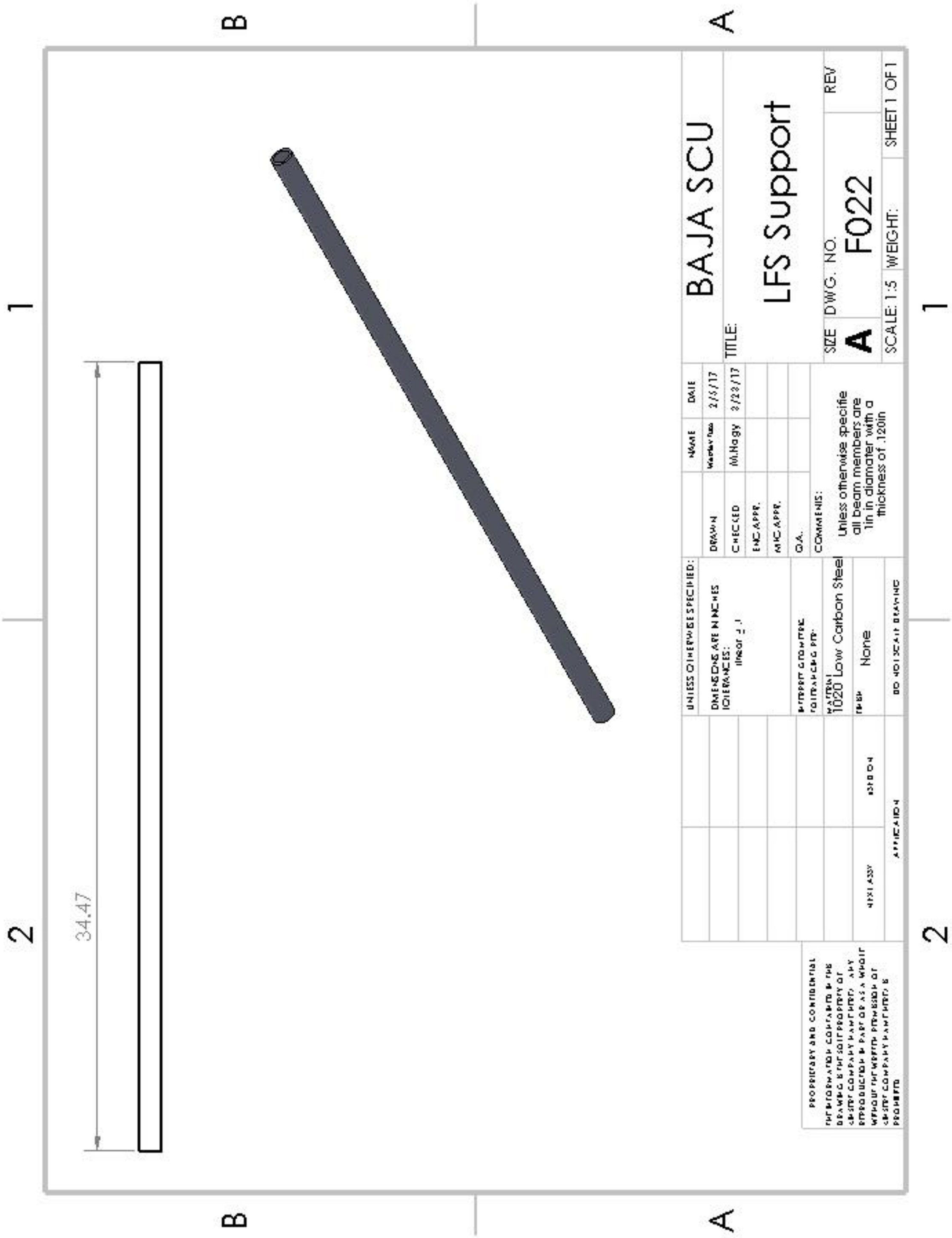

34.47
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
2/5/17
M.Nagy
2/23/17
Unless otherwise specifie
all beam members are
1in in diamater with a
thickness of .120in
MATERIAL
1020 Low Carbon Steel
FINISH
None
DO NOT SCALE DRAWING
BAJA SCU
TITLE:
LFS Support
SIZE
A
DWG. NO.
F022
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1

Figure A.41

Appendix C.2: Suspension:Parts Drawings

Note: The parts provided here are only the parts that the team manufactured

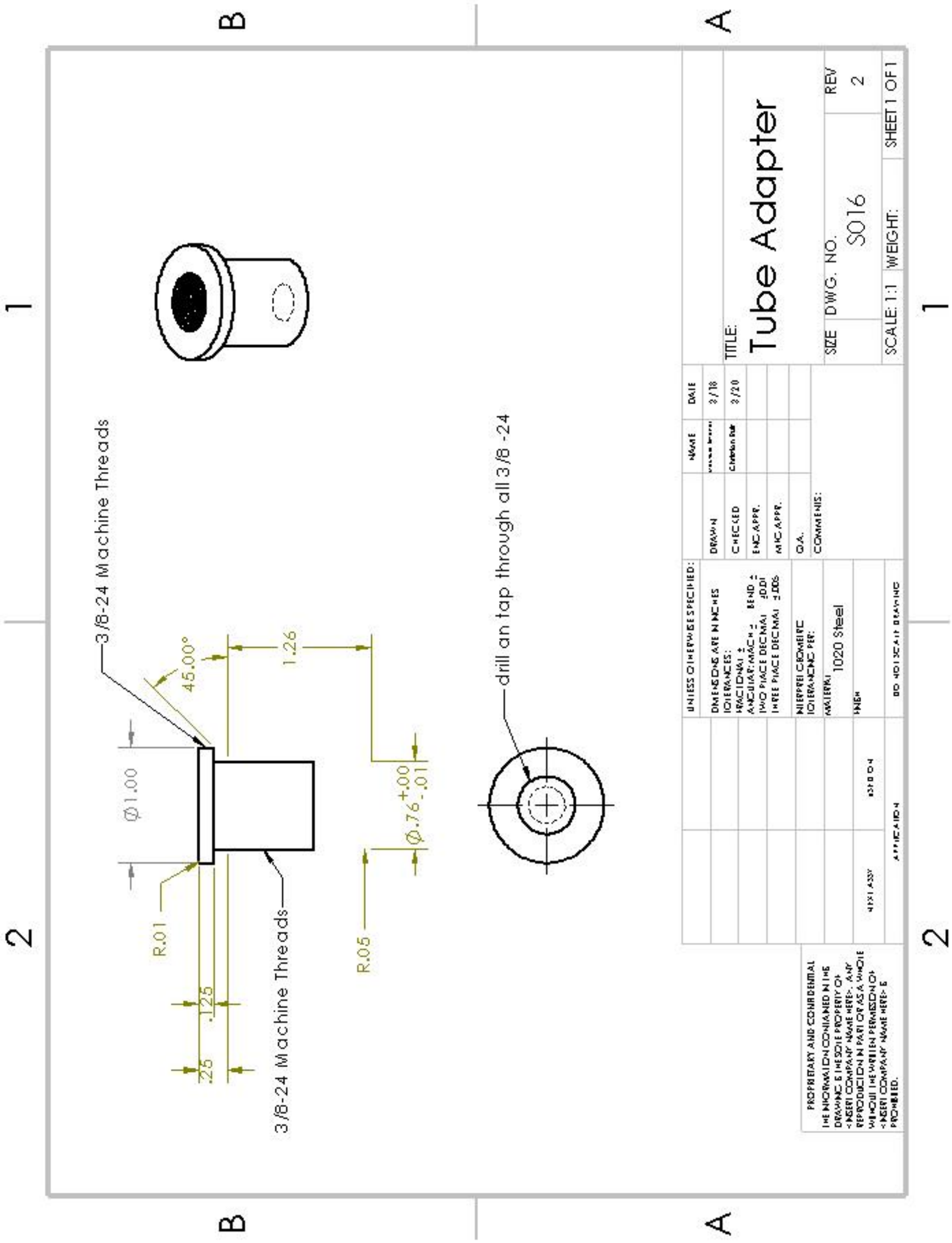
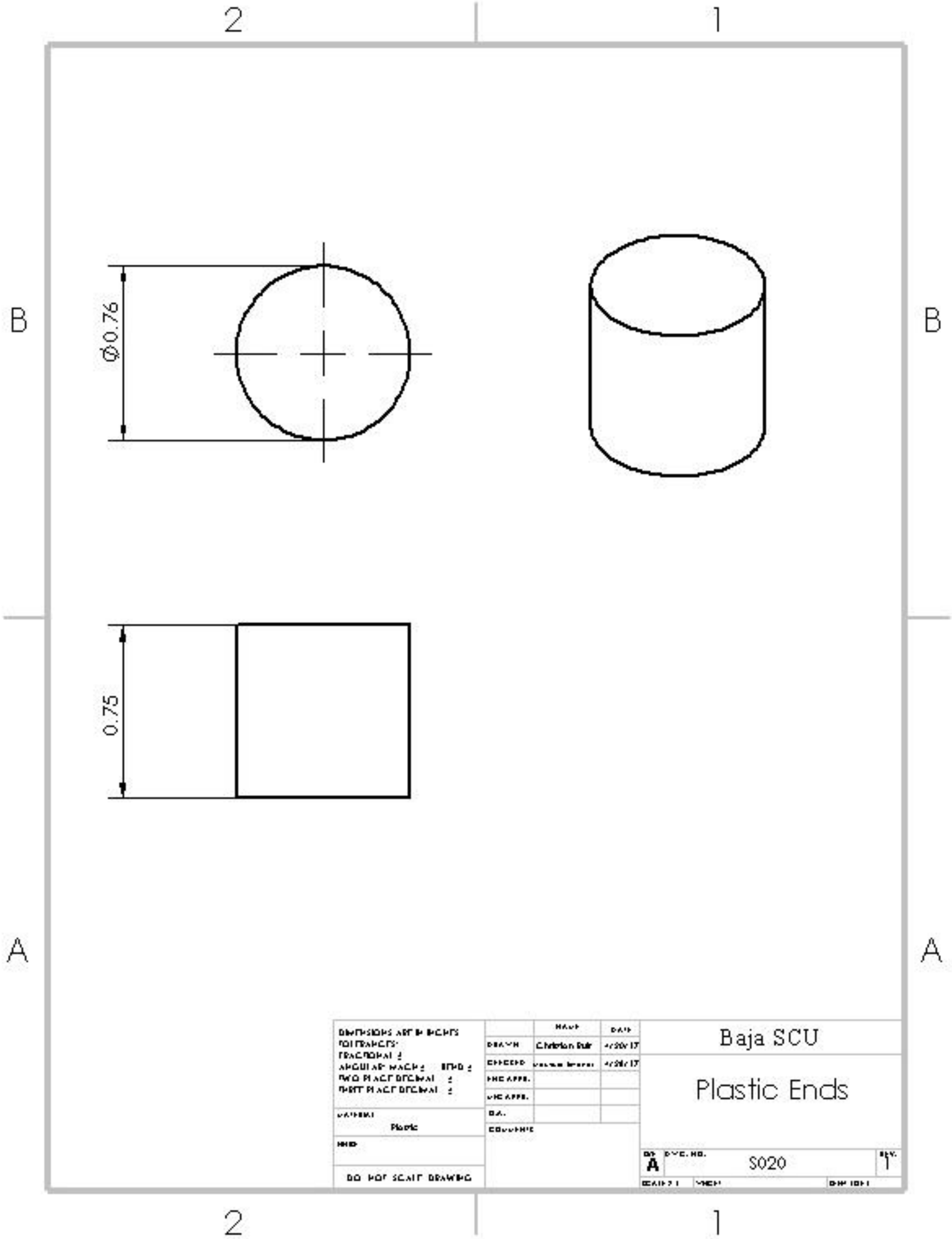


Figure A.42



Ø0.76
0.75
Christian Ruiz
Baja SCU
Plastic Ends
A
S020
1
Plastic
DO NOT SCALE DRAWING

Figure A.43

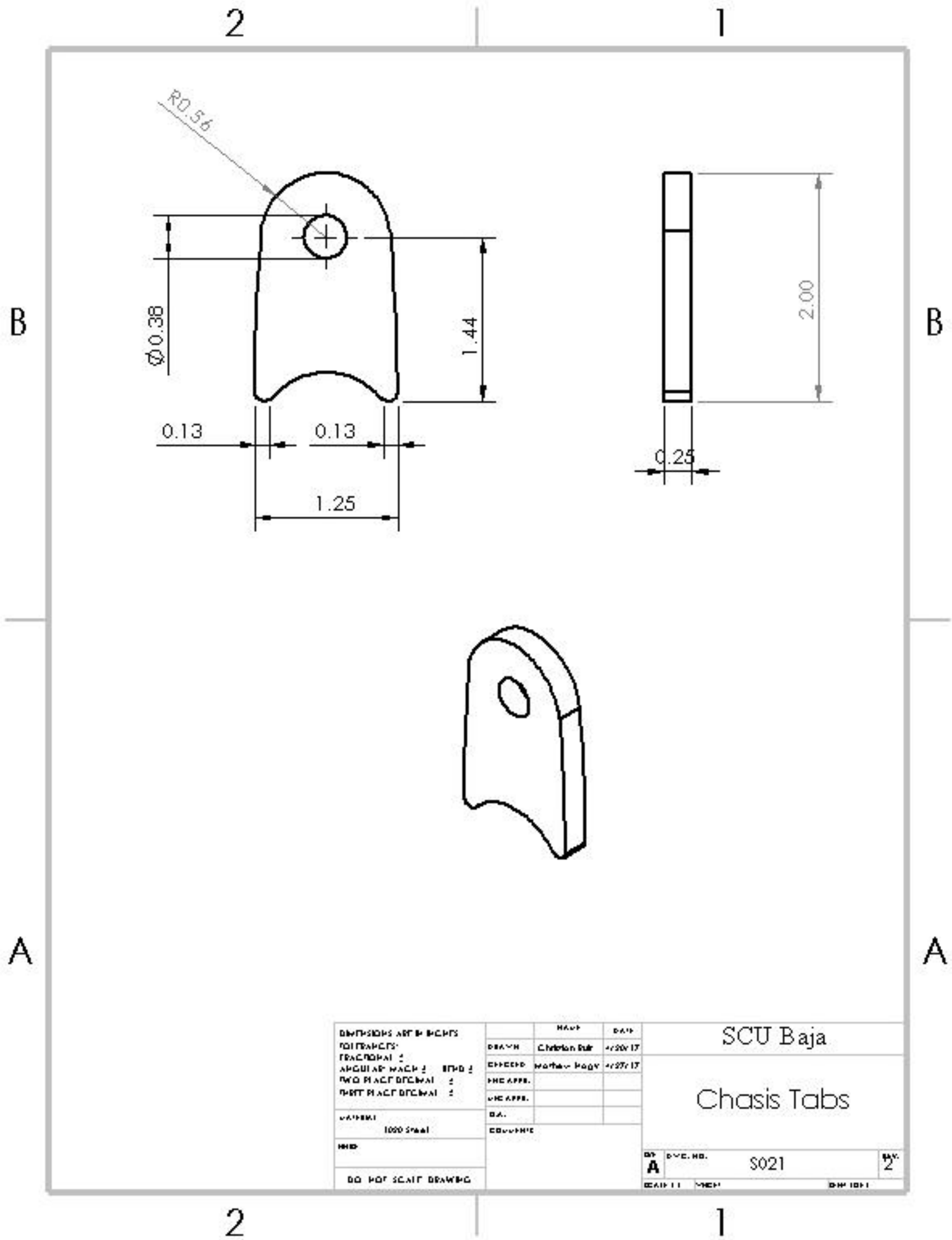

2
1
B
A
R0.56
Ø0.38
1.44
0.13
0.13
1.25
2.00
0.25
SCU Baja
Chasis Tabs
S021
A
2

Figure A.44

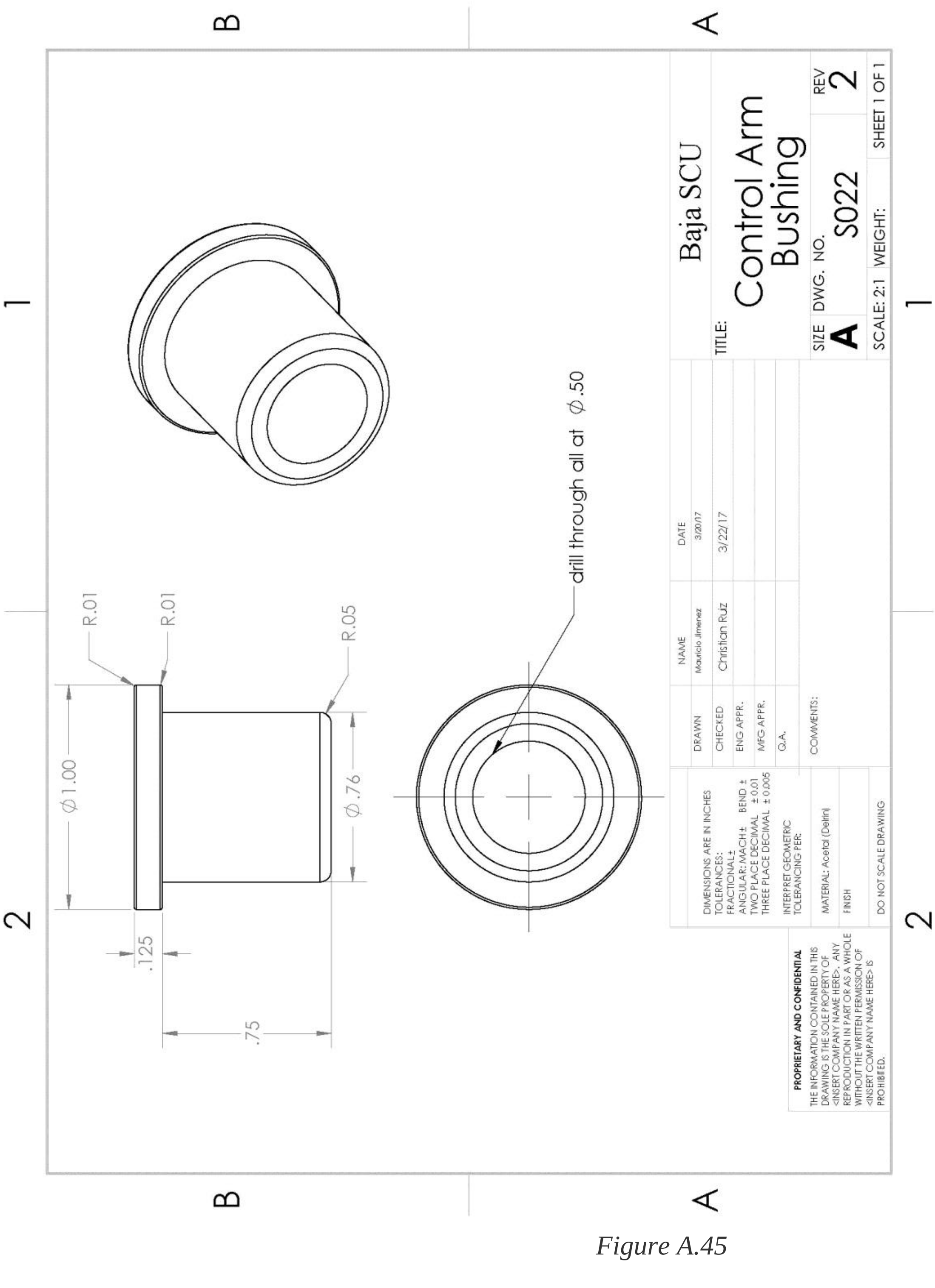

Baja SCU
TITLE:
Control Arm Bushing
SIZE
A
DWG. NO.
S022
REV
2
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
drill through all at ∅.50
∅1.00
∅.76
R.01
R.01
R.05
.125
.75
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
Christian Ruiz
3/22/17
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL: Acetal (Delrin)
FINISH
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL

Figure A.45

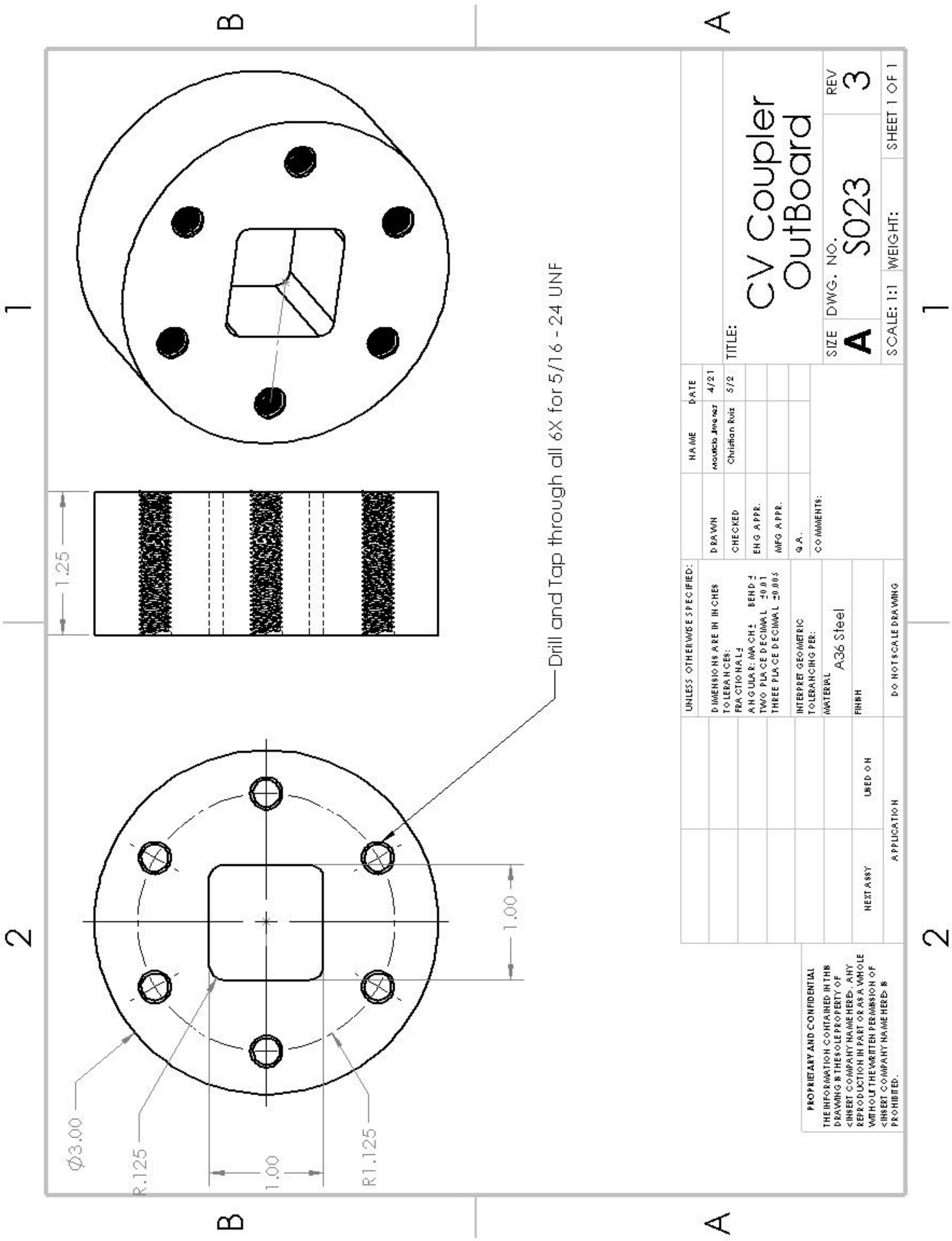

Ø3.00
R.125
1.00
R1.125
1.00
1.25
Drill and Tap through all 6X for 5/16 - 24 UNF
CV Coupler OutBoard
DWG. NO.
S023
SIZE
A
REV
3
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
A36 Steel
DRAWN
CHECKED
Christian Ruiz
PROPRIETARY AND CONFIDENTIAL
DO NOT SCALE DRAWING

Figure A.46

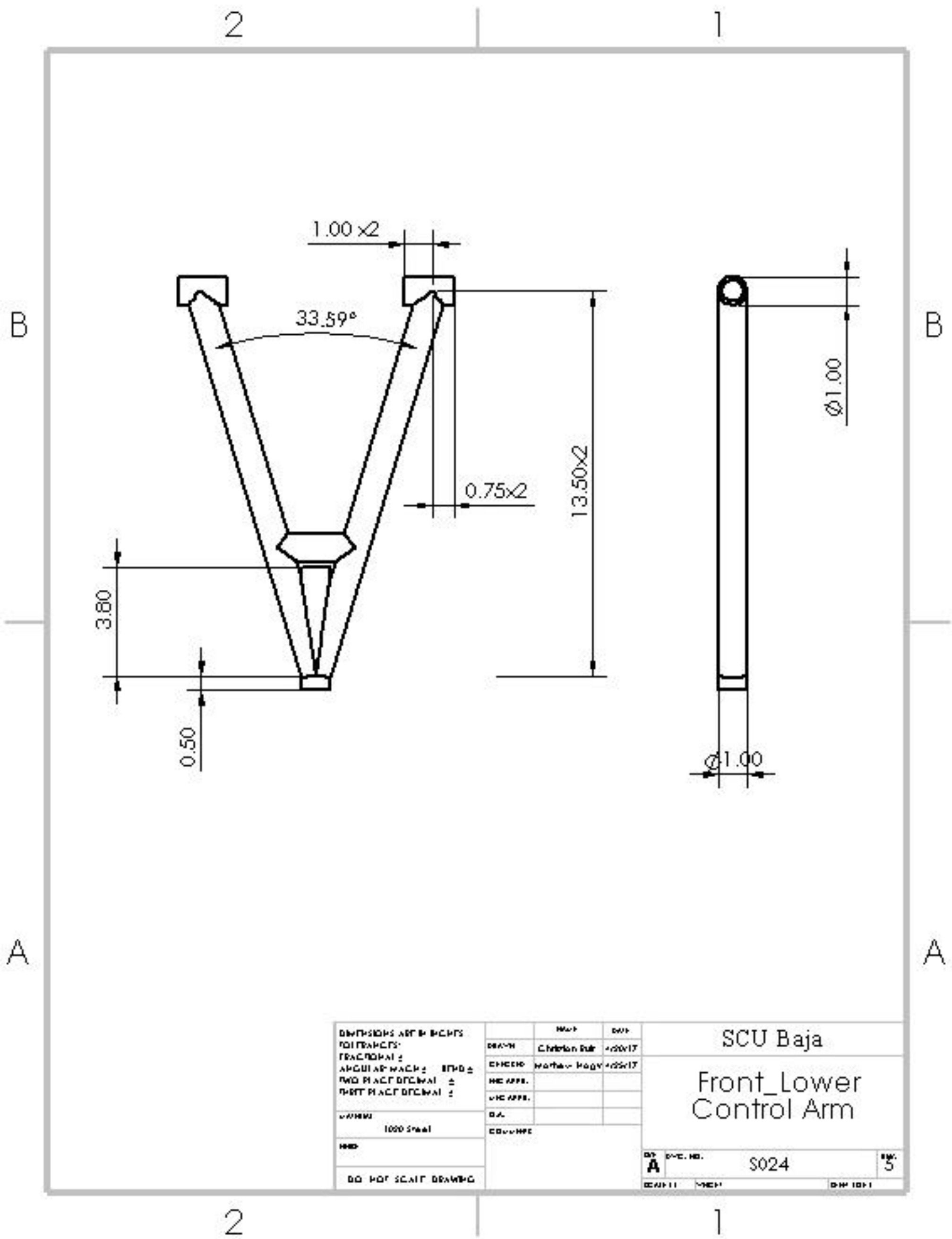

1.00 x2
33.59°
0.75x2
13.50x2
3.80
0.50
Ø1.00
Ø1.00
SCU Baja
Front_Lower
Control Arm
A
S024
5
2
1
B
A

Figure A.47

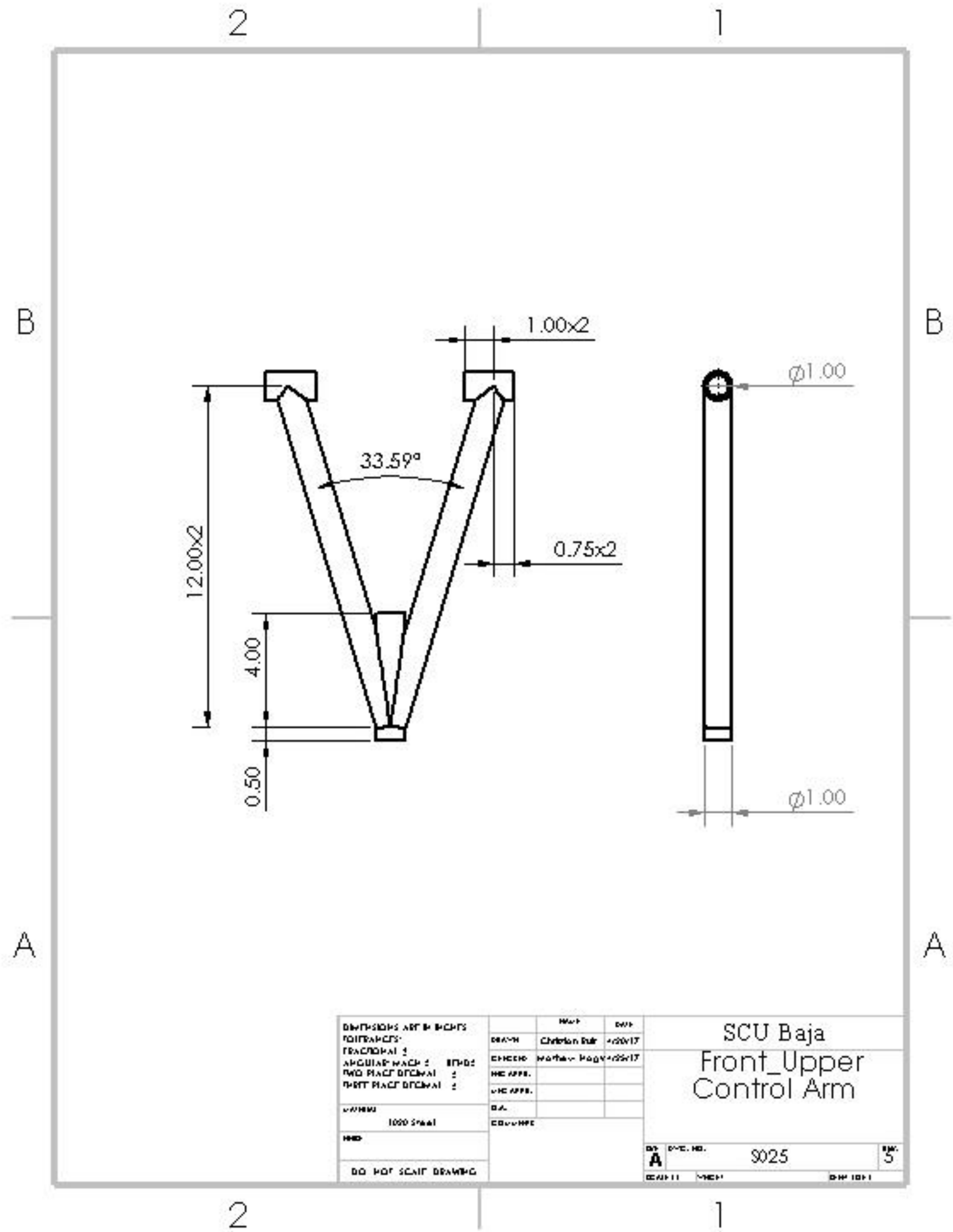
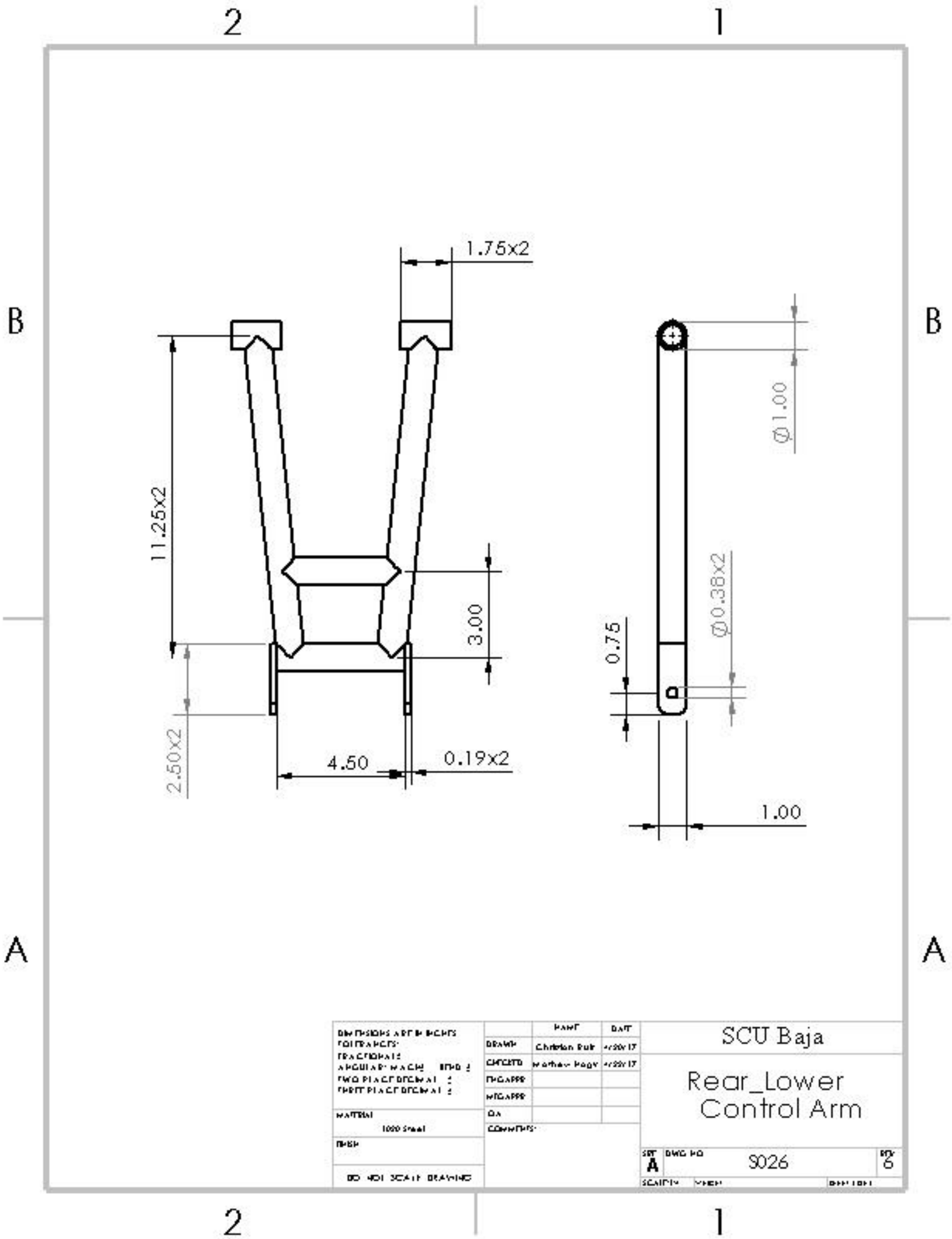

1.00x2
33.59°
0.75x2
12.00x2
4.00
0.50
Ø1.00
Ø1.00
SCU Baja
Front_Upper
Control Arm
S025
5
DO NOT SCALE DRAWING

Figure A.48



2
1
B
A
1.75x2
11.25x2
3.00
2.50x2
4.50
0.19x2
Ø1.00
Ø0.38x2
0.75
1.00
SCU Baja
Rear_Lower
Control Arm
DRAWN
Christian Ruiz
CHECKED
1020 Steel
DO NOT SCALE DRAWING
A
S026

Figure A.49

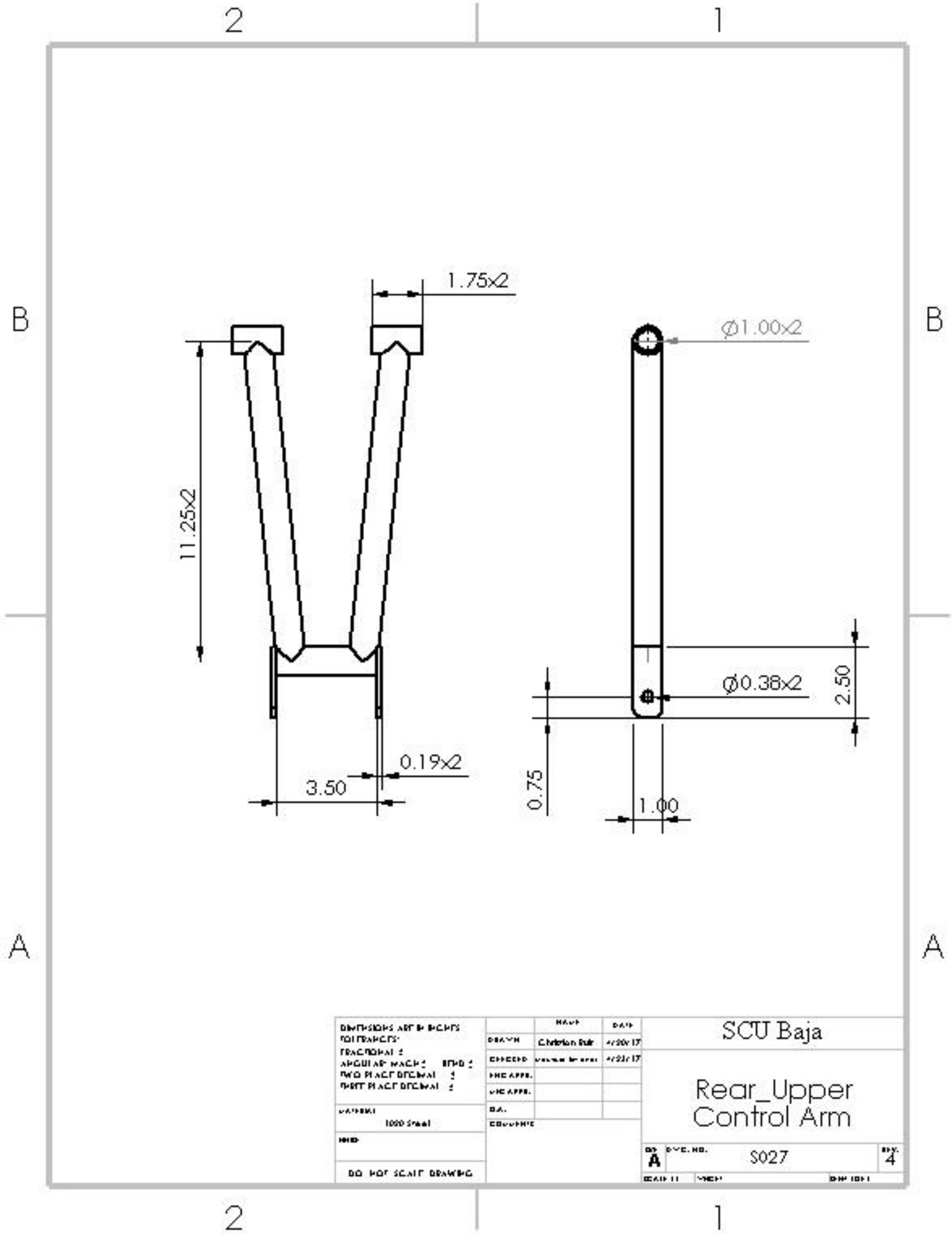

1.75x2
Ø1.00x2
11.25x2
Ø0.38x2
2.50
0.19x2
3.50
0.75
1.00
SCU Baja
Rear_Upper
Control Arm
S027
4
A

Figure A.50

Appendix C.3: Assembly Drawings

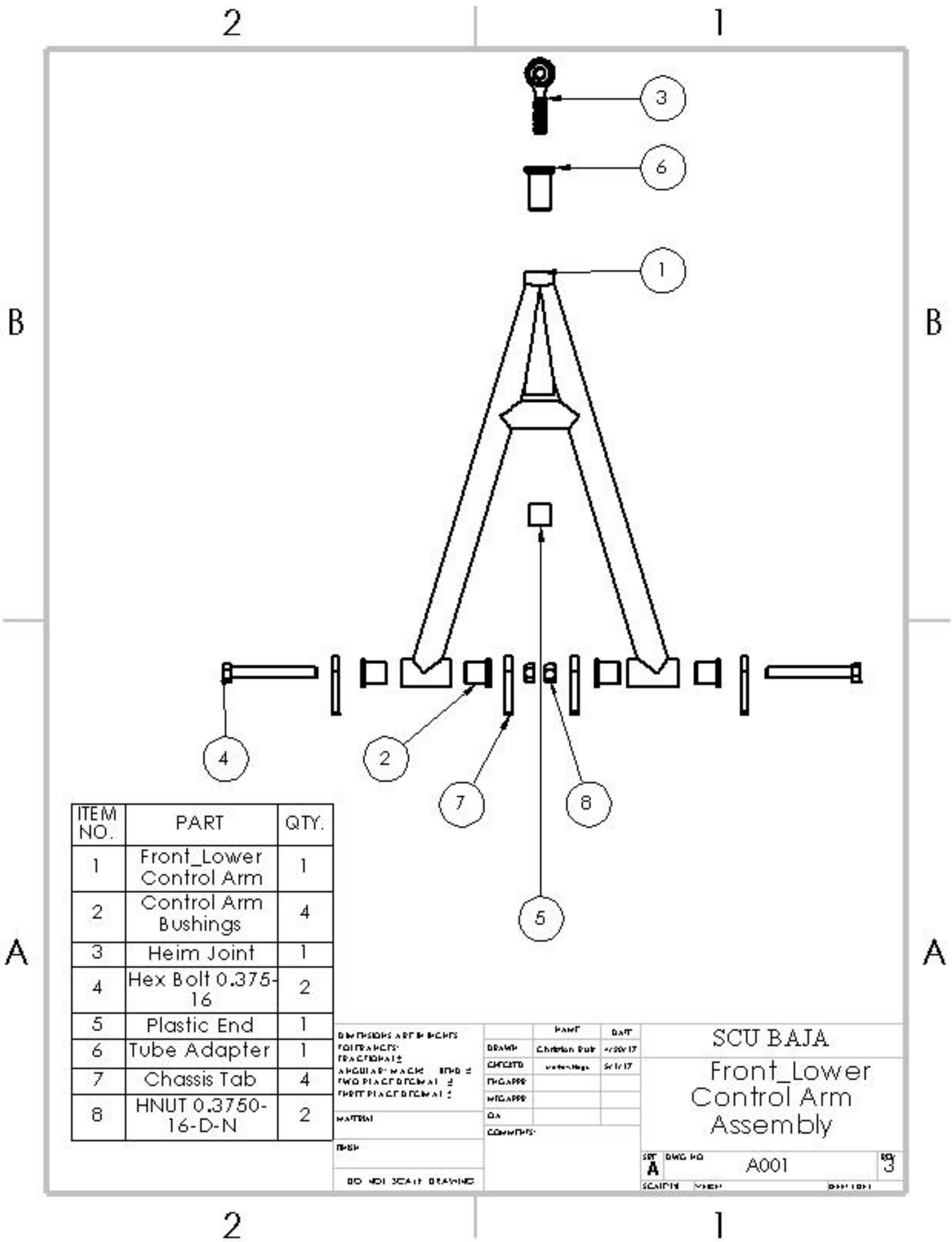


Figure A.51

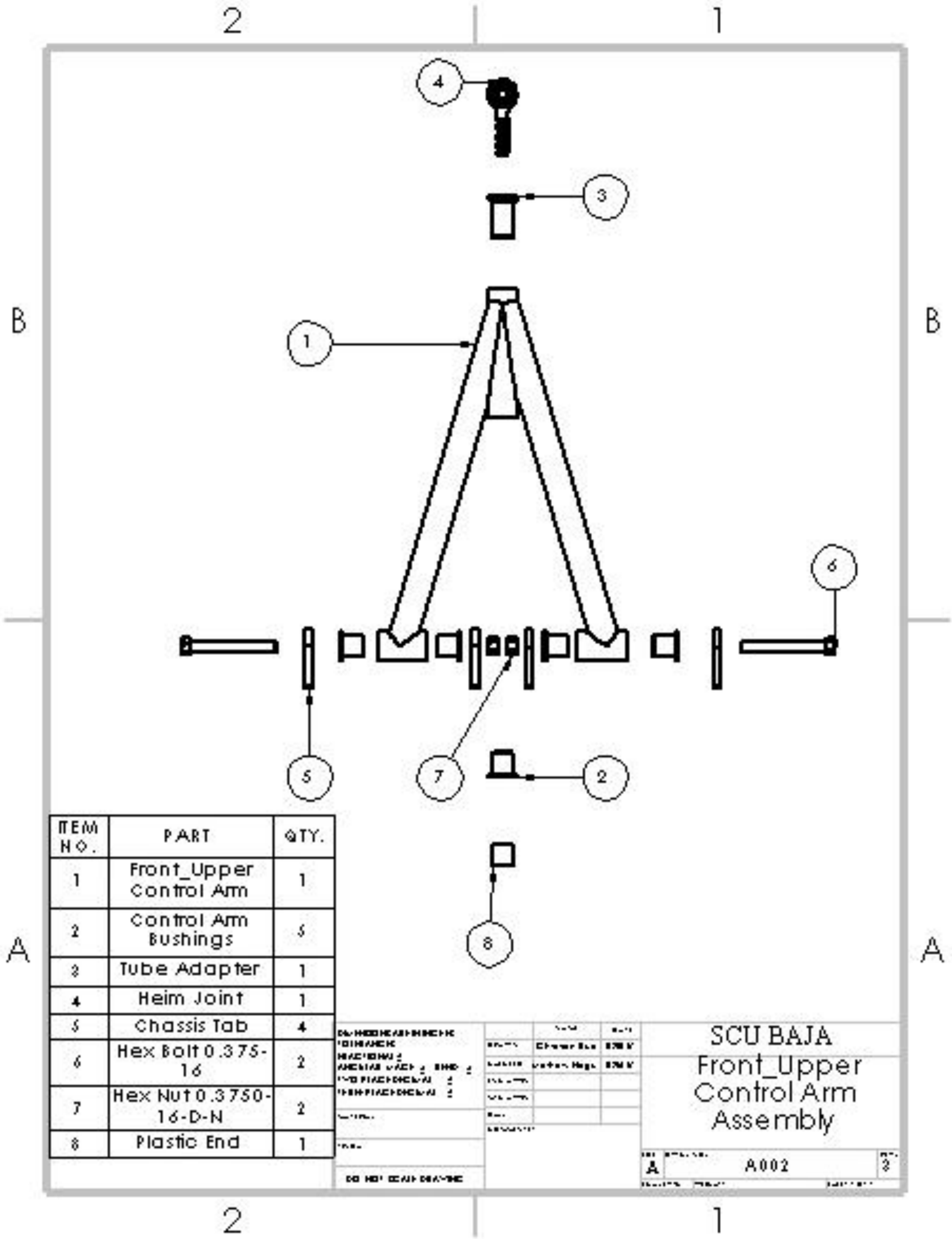

ITEM NO. | PART | QTY.
1 | Front_Upper Control Arm | 1
2 | Control Arm Bushings | 6
3 | Tube Adapter | 1
4 | Heim Joint | 1
5 | Chassis Tab | 4
6 | Hex Bolt 0.375-16 | 2
7 | Hex Nut 0.3750-16-D-N | 2
8 | Plastic End | 1
SCU BAJA
Front_Upper Control Arm Assembly
A
A002
DO NOT SCALE DRAWING

Figure A.52

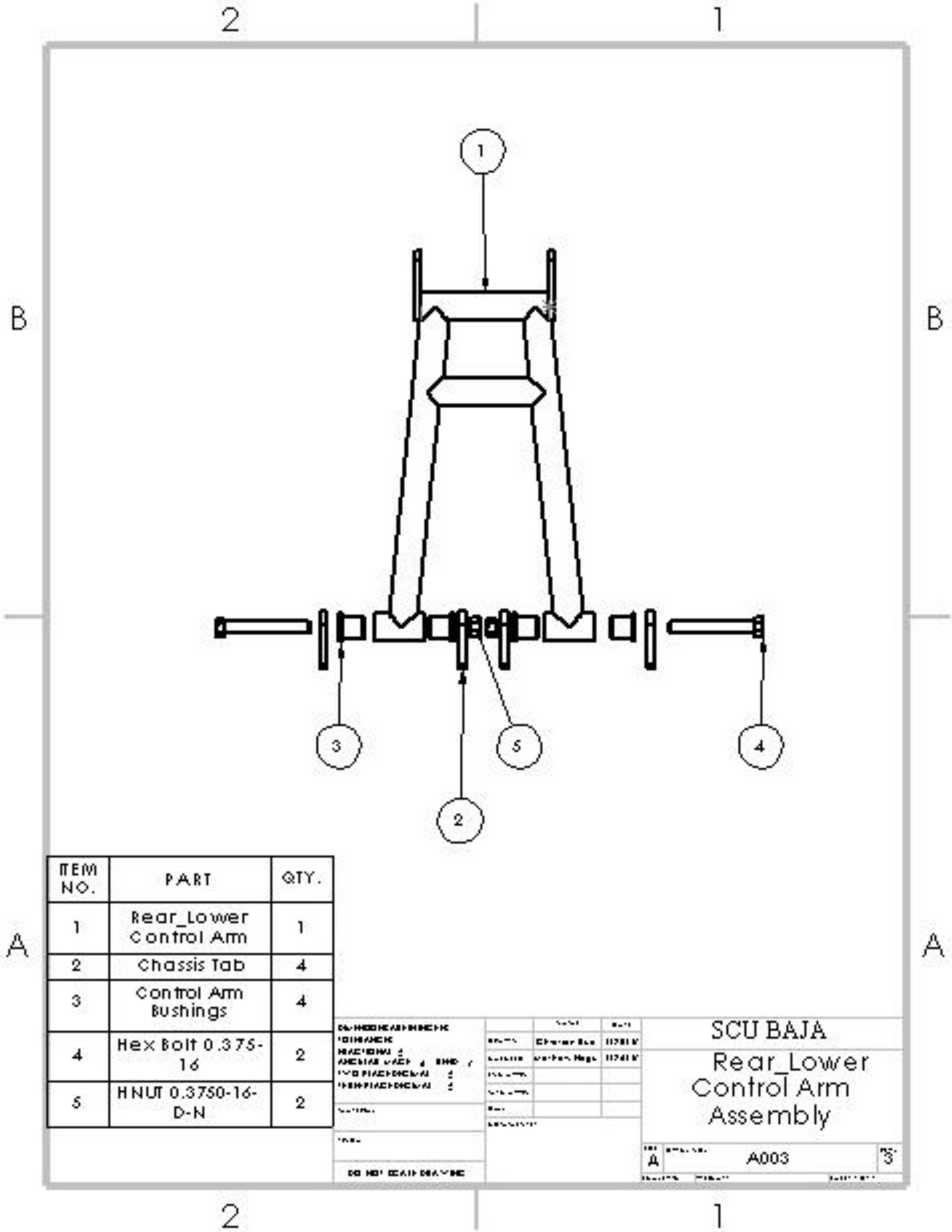

2
1
B
A
ITEM NO.
PART
QTY.
1
Rear_Lower Control Arm
1
2
Chassis Tab
4
3
Control Arm Bushings
4
4
Hex Bolt 0.375-16
2
5
HNUT 0.3750-16-D-N
2
SCU BAJA
Rear_Lower Control Arm Assembly
A
A003
3
DO NOT SCALE DRAWING

Figure A.53

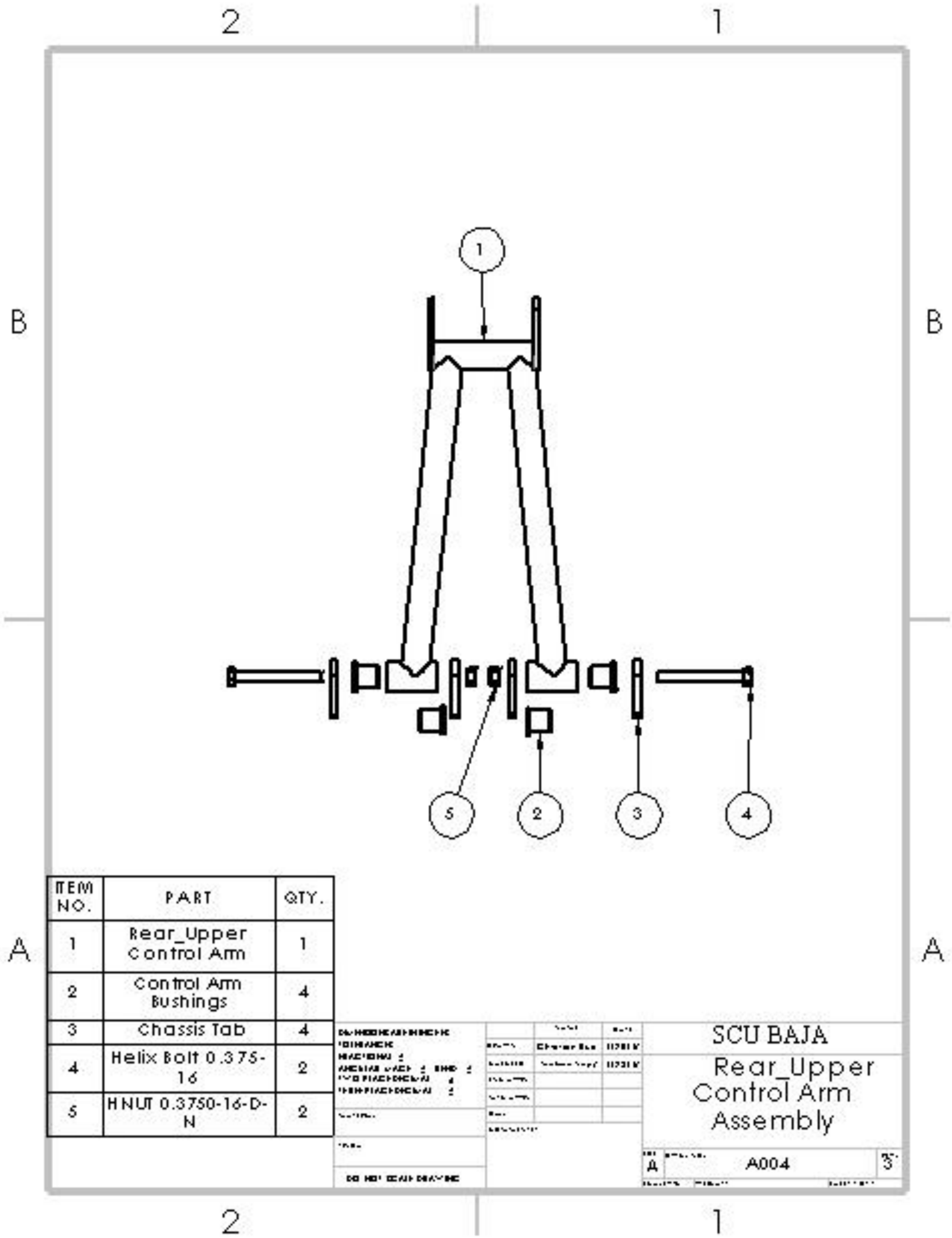
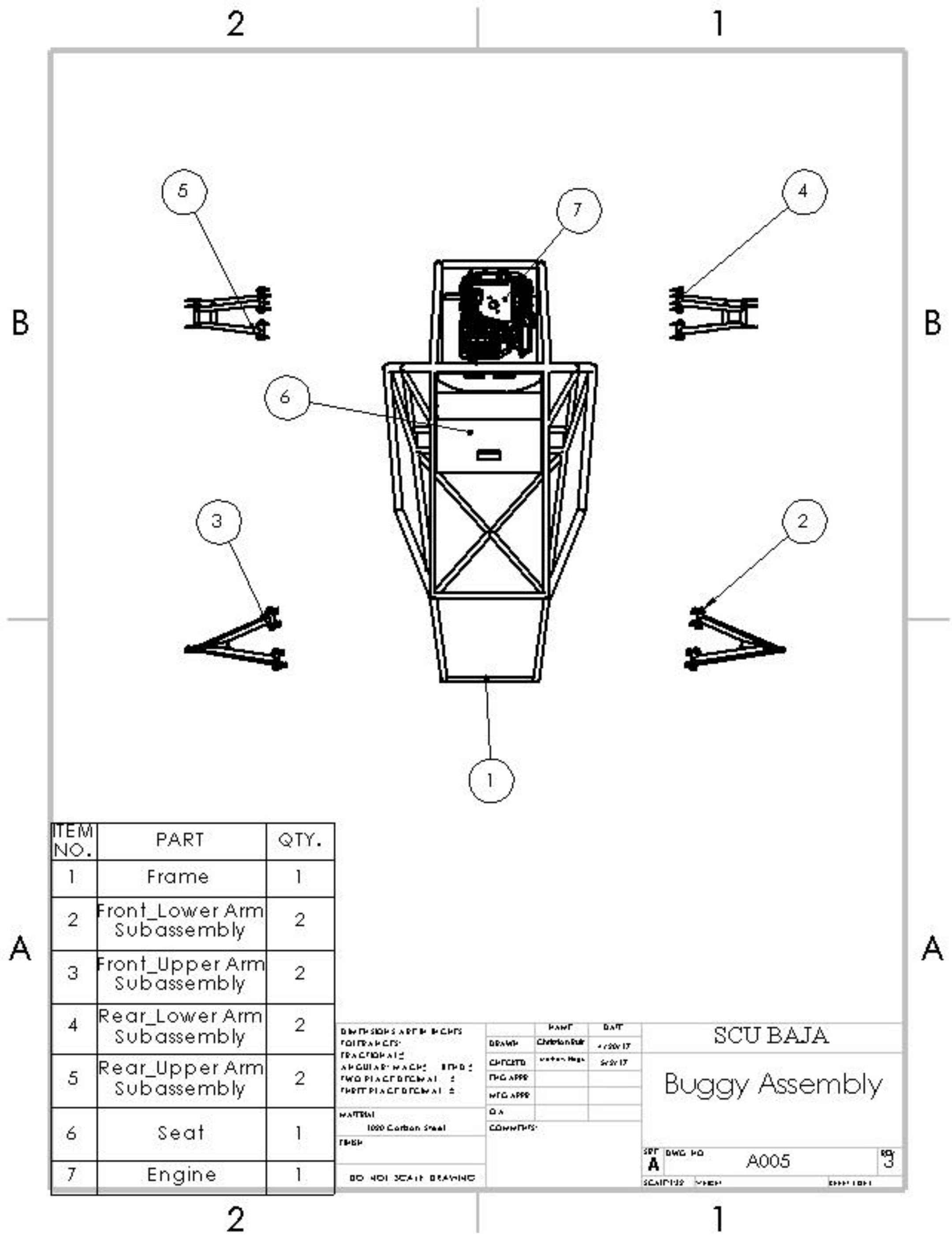

ITEM NO.
PART
QTY.
1
Rear_Upper Control Arm
1
2
Control Arm Bushings
4
3
Chassis Tab
4
4
Helix Bolt 0.375-16
2
5
HNUT 0.3750-16-D-N
2
SCU BAJA
Rear_Upper Control Arm Assembly
A
A004
DO NOT SCALE DRAWING

Figure A.54



ITEM NO.	PART	QTY.
1	Frame	1
2	Front_Lower Arm Subassembly	2
3	Front_Upper Arm Subassembly	2
4	Rear_Lower Arm Subassembly	2
5	Rear_Upper Arm Subassembly	2
6	Seat	1
7	Engine	1

Figure A.55

Appendix D: Product Design Specification (PDS)

Performance:
- Seeking to be as fast or faster than the buggy designed by previous SCU teams (35 mph - 50 mph).
- The suspension must withstand rough terrain and sharp turns.
- The structure must not break in the case of unforeseen impacts/crashes during the competition. A Stiff frame is required to protect the driver and allow the suspension to work as it was designed to do so.
- The automatic transmission must not stall, bind, or seize during the competition.

Size: The buggy structure must meet vehicle width code requirements/laws. The tubing used for the buggy structure must be 2 inches or less in diameter for aesthetics and storage concerns. The buggy must be able to fit in a maximum storage space of half a typical garage space. The size of the buggy must not cause transportation issues in getting the buggy to and back from the competition.

Cost: Manufacturing cost plus the $1250 team registration fee plus individual registration fees.

Quantity: Minimal number of monolithic parts. One (1) final product: a functional race buggy.

Maintenance: Minimal (e.g., break changes, engine oil, transmission oil)

Finish: Corrosion resistant, aesthetically pleasing.

Materials: Light weight, strong, not easily crushed by impact.

Weight: Minimal overall vehicle weight to maximize vehicle speed and acceleration.

Aesthetics: Must present an image of sturdiness, speed, and simplicity.

Product Life: One (1) week (buggy to be used exclusively for competition purposes). For competition the design the product must be made for the possibility of production of 4000 copies.

Customer: The members of the project team who are going to drive the vehicle during the competition, and SAE associates.

Standards/specifications: Maximum vehicle width requirements (to be researched).

Safety: Should protect competition participant drivers from collision injuries. Drivers of the overall final buggy should possess a driver's license.

Appendix E: Survey Results and Decision Matrix

Table B.1: Overview for surveyed results for design of Baja Buggy

Question	First Choise		Second Choice	
	Answer	Percentage (%)	Answer	Percentage (%)
1	Desert	61.11	Savanahh	16.67
2	Power	44.44	Efficiency	33.33
3	Assembled	50.00	Do it yourself	44.44
4	20000+	38.89	10000+	27.78
5	60mph	50.00	40mph	33.33
6	1 seater	44.44	4 Seater	27.78
7	All W. Drive	66.67	Rear W. Drive	16.67
8	Yes	61.11		
9	Fix Yourself	38.89	Mechanic	33.33
10	Performance	50.00	Both	50.00

Table B.2: Transmission Requirements Matrix

Requirements	Description	Weight
User Friendly	Ease of operating	0.2
Manufacturability	Ease in building, machining, and assembly	0.3
Cost	The transmission should be affordable and cost effective	0.3
Efficiency	Mode of power transmission efficiency	0.2

Table B.3 : Transmission Comparison Matrix

	User Friendly (0.2)	Manufacturability (0.3)	Cost (0.3)	Efficiency (0.2)	Total
Manual Gearbox	1	2	2	3	2
Continuously Variable	3	3	3	2	2.8
Combination	2	1	1	2	1.4

Appendix F: Gantt Chart

Figure A.56

Appendix G: Executive Summary (Senior Design Conference)

The main motivation behind this project is what it has to offer students who are transitioning from school to the work force. This project provides ample opportunity to learn about working on a team, doing cost analysis, marketing presentations, design process, engineering analysis, and hands on fabrication. Very few projects are so broad yet completely organized as the SAE (Society of Automotive Engineers) Baja competition, and this is one of the main reasons that the team went forth with this project. The skills and lessons learned in this project can be directly applied to future jobs, as most companies work on projects that are even bigger in scale, thus, practicing compartmentalization and communication are key motivators. Since the last SCU team to partake in the SAE competition was years ago, it was our goal to bring it back once again. Our team was divided into three subdivisions so that each subsystem can be optimally designed and thoroughly analyzed. These groups are: suspension team, frame team, and the drivetrain team.

The focus of the suspension team will be to design a practical suspension system capable of withstanding the harsh off-road terrain. The front and rear suspension system will consist of a double A-arm setup. The drivetrain team will focus on developing a power transmission that will couple a CVT with two chain drive reductions. The gear ratios will allow for plenty of low end torque to overcome obstacles and hill climbs while having enough high end gearing to reach an appropriate top speed. The frame team will focus on producing a light yet structurally sound frame. Their main focus is on reducing the total weight of the vehicle while also meeting the minimum competition requirements and ensuring driver safety. They will be working closely with the suspension team in order to properly mount the double A-arm front and rear suspension onto the frame.

Extensive Finite Element Analysis was performed on the frame and drivetrain to optimize their design. Kinematic and dynamic analysis was also performed on the suspension and brake systems.

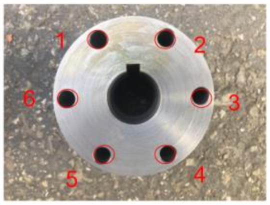
Appendix H: Hand Calculations

Shear capability of 5/16-24 fine thread bolts (http://tinelok.com/grade-5-vs-grade-8-fasteners/):

5750 lb

Total number of bolts per coupler: 6 bolts

Torque (T) from engine: 4800 in-lb



Force (F) = T/[Radius (r)] = (4800 in-lb)/(1.125 in) = 4267 lb

Force per bolt = (4267 lb)/(6 bolts) = 711 lb

711 lb << 5750 lb

The bolts will not fail!

Figure A.57: CV Coupler Bolt Shear Calculations

$\eta_{chain\ drive\ overall} = \eta_{belt} \times (\eta_{chain})^2 \times \eta_{cv} =$ (2x other reduction)

$0.94 \times (0.92)^2 \times 0.94 = 0.75$ or 75% efficient drive system

engine max RPM is 3800 under no load, governed @ 3600 by SAE rules

other teams have tested the engine on Dynos and realistic max operating range is btw 3000-3200 RPM, Engine torque drops dramatically past about 3200 RPM anyway so we have no desire to rev beyond it.

$$F_c = \frac{-(1125)(4-11) + 1000(11-6)}{11\left(\frac{\cos 15}{0.45}\right) + 11\sin(15) - 2\left(\frac{\cos 15}{0.45}\right) - 0.5\cos 15} = \frac{7875 + 5000}{23.61 + 2.85 - 4.29 - 0.48} = \frac{12875}{21.69}$$

$F_c = 593.6$

tire friction $F_f = \mu N$

(locked wheel hard braking) static friction

μ_s dry asphalt ≈ 0.7

μ_s dry concret ≈ 0.8

μ_s dirt road ≈ 0.4

(weight per corner)

$F_{Dmin} = 0.4(150\,lb) = 60\,lb$

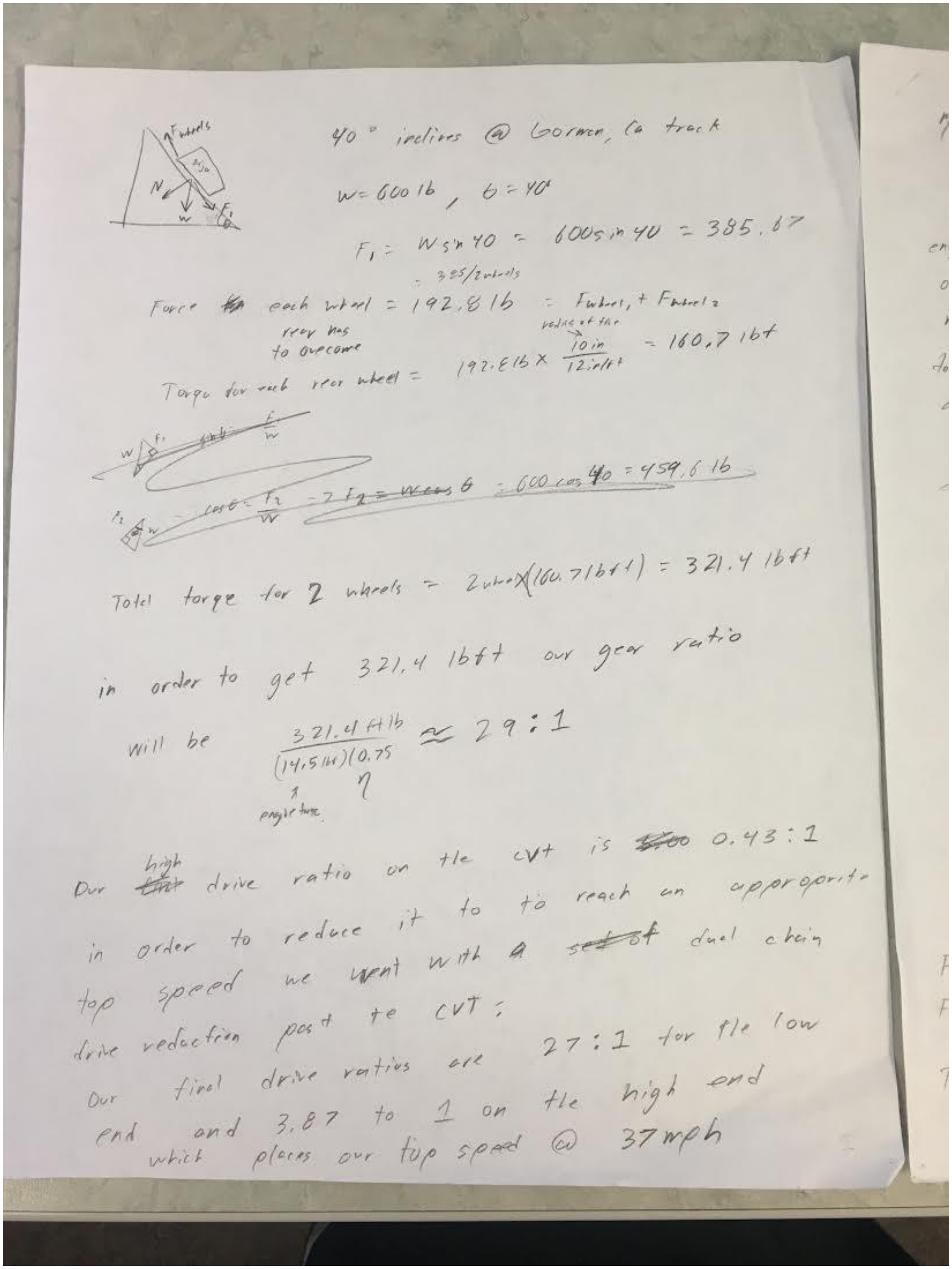
$F_{Dmax} = 0.8(150) = 120\,lb$

in order to achieve most traction under hard acceleration in low gear we need to meet this requirement but not go over it excessively to prevent the tires from just spinning in low traction situations

$T_{traction\ limited} = 2$ rear drive tires $\times F_{Dmax} \times \frac{10\,in}{12\,in/ft}$ (radius of tire)

$= 2 \times 120\,lb \times \frac{10}{12}\,ft = 200$ ft lbs → before slip

Figure A.58


40° inclines @ Gorman, Ca track

w = 600 lb, θ = 40°

F₁ = W sin 40 = 600 sin 40 = 385.67

Force ~~to~~ each wheel = 192.8 lb = 385/2 wheels = F_wheel1 + F_wheel2

rear has to overcome

Torque for each rear wheel = 192.8 lb × 10 in (radius of the tire) / 12 in/ft = 160.7 lbf

~~cos θ = F₂/W ⇒ F₂ = W cos θ = 600 cos 40 = 459.6 lb~~

Total torque for 2 wheels = 2 wheel × (160.7 lbft) = 321.4 lbft

in order to get 321.4 lbft our gear ratio will be

321.4 ft lb / (14.5 lbf)(0.75) ≈ 29 : 1

(14.5: engine torque; 0.75: η)

Our high ~~low~~ drive ratio on the cvt is ~~3.00~~ 0.43 : 1

in order to reduce it to to reach an appropriate top speed we went with a ~~set of~~ dual chain drive reduction post te CVT ;

Our final drive ratios are 27 : 1 for the low end and 3.87 to 1 on the high end which places our top speed @ 37 mph

Figure A.59

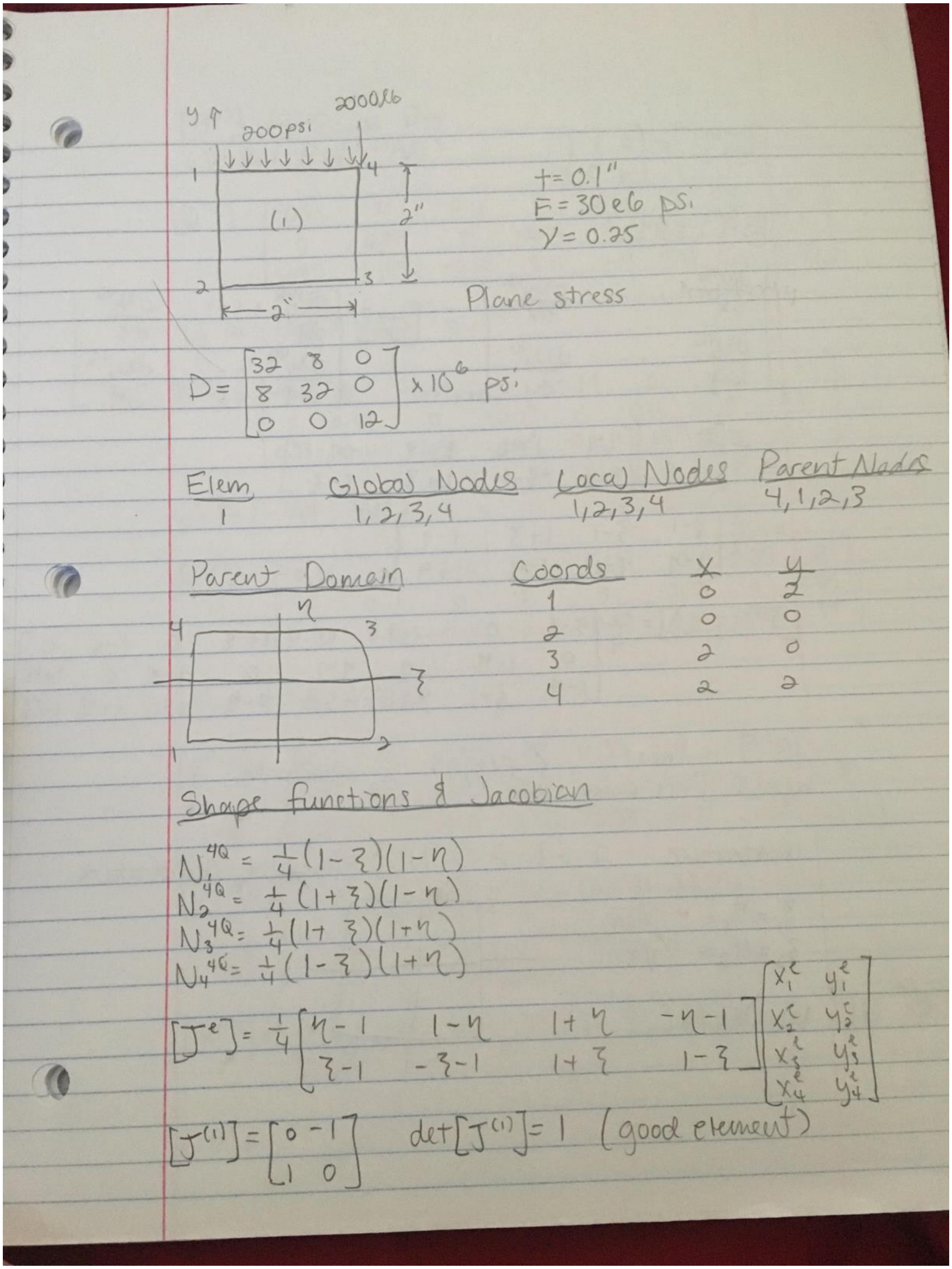


Figure A.60: FEA hand calculation example part 1

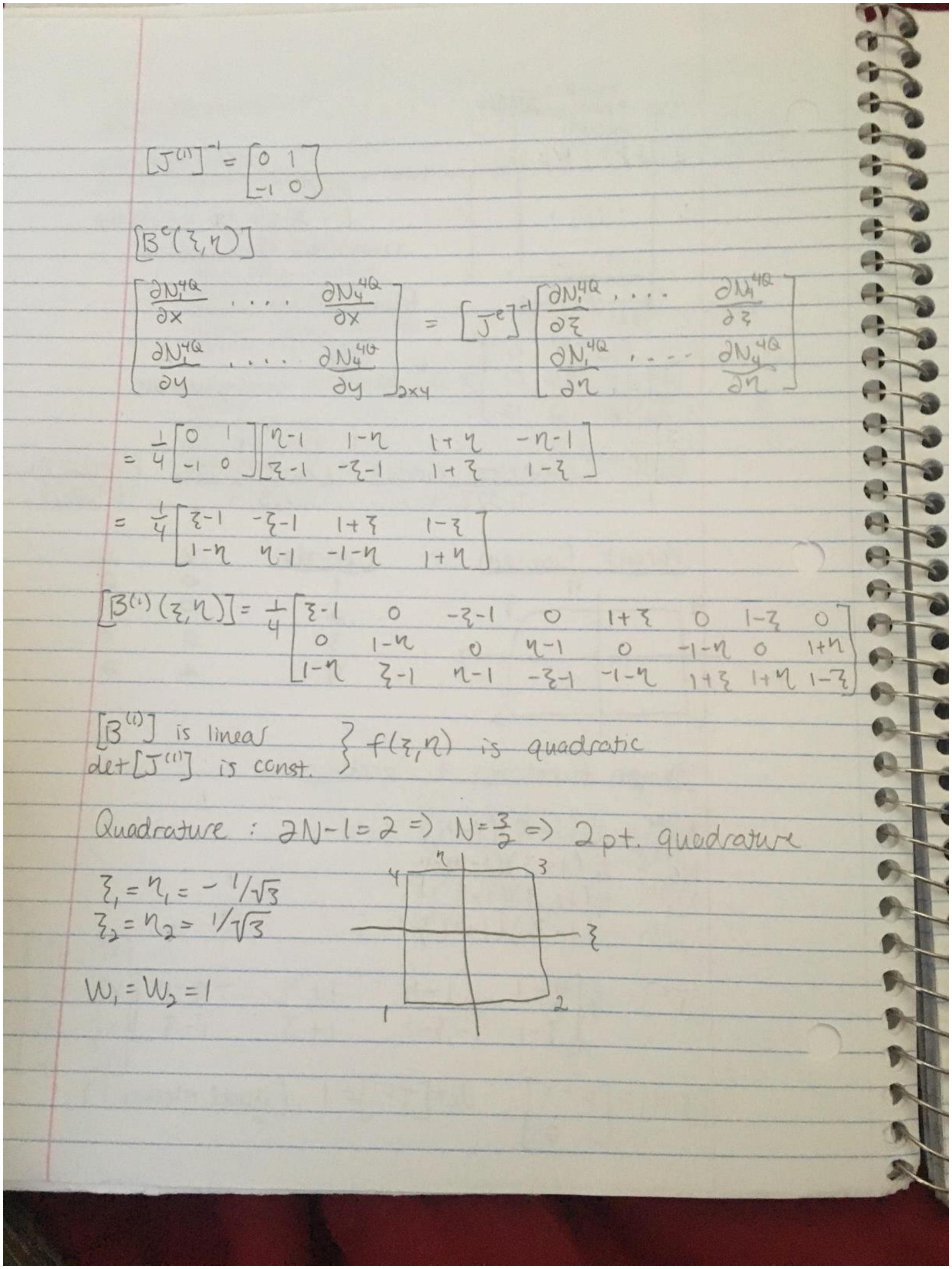
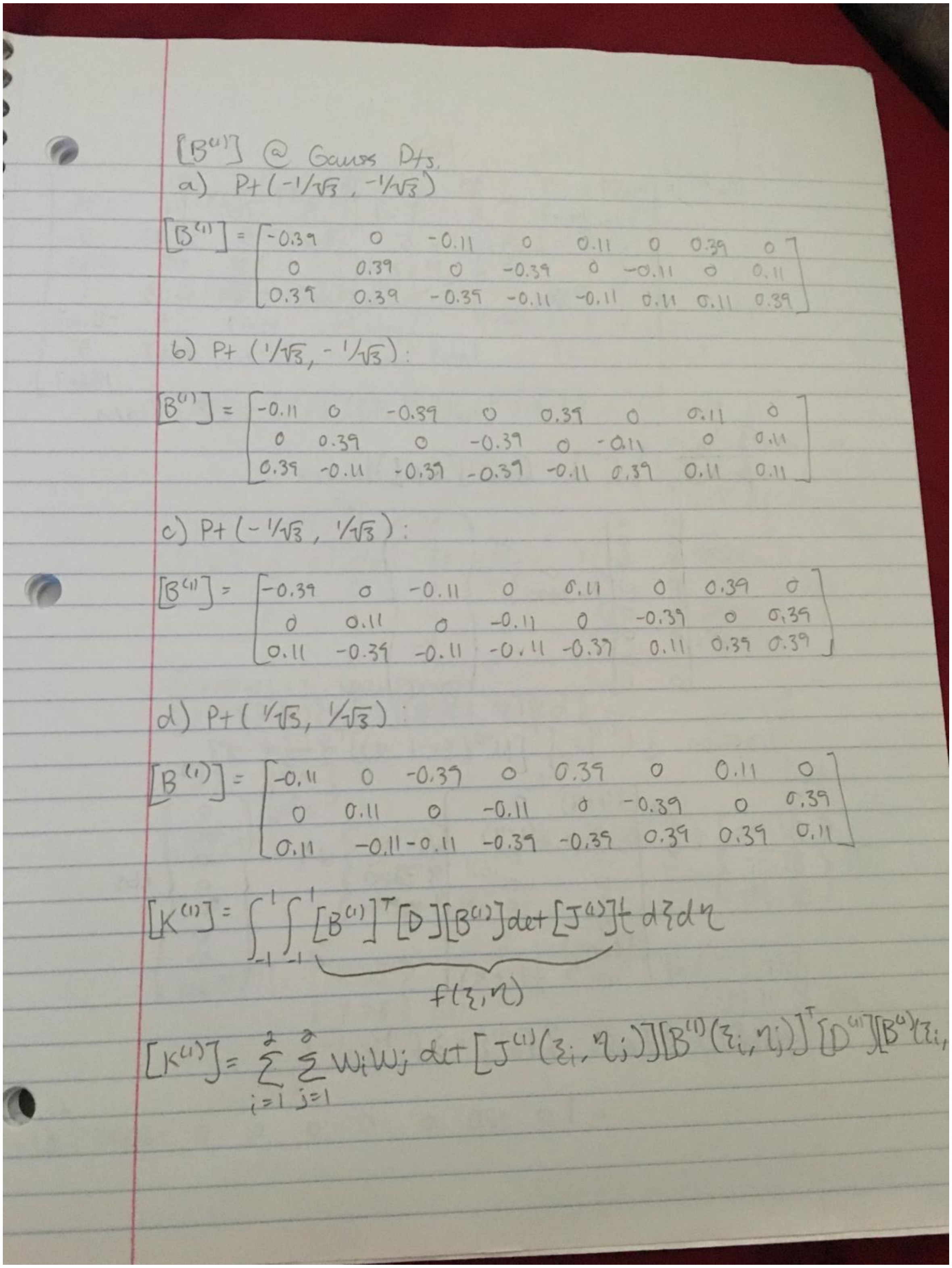


Figure A.61: FEA hand calculation example part 2



$[B^{(1)}]$ @ Gauss Pts.

a) Pt $(-1/\sqrt{3}, -1/\sqrt{3})$

$$[B^{(1)}] = \begin{bmatrix} -0.39 & 0 & -0.11 & 0 & 0.11 & 0 & 0.39 & 0 \\ 0 & 0.39 & 0 & -0.39 & 0 & -0.11 & 0 & 0.11 \\ 0.39 & 0.39 & -0.39 & -0.11 & -0.11 & 0.11 & 0.11 & 0.39 \end{bmatrix}$$

b) Pt $(1/\sqrt{3}, -1/\sqrt{3})$:

$$[B^{(1)}] = \begin{bmatrix} -0.11 & 0 & -0.39 & 0 & 0.39 & 0 & 0.11 & 0 \\ 0 & 0.39 & 0 & -0.39 & 0 & -0.11 & 0 & 0.11 \\ 0.39 & -0.11 & -0.39 & -0.39 & -0.11 & 0.39 & 0.11 & 0.11 \end{bmatrix}$$

c) Pt $(-1/\sqrt{3}, 1/\sqrt{3})$:

$$[B^{(1)}] = \begin{bmatrix} -0.39 & 0 & -0.11 & 0 & 0.11 & 0 & 0.39 & 0 \\ 0 & 0.11 & 0 & -0.11 & 0 & -0.39 & 0 & 0.39 \\ 0.11 & -0.39 & -0.11 & -0.11 & -0.39 & 0.11 & 0.39 & 0.39 \end{bmatrix}$$

d) Pt $(1/\sqrt{3}, 1/\sqrt{3})$:

$$[B^{(1)}] = \begin{bmatrix} -0.11 & 0 & -0.39 & 0 & 0.39 & 0 & 0.11 & 0 \\ 0 & 0.11 & 0 & -0.11 & 0 & -0.39 & 0 & 0.39 \\ 0.11 & -0.11 & -0.11 & -0.39 & -0.39 & 0.39 & 0.39 & 0.11 \end{bmatrix}$$

$$[K^{(1)}] = \int_{-1}^{1}\int_{-1}^{1} \underbrace{[B^{(1)}]^T [D][B^{(1)}] \det[J^{(1)}] t}_{f(\xi,\eta)}\, d\xi\, d\eta$$

$$[K^{(1)}] = \sum_{i=1}^{2}\sum_{j=1}^{2} W_i W_j \det[J^{(1)}(\xi_i, \eta_j)][B^{(1)}(\xi_i, \eta_j)]^T [D^{(1)}][B^{(1)}(\xi_i,$$

Figure A.62: FEA hand calculation example part 3

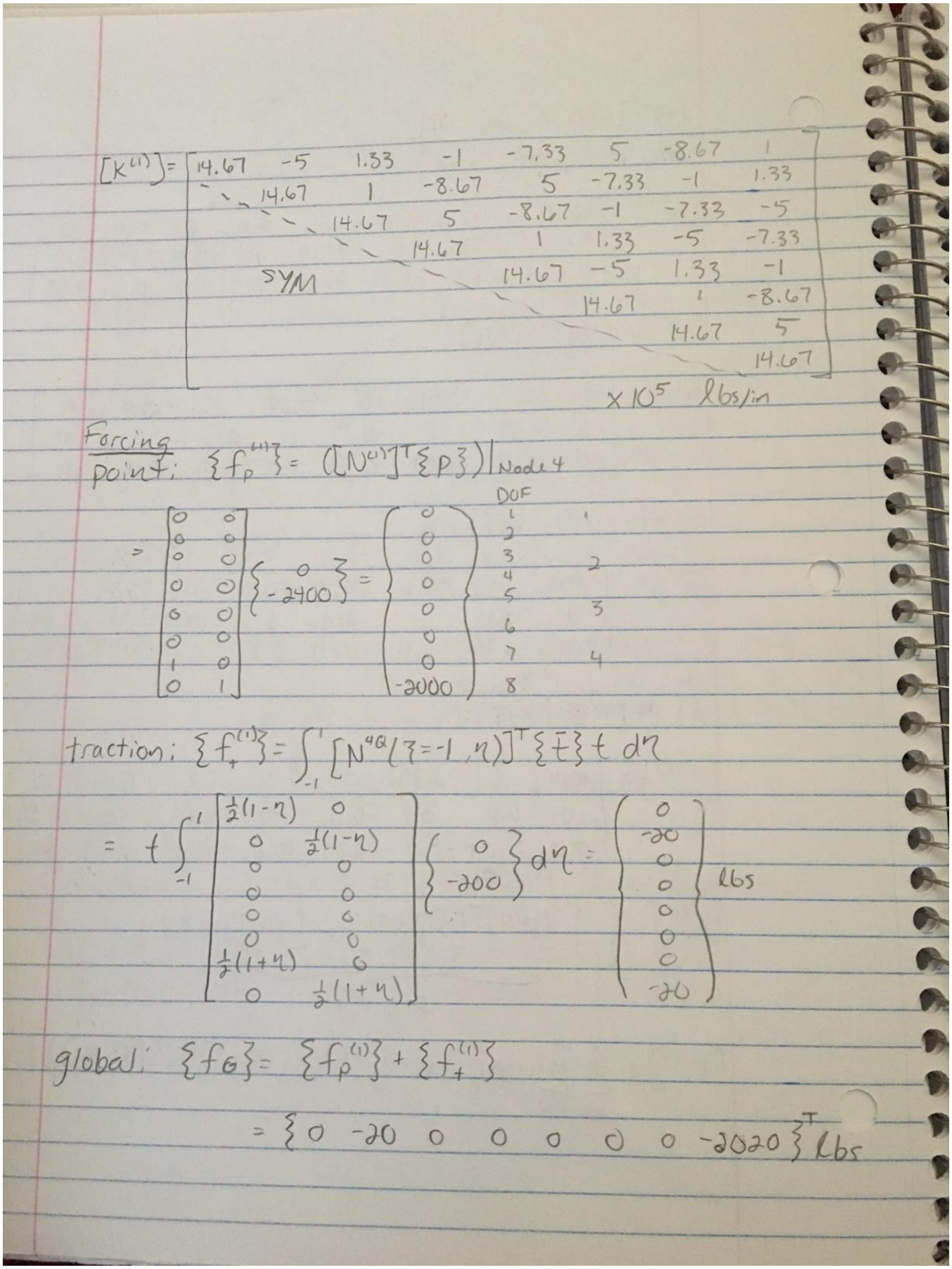


Figure A.64: FEA hand calculation example part 4

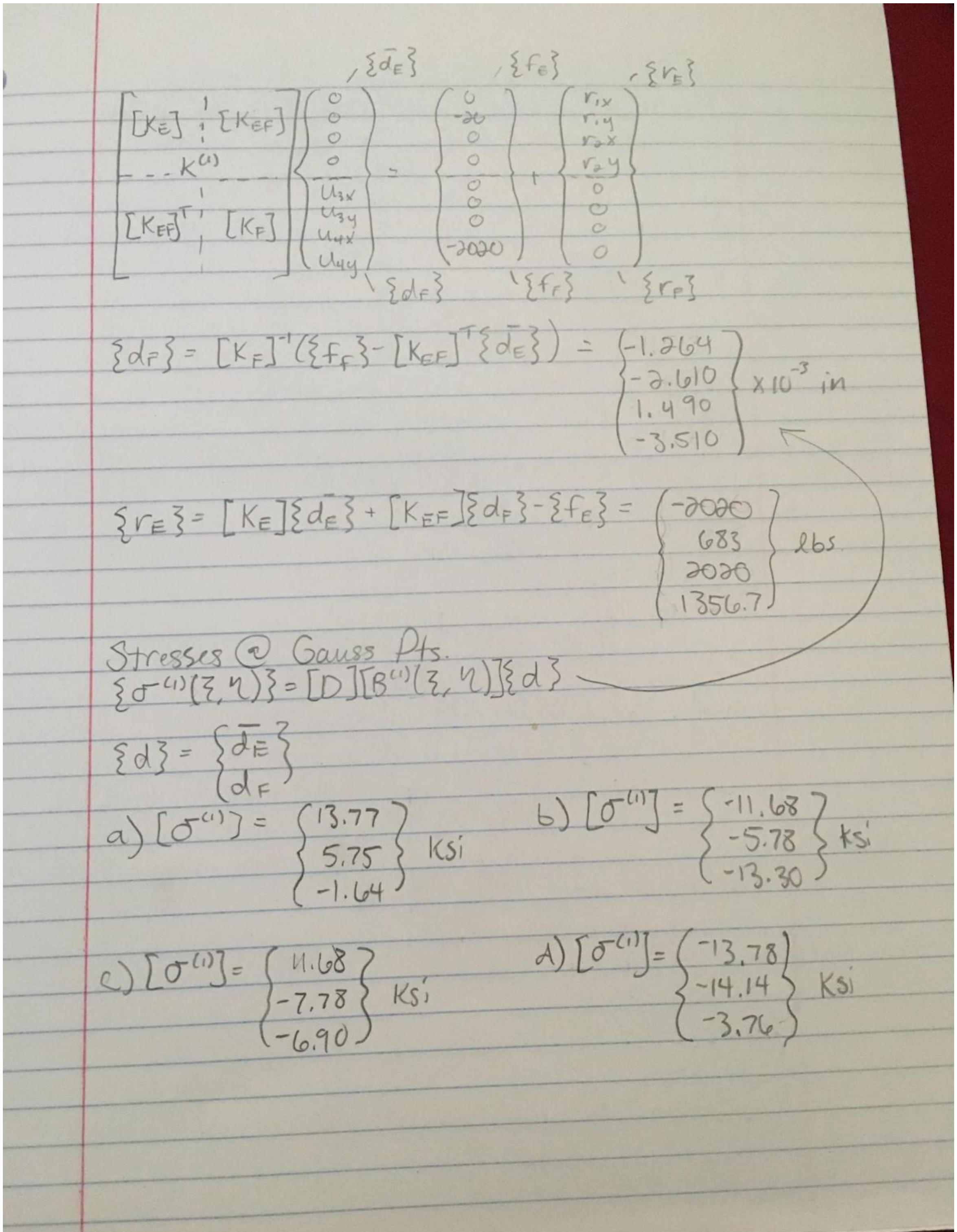
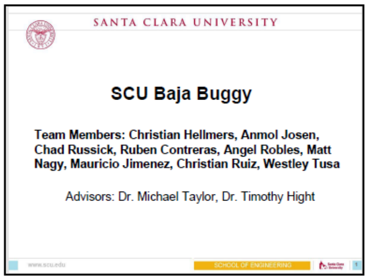
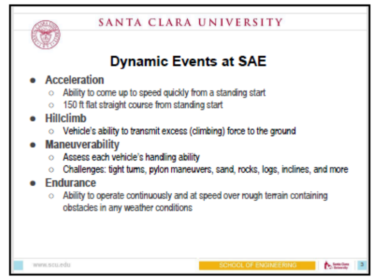


Figure A.65: FEA hand calculation example part 5

Appendix I: Senior Design Conference Slides





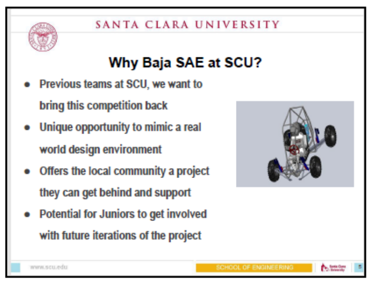


Figure A.66


SANTA CLARA UNIVERSITY
Current Progress
Built the entire frame for the Buggy
All critical parts purchased or machined and ready to be mounted
Front Suspension complete
Conducted stress analysis for drivetrain / frame
Specialty parts for the drivetrain
Finite Element Analysis
SAE Competition
Ready for next year
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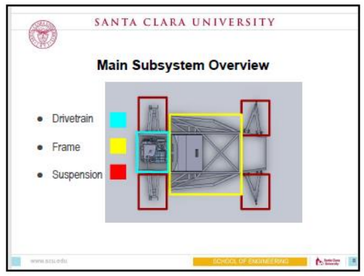
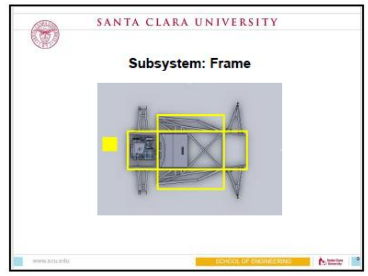
SCHOOL OF ENGINEERING


SANTA CLARA UNIVERSITY
Main Subsystem Overview
Drivetrain
Frame
Suspension
www.scu.edu
SCHOOL OF ENGINEERING


SANTA CLARA UNIVERSITY
Subsystem: Frame
www.scu.edu
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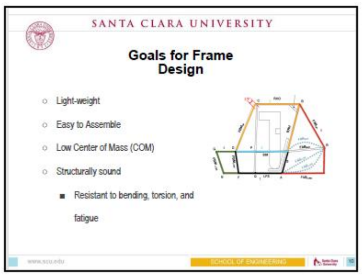
SANTA CLARA UNIVERSITY
Goals for Frame Design
Light-weight
Easy to Assemble
Low Center of Mass (COM)
Structurally sound
Resistant to bending, torsion, and fatigue
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SANTA CLARA UNIVERSITY
Frame Design Iteration 1
Isometric View
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SANTA CLARA UNIVERSITY
Frame Design Iteration 2
Isometric View
www.scu.edu
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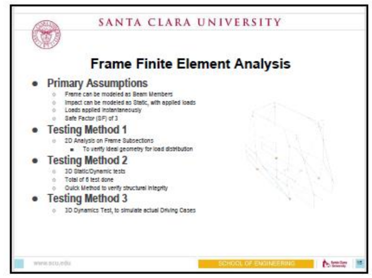
Figure A.67

SANTA CLARA UNIVERSITY
Frame Design Iteration 3
Isometric View
www.scu.edu
SCHOOL OF ENGINEERING

SANTA CLARA UNIVERSITY
Final Design
Isometric View
www.scu.edu
SCHOOL OF ENGINEERING



SANTA CLARA UNIVERSITY
Frame Finite Element Analysis
Primary Assumptions
Frame can be modeled as Beam Members
Impact can be modeled as Static, with applied loads
Loads applied instantaneously
Safe Factor (SF) of 3
Testing Method 1
2D Analysis on Frame Subsections
To verify ideal geometry for load distribution
Testing Method 2
3D Static/Dynamic tests
Total of 6 test done
Quick Method to verify structural integrity
Testing Method 3
3D Dynamics Test, to simulate actual Driving Cases
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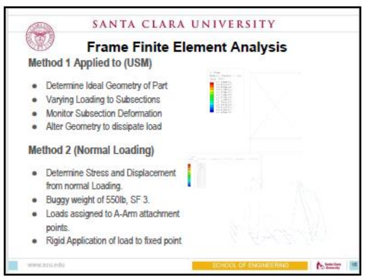

SANTA CLARA UNIVERSITY
Frame Finite Element Analysis
Method 1 Applied to (USM)
Determine Ideal Geometry of Part
Varying Loading to Subsections
Monitor Subsection Deformation
Alter Geometry to dissipate load
Method 2 (Normal Loading)
Determine Stress and Displacement from normal Loading.
Buggy weight of 550lb, SF 3.
Loads assigned to A-Arm attachment points.
Rigid Application of load to fixed point
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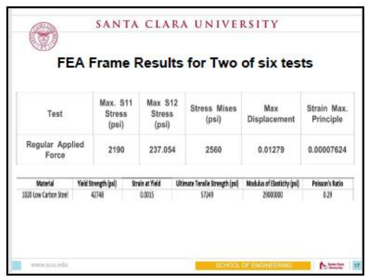

SANTA CLARA UNIVERSITY
FEA Frame Results for Two of six tests
Test
Max. S11 Stress (psi)
Max S12 Stress (psi)
Stress Mises (psi)
Max Displacement
Strain Max. Principle
Regular Applied Force
2190
237.054
2560
0.01279
0.00007624
Material
Yield Strength (psi)
Strain at Yield
Ultimate Tensile Strength (psi)
Modulus of Elasticity (psi)
Poisson's Ratio
1020 Low Carbon Steel
42748
0.0015
57249
0.29
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SANTA CLARA UNIVERSITY
Completed Frame
Rear Frame
Front Frame
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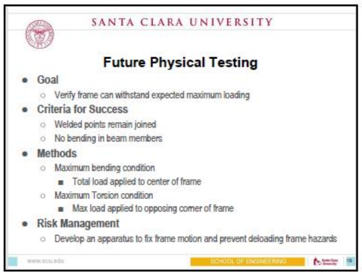
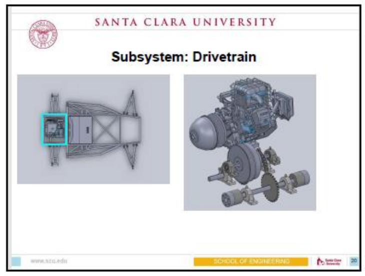
Figure A.68


SANTA CLARA UNIVERSITY
Future Physical Testing
Goal
Verify frame can withstand expected maximum loading
Criteria for Success
Welded points remain joined
No bending in beam members
Methods
Maximum bending condition
Total load applied to center of frame
Maximum Torsion condition
Max load applied to opposing corner of frame
Risk Management
Develop an apparatus to fix frame motion and prevent deloading frame hazards
www.scu.edu
SCHOOL OF ENGINEERING
19


SANTA CLARA UNIVERSITY
Subsystem: Drivetrain
www.scu.edu
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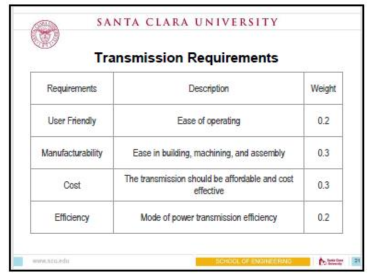
20


SANTA CLARA UNIVERSITY
Transmission Requirements
Requirements | Description | Weight
User Friendly | Ease of operating | 0.2
Manufacturability | Ease in building, machining, and assembly | 0.3
Cost | The transmission should be affordable and cost effective | 0.3
Efficiency | Mode of power transmission efficiency | 0.2
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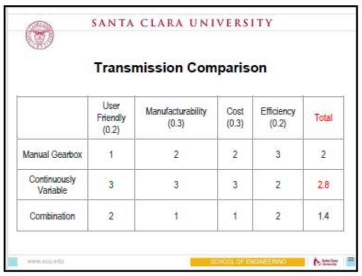
SANTA CLARA UNIVERSITY
Transmission Comparison
| User Friendly (0.2) | Manufacturability (0.3) | Cost (0.3) | Efficiency (0.2) | Total
Manual Gearbox | 1 | 2 | 2 | 3 | 2
Continuously Variable | 3 | 3 | 3 | 2 | 2.8
Combination | 2 | 1 | 1 | 2 | 1.4
www.scu.edu
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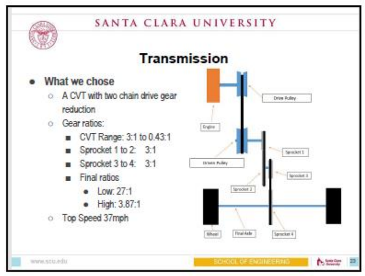
SANTA CLARA UNIVERSITY
Transmission
What we chose
A CVT with two chain drive gear reduction
Gear ratios:
CVT Range: 3:1 to 0.43:1
Sprocket 1 to 2: 3:1
Sprocket 3 to 4: 3:1
Final ratios
Low: 27:1
High: 3.87:1
Top Speed 37mph
Drive Pulley
Engine
Sprocket 1
Driven Pulley
Sprocket 3
Sprocket 2
Wheel
Final Axle
Sprocket 4
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CVT + Sprockets
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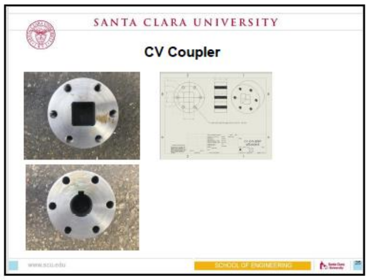
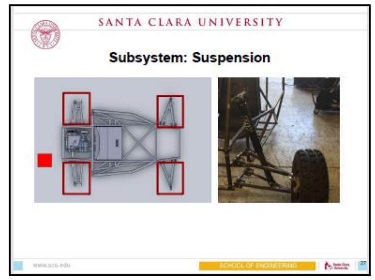
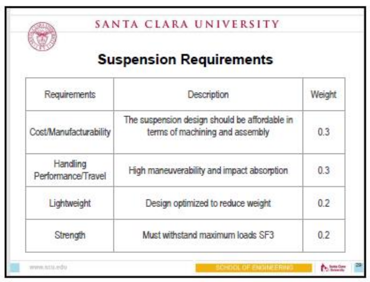
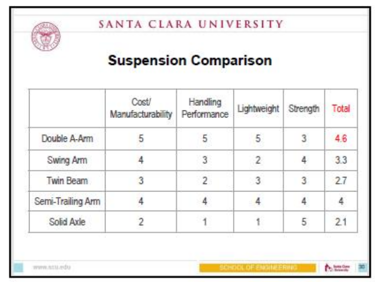
Figure A.69





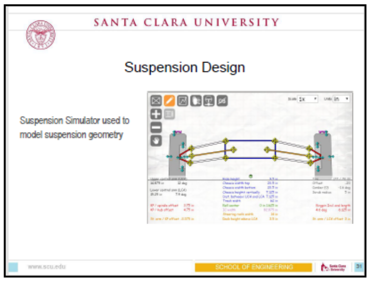


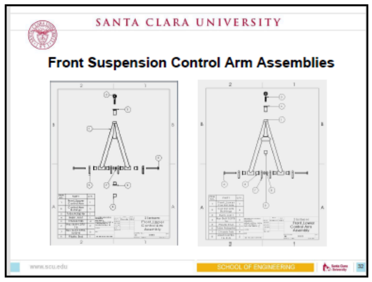
Requirements	Description	Weight
Cost/Manufacturability	The suspension design should be affordable in terms of machining and assembly	0.3
Handling Performance/Travel	High maneuverability and impact absorption	0.3
Lightweight	Design optimized to reduce weight	0.2
Strength	Must withstand maximum loads SF3	0.2

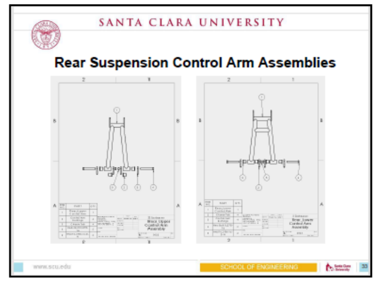


	Cost/ Manufacturability	Handling Performance	Lightweight	Strength	Total
Double A-Arm	5	5	5	3	4.6
Swing Arm	4	3	2	4	3.3
Twin Beam	3	2	3	3	2.7
Semi-Trailing Arm	4	4	4	4	4
Solid Axle	2	1	1	5	2.1

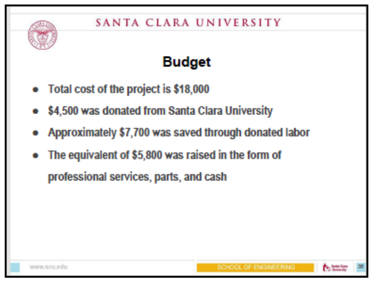
Figure A.70


SANTA CLARA UNIVERSITY
Suspension Design
Suspension Simulator used to model suspension geometry


SANTA CLARA UNIVERSITY
Front Suspension Control Arm Assemblies


SANTA CLARA UNIVERSITY
Rear Suspension Control Arm Assemblies


SANTA CLARA UNIVERSITY
Front Suspension Control Arm Assemblies


SANTA CLARA UNIVERSITY
Budget
Total cost of the project is $18,000
$4,500 was donated from Santa Clara University
Approximately $7,700 was saved through donated labor
The equivalent of $5,800 was raised in the form of professional services, parts, and cash

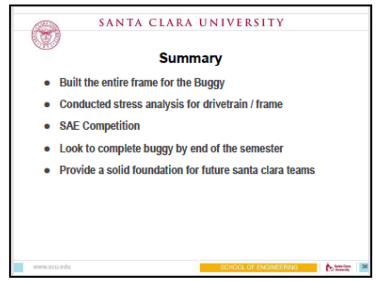
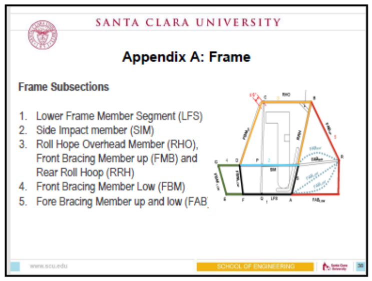
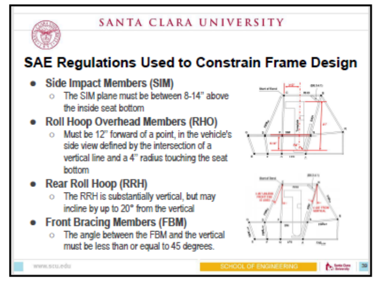
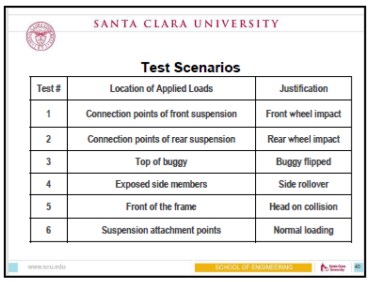

SANTA CLARA UNIVERSITY
Summary
Built the entire frame for the Buggy
Conducted stress analysis for drivetrain / frame
SAE Competition
Look to complete buggy by end of the semester
Provide a solid foundation for future santa clara teams

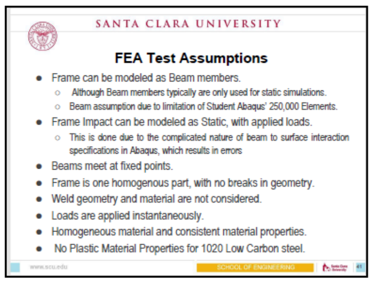
Figure A.71

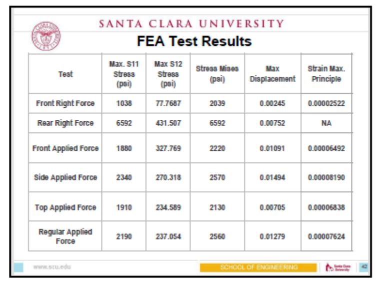






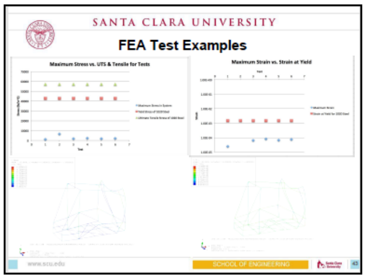
Test #	Location of Applied Loads	Justification
1	Connection points of front suspension	Front wheel impact
2	Connection points of rear suspension	Rear wheel impact
3	Top of buggy	Buggy flipped
4	Exposed side members	Side rollover
5	Front of the frame	Head on collision
6	Suspension attachment points	Normal loading





Test	Max. S11 Stress (psi)	Max S12 Stress (psi)	Stress Mises (psi)	Max Displacement	Strain Max. Principle
Front Right Force	1038	77.7687	2039	0.00245	0.00002522
Rear Right Force	6592	431.507	6592	0.00752	NA
Front Applied Force	1880	327.769	2220	0.01091	0.00006492
Side Applied Force	2340	270.318	2570	0.01494	0.00008190
Top Applied Force	1910	234.589	2130	0.00705	0.00006838
Regular Applied Force	2190	237.054	2560	0.01279	0.00007624

Figure A.72


SANTA CLARA UNIVERSITY
FEA Test Examples
Maximum Stress vs. UTS & Tensile for Tests
Maximum Strain vs. Strain at Yield
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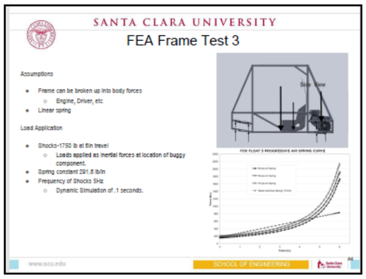
SANTA CLARA UNIVERSITY
FEA Frame Test 3
Assumptions
Frame can be broken up into body forces
Engine, Driver, etc
Linear spring
Load Application
Shocks-1750 lb at 6in travel
Loads applied as inertial forces at location of buggy component.
Spring constant 291.6 lb/in
Frequency of Shocks 5Hz
Dynamic Simulation of .1 seconds.
Side View
FOX FLOAT 3 PROGRESSIVE AIR SPRING CURVE
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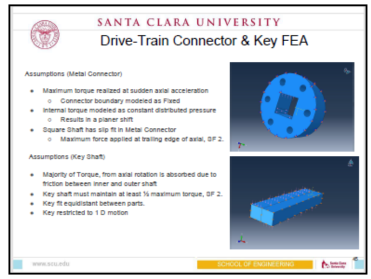
SANTA CLARA UNIVERSITY
Drive-Train Connector & Key FEA
Assumptions (Metal Connector)
Maximum torque realized at sudden axial acceleration
Connector boundary modeled as Fixed
Internal torque modeled as constant distributed pressure
Results in a planer shift
Square Shaft has slip fit in Metal Connector
Maximum force applied at trailing edge of axial, SF 2.
Assumptions (Key Shaft)
Majority of Torque, from axial rotation is absorbed due to friction between inner and outer shaft
Key shaft must maintain at least ½ maximum torque, SF 2.
Key fit equidistant between parts.
Key restricted to 1 D motion
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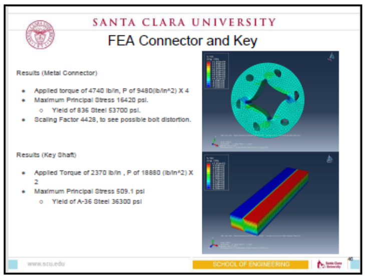
SANTA CLARA UNIVERSITY
FEA Connector and Key
Results (Metal Connector)
Applied torque of 4740 lb/in, P of 9480(lb/in^2) X 4
Maximum Principal Stress 16420 psi.
Yield of 836 Steel 53700 psi.
Scaling Factor 4428, to see possible bolt distortion.
Results (Key Shaft)
Applied Torque of 2370 lb/in , P of 18880 (lb/in^2) X 2
Maximum Principal Stress 509.1 psi
Yield of A-36 Steel 36300 psi
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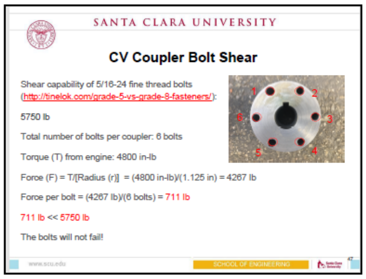
SANTA CLARA UNIVERSITY
CV Coupler Bolt Shear
Shear capability of 5/16-24 fine thread bolts (http://tinelok.com/grade-5-vs-grade-8-fasteners/):
5750 lb
Total number of bolts per coupler: 6 bolts
Torque (T) from engine: 4800 in-lb
Force (F) = T/[Radius (r)] = (4800 in-lb)/(1.125 in) = 4267 lb
Force per bolt = (4267 lb)/(6 bolts) = 711 lb
711 lb << 5750 lb
The bolts will not fail!
1
2
3
4
5
6
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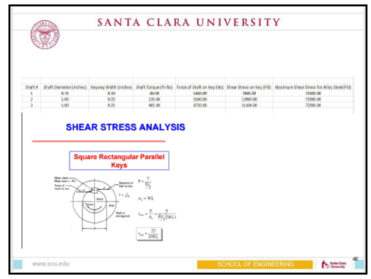
SANTA CLARA UNIVERSITY
SHEAR STRESS ANALYSIS
Square Rectangular Parallel Keys
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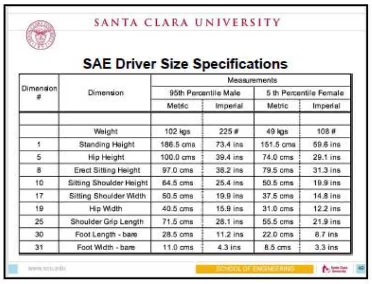
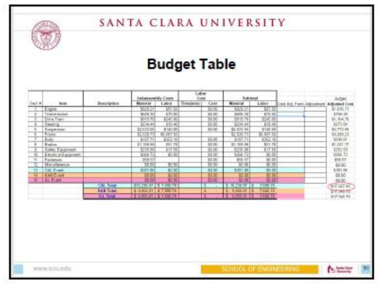
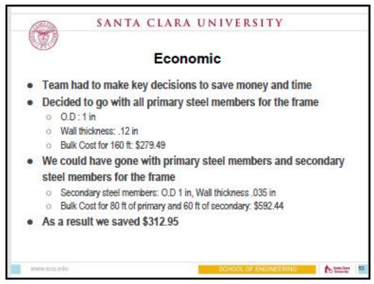
Figure A.73



Dimension #	Dimension	Measurements			
		95th Percentile Male		5 th Percentile Female	
		Metric	Imperial	Metric	Imperial
	Weight	102 kgs	225 #	49 kgs	108 #
1	Standing Height	186.5 cms	73.4 ins	151.5 cms	59.6 ins
5	Hip Height	100.0 cms	39.4 ins	74.0 cms	29.1 ins
8	Erect Sitting Height	97.0 cms	38.2 ins	79.5 cms	31.3 ins
10	Sitting Shoulder Height	64.5 cms	25.4 ins	50.5 cms	19.9 ins
17	Sitting Shoulder Width	50.5 cms	19.9 ins	37.5 cms	14.8 ins
19	Hip Width	40.5 cms	15.9 ins	31.0 cms	12.2 ins
25	Shoulder Grip Length	71.5 cms	28.1 ins	55.5 cms	21.9 ins
30	Foot Length - bare	28.5 cms	11.2 ins	22.0 cms	8.7 ins
31	Foot Width - bare	11.0 cms	4.3 ins	8.5 cms	3.3 ins





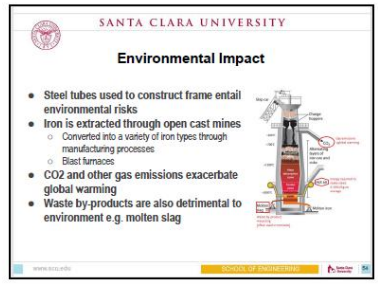
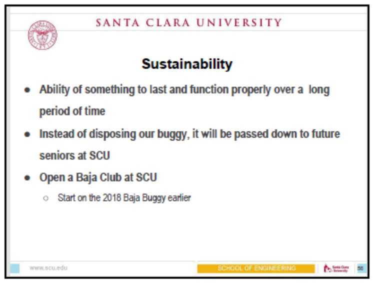


Figure A.74



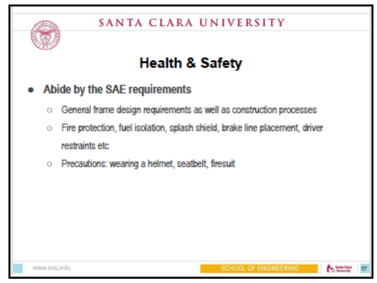


Figure A.75

Appendix J: Cost Report

Subsystem	Component Description	Part #	# of items
Frame			
	FBM(Low)	F001	2
	FBM(Up)	F002	2
	LFS	F003	2
	FAB(up)	F004	2
	FAB(mid)	F005	2
	FAB(low)	F006	3
	SIM	F007	2
	SIM Brace 1	F008	2
	SIM Brace 2	F009	2
	Suspension Bar	F010	2
	RRH	F011	1
	RRH Bracing Member	F012	1
	Gusset	F013	2
	Support Beam	F014	2
	DLC	F015	1
	FLC	F016	1
	QLC	F017	1
	ALC	F018	1
	USM1	F019	1
	USM2	F020	1
	USM3	F021	1
	LFS Support Members	F022	2

Subsystem	Component Description	Part #	# of items
Suspension			
	Rims (Front)	S001	2
	Rims (Rear)	S002	2
	Tires (Front)	S003	2
	Tires (Rear)	S004	2
	Hubs (Front)	S005	2
	Hubs (Rear)	S006	2
	Bearing (Front)	S007	2
	Bearing (Rear)	S008	2
	Bearing Carrier (Rear)	S009	2
	Spindles (Front)	S010	2
	Rotors (Front)	S011	2
	Rotors (Rear)	S012	2
	Calipers (Front)	S013	2
	Calipers (Rear)	S014	2
	Shocks	S015	4
	Tube Adapter	S016	8
	Control Arm Tube Mount	S017	16

Subsystem	Component Description	Part #	# of items
	Front Control Arm Ball Joint Mount	S018	4
	Front Control Arm A-Tube long	S019	8
	Front Control Arm A-Tube Connector	S020	4
	Control Arms (Rear)	S019	4
	Chasis Tabs	S020	16
	bushings	S020	16
	Hex bolt	S021	16

Subsystem	Component Description	Part #	# of items
Transmission			
	Chain	T001	1
	Engine	T002	1
	Sprockets	T003	4
	CVT (includes drive pulley, driven pulley, belt)	T004	1
	cv axle coupler	T005	1

Subsystem	Component Description	Part #	# of items
Controls			
	Steering wheel	C001	1
	Steering shaft and hub	C002	1
	Steering shaft mount	C003	2
	Pedals – 2	C004	2
	Brake master cylinder	C005	1
	Hydraulic pressure switch (for brake light)	C006	2
	Various fasteners	C007	Undetermined
	Steering Rack w/ u-joint and stub shaft	C008	1

Subsystem	Component Description	Part #	# of items
Safety Equip.			
	Fire extinguisher mount	SE001	1
	Fire extinguisher	SE002	1
	Kill switch	SE003	2
	Rollover gas cap	SE004	1
	Drip pan	SE005	1
	Drip pan hose	SE006	1
	Seat	SE007	1
	Harness	SE008	1
	Helmet	SE009	1
	Firewall	SE010	1
	Splash shield	SE011	1
	CVT belt guard	SE012	1
	Gear/chain guard	SE013	1
	Arm Reststraints	SE014	1

Subsystem	Component Description	Part #	# of items
Electronics			
	Brake light	E001	1
	Battery	E002	1
	Battery strap	E003	1

Transponder	E004	1
Wiring	E005	Undetermined
Transponder	E006	1

B/M/O	Vendor	Cost/Part	Person Responsible	Man-Hours
M	Tube Service Co.	$3.18	Westley, Christian R	3
M	Tube Service Co.	$10.34	Westley, Christian R	3
M	Tube Service Co.	$16.16	Westley, Christian R	3
M	Tube Service Co.	$11.70	Westley, Christian R	3
M	Tube Service Co.	$5.29	Westley, Christian R	3
M	Tube Service Co.	$6.69	Westley, Christian R	3
M	Tube Service Co.	$16.16	Westley, Christian R	3
M	Tube Service Co.	$7.99	Westley, Christian R	3
M	Tube Service Co.	$6.13	Westley, Christian R	3
M	Tube Service Co.	$4.22	Westley, Christian R	3
M	Tube Service Co.	$17.56	Westley, Christian R	3
M	Tube Service Co.	$7.16	Westley, Christian R	3
M	Tube Service Co.	$3.62	Westley, Christian R	3
M	Tube Service Co.	$13.38	Westley, Christian R	3
M	Tube Service Co.	$2.26	Westley, Christian R	3
M	Tube Service Co.	$2.26	Westley, Christian R	3
M	Tube Service Co.	$2.79	Westley, Christian R	3
M	Tube Service Co.	$4.18	Westley, Christian R	3
M	Tube Service Co.	$3.62	Westley, Christian R	3
M	Tube Service Co.	$3.76	Westley, Christian R	3
M	Tube Service Co.	$1.53	Westley, Christian R	3
M	Tube Service Co.	$9.61	Westley, Christian R	3

B/M/O	Vendor	Cost/Part	Responsible Person	Man-Hours
O	SCU Machine Shop	$0.00	Mauricio, Matt, Angel	0
O	Dennis Kirk	$45.00	Mauricio, Matt, Angel	0
O	SCU Machine Shop	$0.00	Mauricio, Matt, Angel	0
O	SCU Machine Shop	$0.00	Mauricio, Matt, Angel	0
B	Yamaha	$75.00	Mauricio, Matt, Angel	0
B	Polaris	$81.00	Mauricio, Matt, Angel	0
B	The Big Bearing Store	$15.00	Mauricio, Matt, Angel	0
B	The Big Bearing Store	$27.00	Mauricio, Matt, Angel	0
B	Polaris	$26.00	Mauricio, Matt, Angel	0
B	Yamaha	$125.00	Mauricio, Matt, Angel	0
B	Yamaha	$20.00	Mauricio, Matt, Angel	0
B	SCU Machine Shop	$20.00	Mauricio, Matt, Angel	0
B	Yamaha	$25.00	Mauricio, Matt, Angel	0
B	Yamaha	$25.00	Mauricio, Matt, Angel	0
B	Fox	$125.00	Mauricio, Matt, Angel	0
B	SCU Machine Shop	$30.00	Mauricio, Matt, Angel	3
M	Tube Service Co.	$5.33	Mauricio, Matt, Angel	1.5

M	Tube Service Co.	$7.00	Mauricio, Matt, Angel	0.5
M	Tube Service Co.		Mauricio, Matt, Angel	0.75
M	Tube Service Co.		Mauricio, Matt, Angel	0.5
M	Tube Service Co.	$5.33	Mauricio, Matt, Angel	3
M	SCU Machine Shop	$30.00	Mauricio, Matt, Angel	4
M				
B	Tube Service Co.			

B/M/O	Vendor	Cost/Part	Responsible Person	Man-Hours
B	Tractor Supply Co.	$29.00	Chad Russik, Reuben	0
B	Briggs & Stratton	$250.00	Chad Russik, Reuben	0
B	Martin Sprocket	$15.31	Chad Russik, Reuben	0
B	CVTech	$225.00	Chad Russik, Reuben	0
M				

B/M/O	Vendor	Cost/Part	Responsible Person	Man-Hours
B	Quality Drive Systems	$29.00	Mauricio,Angel	0
B	Quality Drive Systems	$20.00	Mauricio,Angel	0
B	Quality Drive Systems	$15.00	Mauricio,Angel	0
B	Bmi Karts	$15.00	Mauricio,Angel	0
B	BMI Karts	$40.00	Mauricio,Angel	0
B	Summit Racing	$12.00	Mauricio,Angel	0
B	Industrial Depot		Mauricio,Angel	0
B	Quality Drive Systems	$115.00	Mauricio,Angel	0

B/M/O	Vendor	Cost/Part	Responsible Person	Man-Hours
B	Scott Drake	$62.00	Anmol	0
B	First Alert	$13.00	Anmol	0
B	Polaris	$26.00	Anmol	0
B	Briggs & Stratton	$50.00	Anmol	0
B	Briggs & Stratton	$50.00	Anmol	0
B	Oreilly Auto Parts	$8.00	Anmol	0
O	SCU Machine Shop	$0.00	Anmol	0
B	Quality Drive Systems	$115.00	Anmol	0
O		$100.00	Anmol	0
M	Gorilla Metals	$40.00	Anmol	0
B	Gorilla Metals	$10.00	Anmol	0
B	Go Karts USA	$20.00	Anmol	0
B	Go Karts USA	$25.00	Anmol	0
B	Quality Drive Systems	$20	Anmol	0

B/M/O	Vendor	Cost/Part	Responsible Person	Man-Hours
B	Go Karts USA	$40.00	Christian H	0
B	Go Karts USA	$45.00	Christian H	0
B	Go Karts USA	$15.00	Christian H	0

B	Go Karts USA	$200.00	Christian H	0
B	Go Karts USA	$35.00	Christian H	0
B	Go Karts USA	$65.00	Christian H	0

Order/Start	Recieve/Finish			
			11.4	
October 7, 2016	January 16, 2017	$37.12		
October 7, 2016	January 16, 2017	$58.00		$6.35
October 7, 2016	January 16, 2017	$42.00		$20.69
October 7, 2016	January 16, 2017	$19.00		$32.33
October 7, 2016	January 16, 2017	$16.00		$23.41
October 7, 2016	January 16, 2017	$58.00		$10.59
October 7, 2016	January 16, 2017	$28.67		$20.06
October 7, 2016	January 16, 2017	$22.00		$32.33
October 7, 2016	January 16, 2017	$15.13		$15.98
October 7, 2016	January 16, 2017	$126.00		$12.26
October 7, 2016	January 16, 2017	$51.38		$8.43
October 7, 2016	January 16, 2017	$13.00		$17.56
October 7, 2016	January 16, 2017	$48.00		$7.16
October 7, 2016	January 16, 2017	$16.19		$7.25
October 7, 2016	January 16, 2017	$16.19		$26.75
October 7, 2016	January 16, 2017	$20.00		$2.26
October 7, 2016	January 16, 2017	$30.00		$2.26
October 7, 2016	January 16, 2017	$26.00		$2.79
October 7, 2016	January 16, 2017	$27.00		$4.18
October 7, 2016	January 16, 2017	$11.00		$3.62
October 7, 2016	January 16, 2017	$34.47		$3.76
October 7, 2016	January 16, 2017	$19.12		$1.53
				$0.00

Order/Start	Recieve/Finish		
October 7, 2016	October 20, 2016		
October 7, 2016	January 16, 2017		
October 7, 2016	October 20, 2016		
October 7, 2016	October 20, 2016	$150.00	$312.00
October 7, 2016	October 20, 2016	$162.00	
October 7, 2016	January 16, 2017	$30.00	
October 7, 2016	In Progress	$54.00	
October 7, 2016	In Progress	$52.00	
October 7, 2016	In Progress	$250.00	
October 7, 2016	In Progress	$40.00	
October 7, 2016	In Progress	$40.00	
October 7, 2016	In Progress	$50.00	
October 7, 2016	In Progress	$50.00	
October 7, 2016	In Progress	$500.00	
October 7, 2016	In Progress		
March 7, 2017	In Progress		
March 7, 2017	In Progress		

March 7, 2017	In Progress	
March 7, 2017	In Progress	
March 7, 2017	In Progress	
March 7, 2017	In Progress	
Febuary 25, 2017	In Progress	
Order/Start	Recieve/Finish	
###############	In Progress	
October 30, 2016	January 29,2017	
###############	In Progress	$61.24
###############	January 2, 2017	
Order/Start	Recieve/Finish	
###############	In Progress	
###############	In Progress	
###############	In Progress	
###############	In Progress	
###############	In Progress	
###############	In Progress	
###############	In Progress	
###############	In Progress	
Order/Start	Recieve/Finish	
January 21,2017	In Progress	
January 18,2017	In Progress	
January 18,2017	In Progress	
January 18,2017	In Progress	
January 18,2017	In Progress	
January 18,2017	In Progress	
January 1,2017	January 9, 2017	
October 16,2017	In Progress	
January 21,2017	In Progress	
January 10, 2017	In Progress	
January 21,2017	In Progress	
January 21,2017	In Progress	
January 21,2017	In Progress	
January 21,2017	In Progress	
Order/Start	Recieve/Finish	
January 21,2017	In Progress	
January 21,2017	In Progress	
January 21,2017	In Progress	

January 21,2017	In Progress
January 21,2017	In Progress
January 21,2017	In Progress

$261.53

-The objective of the cost report is to report the cost value (suggested retail price) of the items selected to build the car. The objective is **not** to report the cheapest price that an item can be purchased. For example, if two schools are using the same CVT they both should be reporting the same price, even though they might have purchased them for different prices, since both schools get the same value from the CVT.
-The cost report should serve as two functions, (1) a bill of materials for the car, and (2) it should help equalize teams that choose to use items of high value with teams that use items of low value.
-In industry it is very important to look at design and performance, as well as cost. Cost is the key driving force to many design decisions. If shocks are selected that cost $4000, the team should understand it will loose points in cost, but it might improve the score in the dynamic events. During design presentations these cost decisions should be discussed.

Common Mistakes

- Teams did not use the correct template; the only template that is allowed is the template which posted for that year. If you submit an older template you will receive a score of 0.
- Teams found prices at discount companies that were not suggested retail prices. Remember to use the current retail price of all Polaris parts.
- Teams did not get signatures on the summary cost page. It is required that you print out the summary cost with captain and advisor approval signatures. This must be scanned and placed in the PDF as page #1.
- Reports were not labeled correctly -
- Make sure everything is filled out. Don't leave anything blank (quantities, descriptions, sub-assembly times, etc).
- **- Bring a printed copy of the cost report with you to competition.**
- It is very helpful to bring drawings of any components that are hidden or enclosed. For example, a exploded view of a transmission or the component drawings. These may also be included in your Cost Documentation (PDF) file. Cost judges appreciate this and will reward you for it when an inevitable judgement call is needed.
- Sharing or converting this document has caused format issues in the past. These issues will prevent us from scoring your report properly and may result in a loss of points. Please take care to avoid anything that may modify this file. This will help prevent the unfortunate circumstance that the report you've worked hard on cannot be counted. Examples include GSheets, converting to Mac formats, sharing the workbook within Excel.

Submission of reports

All reports MUST be done using that year's template. Only one **electronic copy** will need to be submitted by each team and this will be for all competitions in which the team is competing. The template must be submitted as an Excel file (.xls or .xlsx). This file should not include images/drawings, etc - it should only include the information in this template.
All supporting documents (i.e.: receipts, drawings, cost overview, pictures, scanned copy of the summary cost sheet with signature) should be included in the .PDF file. Only .PDF file will be scored. Files should be kept to a reasonable size (~4.0MB is sufficient); however, maximium size limit has been eliminated.

If the cost of your vehicle changes after you have submitted your cost report, then at registration you **must** submit a "**Cost Adjustment Form**". When submitting this form you must have receipts or form "B" attached for each changed item. See the rules for more details on the Cost Adjustment form.

DO NOT SUBMIT REPORTS EMBEDDED WITH MACROS IN THE FILE OR REPORTS WITH A .XLSM EXTENSION.   REPORTS SUBMITTED IN THIS FORMAT WILL NOT BE GRADED.

Common Prices

Here is a list of websites that we will be using for scoring to verify prices. If you do not have documentation on all your items, use one of these sites for your documentation.

www.chassisshop.com www.mcmaster.com www.polarissuppliers.com/sae_team/SAE_parts.pdf

Foreign Teams

All cost numbers are in **US dollars at US cost**. Non US teams must find the prices for each item they are using in the US. If the exact item can not be found, then an item of similar use, function and durability should be used. **Foreign receipts are not acceptable.**

Cost Reporting Data

Definition – "Retail List Price" is the full retail price either as quoted by the manufacturer or the retailer for sales of the quantity that is purchased. For example: purchased seats are priced as a single unit; four identical purchased shocks can be priced as a group of four; small bolts and nuts can be priced singularly or based on the box price; however they were purchased. The Retail List Price is frequently more than you actually paid for the item and is never less than you actually paid.

Retail List Prices should not include sales tax, VAT taxes or packaging and shipping costs from the seller to the team's shop – provided such items are itemized separately and not built into the retail price.

Cost Documentation – "Cost Documentation" can be any of the following: (a) Receipts or invoices for the items as purchased, (b) Catalog pages showing the items and price, (c) On-line prices, (d) Quotations from a manufacturer or fabricator, or (e) Price tags provided that original tag identifies the item to which it was affixed.
All cost documentation must be dated either as part the document itself or, in the case of undated references, e.g. catalog pages, price tags, by writing a date on the submission.   As of January 1 of the competition year, receipts are no more than three (3) years old. Polaris part prices must be current for that year.

Purchased Items – Use the Retail List Price (Suggested Retail Price)

Contributed, Discounted and Sale Items – Use the Retail List Price. Even if you bought the part on sale or at a discount use the Retail List Price - do not use the sale or discount price.

Custom Manufactured Items – Use a quotation showing the Retail List Price. Manufacturer's quotations must be based on the price the company would charge a typical customer - not on any special price given to your team.

Reused, Salvaged Items or items purchased from auction sites – Use the current Retail List Price for the item. If you are reusing a part that is no longer in production, then you must provide cost documentation for the nearest equivalent item that is currently available. For example: if you are reusing a brake light that's no longer made, then you may substitute the price for an equivalent item that's available.

Foreign Purchased Items – If the item or similar item is available in the United States use the retail price published in the U.S. If the item is not available in the U.S. then find an item that is similar in function, size and durability.

Important Note – Keep in mind that the cost report is based on retail list price and is therefore somewhat artificial. The cost report total price is likely to be considerably higher than your actual production budget.

*****Make sure to read the cost guide which is included in this file on the next worksheet.*****

Format

This year's cost report will be a 3 level bill of materials with standardized summaries in the 13 major cost areas. The 3 levels consist of:

-Level 1 is the "Summary Cost" worksheet

-Level 2 is the group of 13 Form "A" worksheets. Each of these sheets come preloaded with a reasonable number of lines which may be adjusted as required.

-Level 3 is the group of 13 Form "B" worksheets. Note that each of these worksheets may have multiple items.

Documentation

Receipts, catalog pages, or other documentation of cost must be included in the .PDF. To help make the documentation clear and readable, each receipt must have the appropriate final cost circled. Each receipt should also have the section title, Form A line number, and Form B (if needed) line number clearly marked. All of these receipts must be included in the .PDF file. Documentation should be in the same order as presented in the report. For example, all the engine documentation first, followed by the transmission documentation, etc.

Receipts, as of January 1 of the competition year, are no more than three (3) years old. Polaris part prices must be current for that year.

Editing the worksheets

The worksheets have been designed to be used by most teams with little modification. The majority of the teams will find that one or more of the worksheets is too short to cover all the components used in one functional area (Form A), fabricated items must be linked from Form B to Form A, or there are more fabrication items than shown (Form B). Therefore, it is expected that the spreadsheets will need to be modified. Use the following guidelines:

-You MAY **NOT** change the column headings, the categories, or the summation methods.

-You MAY add additional lines to accommodate your particular design. You may also need to add additional sections to a Form B (and the resulting line in the corresponding Form A) as required. Minor changes to the formatting of cells (i.e. visible decimal places) is permitted when necessary to communicate within Forms A and B. If you add lines, it is your responsibility to ensure that formulas pick up all additional lines and carry through the forms properly.

Form A Issues and Editing

You may insert additional lines as required. As long as you insert the lines above the summation Formulas, the spreadsheet will pick up the costs in the new lines. You may need to renumber the lines; this has no effect on the cost rollup. Be careful that the line numbers match the appropriate Form B items. It is good practice to put all the Form B items at the top of the sheet, purchased items below.

Be careful not to 'CUT' items or drag and drop. Use 'COPY' functions. Failure to do so may lead to dropped links to the final worksheet.

Form B Issues and Editing

To add an additional section for a fabricated item, highlight lines 2 through 27, 'COPY', highlight the upper left corner below the last used section (Cell A106 to start with in most of the Form B's, cell A269 for the larger ones), and 'PASTE'. Be sure to add a page break above it and change the item number appropriately. Next, you will need to add the three links to the appropriate Form B. Go to the appropriate line on the appropriate Form B, highlight the 'Part Name' cell, enter an '=' to start a Formula, then (without completing the Formula) switch to Form B, find and highlight the new Part Name cell, and hit 'enter'. This will transfer the location and send you back to Form A. Repeat with materials and labor cost cells.

There are two ways to calculate part costs on Form B: you can enter Density, Amount, Weight, and $/Unit, and the final cost will be calculated for you. Alternatively, you can leave the Density column blank and the cost will be calculated on the basis of Amount, and $/Unit.

There may be some cases where the cost calculation does not fit your situation. Use your preferred calculation method, highlight the calculation in light yellow, and provide an explanation at the bottom of that page (Insert blank lines as required).

The **Amount** should be the gross amount of material you started with, not the finished amount of material in the finished part. i.e. If you machine a full transmission case, use the weight of the starting billet, not the final case.

Be careful not to 'CUT' items or drag and drop. Use 'COPY' functions. Failure to do so may lead to dropped links to the matching Form A.

The Cost Report is a representation of the *Actual Prototype Cost* - consequently, manufacturing and labor costs are intended to reflect the actual vehicle's manufacturing methods, not idealistic techniques. If you have an innovative / non-standard method, come prepared to support it.

Cost Adjustment Form

This form is to be used only if you add something to your car after the submission of your report. This must be submitted at registration during each competition.

Single item changes for subassembly can be shown on the cost adjustment form. Multiple changes, please attach a separate spreadsheet showing each individual item changed and the corresponding cost.

Form B and receipts must be submitted as required by the cost guide.

Sample

There is a sample pair of Form A and Form B at the end of the worksheets (last tab). They are identical to the others with the exception that they do not roll up to the final worksheet.