

Composite Suspension for Formula SAE Vehicle

A Senior Project

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by

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1. Introduction

The California Polytechnic State University Formula Society of Automotive Engineers (FSAE) team has requested a redesign of the 2008 vehicle's suspension to minimize weight while increasing strength and stiffness. The team determined that the best way to achieve this improvement is through the use of composites in the A-arms, push/pull rods, and steering rods. The purpose of this project is to conduct a full cost-benefit analysis between steel and composite suspension components to determine which material is best for the FSAE vehicle. The following report from Reid Olsen, Eric Melchiori and Andrew Bookholt of Composite Suspension Solutions shows how that comparison was conducted and its results.

2. Problem Statement

Suspension components on any racecar must maintain a balance between weight, stiffness, strength, cost and manufacturability. Due to the nature of the scoring in the Formula SAE competition, weight, stiffness and strength are normally the three driving factors. The static and dynamic events that require a strong, stiff and lightweight part are worth nearly 90% of the team's score. The cost and manufacturing portions of the competition are worth much less and have a smaller impact on the final score. They must be

factored into the design process, but do not normally drive final design decisions.

Without factoring in cost and manufacturability, composites are the ideal material for many suspension components. Pushrods, A-arms and steering arms are well suited to composites due to the

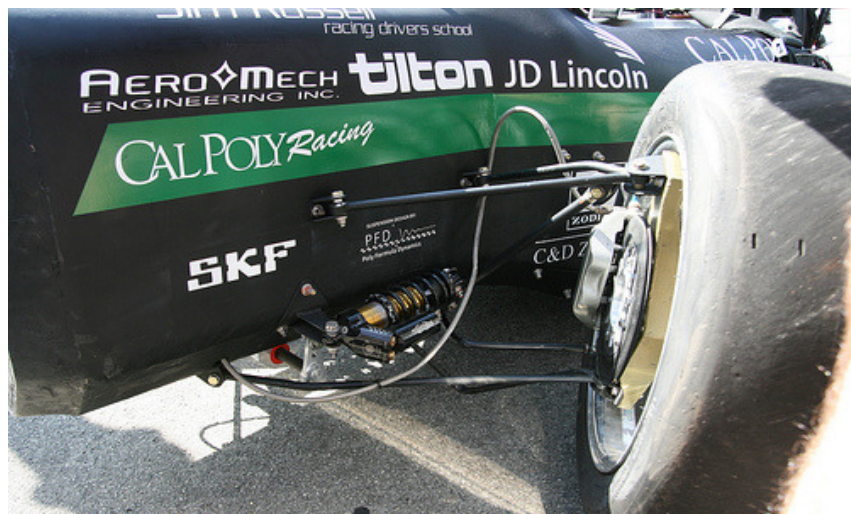


Figure 1: Broken Suspension Components

axial tension-compression load path they experience. Composite materials can be tailored to meet this load path better than any other material due to their anisotropic properties. Also, the high stiffness and strength to weight ratio of carbon fiber produces a part with increased strength and stiffness and decreased weight.

In racecar design and construction, teams often use a part that is very light but too weak because it was designed incorrectly. This occurs more often when the loading condition comes from a calculated estimation instead of empirical testing. The strength to weight ratio of composites is so great that pushing the material to its limit becomes less advantageous. As a result, higher factors of safety can be used while still maintaining a lightweight vehicle. Figure 1 shows what can happen to steel components designed using incorrect loading conditions.

Composite Suspension Solutions has provided the FSAE team with the tools necessary to establish a data acquisition system to properly determine loading conditions. The data acquisition system is comprised of strain gages adhered to each A-arm, all of which will supply strains to an onboard data logger. The information from each driving session can be analyzed to determine maximum loading conditions. Determining the loads experimentally will allow the team to use smaller and lighter parts because smaller factors of safety can be used.

3. Background

3.1 Manufacturing

There are many different types of composite tubes available. Composite tubes are made with a variety of manufacturing procedures and material choices that produce specific structural properties. Each suspension component has its own requirements that suit the different strengths and weaknesses of the specific carbon fiber layups. The two major manufacturing processes, roll-wrapping and pultruding, provide a different final part that may work well for one component on the car but not for another. The composite tubes shown in Figure 2 are pre-manufactured and readily available for purchase. Cutting the tube to length is the only manufacturing process required.



Figure 2: Roll Wrapped Composite Tubes

The most common type of composite tubing available is manufactured by wrapping unidirectional material around a mandrel. The part is then cured and removed from the mandrel. The final part is stiff and strong along the axis of the tube and can resist low to medium level impacts. It is suitable for suspension components that could hit objects on the course such as cones. However, because some of the fiber is not aligned with the tubing axis, it has material that does not add any stiffness or strength to the tube in tension or compression. This added material adds unnecessary weight to a component that is not in danger of striking an object.

A pultruded tube has 100% of its fiber aligned with the axis of the tube. Every fiber contributes strength and stiffness to the component in the axial direction. Pultruded tubes are made by pulling carbon fiber through a die before it is cured. They are prone to delamination (a catastrophic failure) from light impacts because there is no fiber in the transverse direction. This is a significant problem for components that are exposed to damage from cones. Therefore, any components made from pultruded tubes must be shielded from exterior damage.

Carbon fiber is a relatively brittle material that does not withstand impact well. Aramid, better known as Kevlar, is extremely resistant to impact and is used in bulletproof vests. However, it is not nearly as stiff or light as carbon fiber. Therefore, the ideal option for a tube that is exposed to impact is a weave of both carbon fiber and Kevlar tubes. The center tube shown in Figure 2: Roll Wrapped Composite Tubes is an example of a roll wrapped, carbon fiber- Kevlar tube.

3.2 Bonding Metallic-Composite Joints

The bond between the composite tubes and metal joints were difficult to predict and design. The bond strength and durability depended entirely on the composite and adhesives being used, the metal that we bonded, and the surface preparation of both parts. For example, aluminum reacts differently to adhesives than steel, it interacts with carbon fiber differently than it does fiberglass over time, and requires different surface preparation than steel. These factors made it difficult to conduct proper analysis without extensive testing.

The most important tests conducted determined the best way to bond aluminum to carbon fiber. Due to the oxidation that instantly develops on the surface of aluminum, the surface treatment required to produce a strong bond was more extensive than steel. The aluminum must be treated using a complex process that introduced variability into the manufacturing process. The steel components only needed to be sanded and cleaned before the adhesive was applied to achieve a strong bond.

There are a few different types of surface preparation procedures that are recognized in industry for treating aluminum. We determined that some of them were prohibitively difficult to adapt the procedures to a small scale, club-level operation that does not have access to or money for the purchase of the chemicals required for standard treatment procedures. The most common process for treating aluminum prior to adhesive bonding is the Optimized Forest Products Laboratory (FPL) Etch. The FPL Etch leaves an aluminum oxide layer on the metal as opposed to an aluminum hydroxide layer. The aluminum oxide layer bonds much better than the aluminum hydroxide layer. The FPL process uses a pre-etch degreaser to clean the aluminum, an alkaline solution to remove the degreaser and an etch solution to finalize the process. The final solution consists of sulfuric acid, sodium dichromate and pre-dissolved aluminum.

Another way to treat aluminum is the Phosphoric Acid Anodize process. Developed by Boeing in 1975, the PAA process leaves an aluminum oxide layer nearly 10 times thicker than that of the FPL process. This increases the bond depth dramatically, making the final part stronger and more resistant to damage. The PAA process uses the same process as the FPL treatment but goes one step further. An anodizing solution is added at the end to increase the depth of the oxide layer.

The final option, which we used, was to buy an off-the-shelf etching kit such as West System's 860 Aluminum Etch kit (shown in Figure 3.) This kit was purchased at a relatively low cost, but required an extensive amount of testing to prove its benefit during the bonding process.



Figure 3: West System's Aluminum Etch Kit

Bonding aluminum to carbon fiber creates another problem that steel does not suffer from. Over an extended period of time, electrolysis breaks down the bond between the aluminum and composite. It weakens the bond and causes it to fail at a much lower stress level than that of the initial bond. We determined that the FSAE team will not use the vehicle long enough to require testing of these effects over an extended period of time.

3.3 Data Acquisition Systems

Before any composite structural analysis can be performed, it is best to determine accurate load measurements through vehicular testing. The simplest and most cost effective method for establishing

these loads is to apply foil-type strain gages to the existing suspension components. Strain gages are also attractive to this application because of the several amplified differential voltage inputs provided by the Versatile Input Module (VIM) interfaced to the Motec engine management system. The ultimate goal of preliminary strain gage application is to run the car under typical operating conditions to establish dynamic loads for each member. We were unable to determine the loading conditions on the vehicle because it was not running in time to conduct testing.

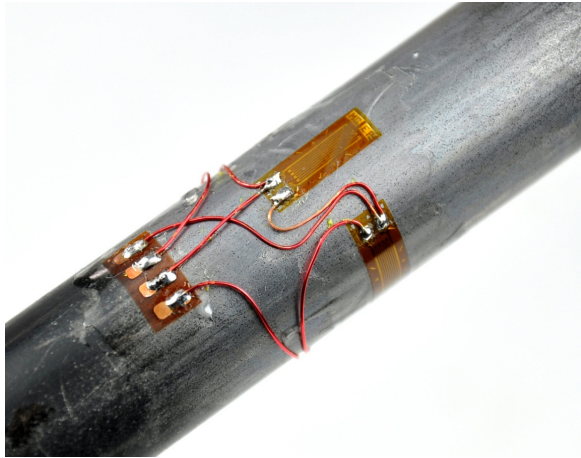


Figure 4: Strain Gage Layout

In order to establish accurate suspension load values, the strain gages were selected to suit the estimated strain levels on the composite suspension components. Also, they must fit certain size constraints due to the small diameter (.375") of some components. Vishay Micro-Measurements is an industry leader in strain gage technology, and they offer educational strain gages at very low cost (\$1/gage).

A rough estimate of the strain range the components will endure under operation was calculated and can be found in Appendix H. *Tube Sizing Results* Preliminary calculations indicate the strain will range from 125 to 1390 μ strain. The gages must fit the circumference of the tubes, but must not be small to avoid thermal power dissipation effects. 350 Ω strain gages suit the final carbon fiber components due to the poor thermal conductivity of polymers. The gages were wired in a full-bridge configuration, with two longitudinal gages and two transverse gages arranged in a band around the circumference of the component. This configuration increases the accuracy of axial strain measurements and eliminates any effects from bending. It is also advantageous for lead-wire and temperature compensation.

When the team prepares the vehicle for testing, the gages will connect to the VIM through two leads per full strain gage bridge. Since some of these leads will pass near the engine, electromagnetic interference may negatively affect signal quality and will have to be decreased. Strain gages are particularly prone to interference due to their very small voltage signals. Long lead wires act as a large antenna if not properly shielded, so grounded braided shielding and other methods will be pursued if EMI in fact does distort the signal beyond acceptable limits. The VIM has eight differential voltage inputs that update at 1000 Hz. The resolution of these inputs is 15 bits. If the gages are excited at 3 Volts, the measurement will move .00018 V/step.

4. Objectives

The goal of this project was to build a suspension system to allow the Cal Poly FSAE team to determine what material they want to use to construct their next suspension components from. At competition, the car is evaluated on dynamic events such as endurance, autocross, skidpad and acceleration as well as static categories such as cost and design. The goal of the competition is to maximize the total value of the vehicle's performance at competition. By conducting an extensive trade study between steel and composite components, we will give the team the ability to maximize the point value at competition.

While the previous suspension design team focused on geometry and the dynamic handling of the vehicle, the current focus will be on the structural aspects of the suspension. The major tubular components, A-arms and pushrods were converted from steel to composite. We believe this will reduce the weight of the car while increasing the stiffness and strength. In doing so, it will improve the car in the five most important categories at competition; endurance, autocross, acceleration, skidpad and design. However, it will most likely increase cost and manufacturing time.

The Quality Function Deployment analysis (Appendix A. *Quality Function Deployment*) relates specifications in the composite suspension to benefits in the dynamic events. From the QFD analysis, the top three design objectives are strength, weight, and stiffness. Strength is the most important because failure of a component will result in disqualification. Weight was rated the next most important because it increases performance in every event. The third ranked category from the QFD is stiffness. Stiffness is an important aspect to any high performance vehicle because excessive deflection is detrimental to performance and response in handling and acceleration. The stiffness of the current car is unknown so part of the project was to determine how much each component deflects. Cost, manufacturability, and aesthetics were also design considerations but only weighed in at 4%, 6%, and 2%, respectively, during our QFD analysis.

Extensive analysis, testing and comparison were needed to determine if the parts met the requirements set forth by the FSAE team. The analysis stage (A in the compliance matrix) consisted of hand calculations and Finite Element Analysis to ensure the final design met the strength, weight, and stiffness criteria. Testing (T in the compliance matrix) followed completion of the manufacturing process to determine if the composite suspension met the requirements. For stiffness and weight, this included comparing the test results (S in the compliance matrix) to the existing components.

Table 1: Compliance Matrix

	Requirements	Tolerance	Risk	Compliance
1. Strength	1.5 Safety Factor	+10% -0%	H	A,T
2. Weight	20% system reduction	+N/A -10%	H	A,T,S
3. Stiffness	10% Increase	+10% -0%	H	A,T,S
4. Manufacturability	N/A	N/A	M	T
5. Cost	20% increase	+10 % -N/A	L	S
6. Aesthetics	N/A	N/A	L	I

The compliance matrix (Table 1) shows the goals for each specification from the QFD. Each specification has a certain value to meet (if applicable) with an acceptable tolerance level for that value. For strength and stiffness, it will be unacceptable if the final product is any weaker or any less stiff than its specified value. This would have a severe detrimental effect on the entire vehicle's performance. However, if the final parts are too stiff or too strong, it would have a negative effect on the weight of the component. If any of these three specifications are not met, the project would be a failure. Therefore, they all have a high risk so each was thoroughly analyzed and tested to ensure the requirements were met.

Manufacturability, cost, and aesthetics are lower risk goals and are more difficult to test for compliance. Manufacturability and aesthetics will be based on the judgment of both Composite Suspension Solutions and the Formula SAE team. Cost rules change from year to year, so it will be difficult to determine whether the cost of the car increases or decreases because of the composite suspension.

5. Design Concepts

5.1 Idea Generation and Decision Matrix Breakdown

During the design process, the decision was made to use predominantly carbon fiber tubes over other materials because of its superior strength and low weight. The next step was to determine how to produce the lightest, strongest and stiffest suspension components. Six potential ideas were further narrowed down to a final design using decision matrices.

Six design targets were chosen to evaluate each of the choices in both decision matrices. Each design target was weighted on a scale from one to five, with five being the most important. The weight factors differed for both decision matrices because the design aspects have different levels of importance on the two component parts. Since the ultimate goal of this project is to lighten the existing suspension of the FSAE car, weight was assigned a factor of five for the tube and four for the joints. The car would be disqualified from competition if the suspension were to fail, so strength also received a weight factor of five for both components. Excessive deflection during track events would change suspension geometry under dynamic loading, so stiffness received a weight factor of four for both components. Cost was marginally important for both components because the suspension must stay within the SAE budget for this project. Aesthetics and manufacturability were of lower importance and received weight factors of one and two, respectively.

5.2 Tube Assembly

5.2.1 Custom Made Round Tube

Custom, hand-made round tubes were the first option. The biggest advantage to constructing the tube in-house is that any combination of wall thickness and diameter can be produced. Also, it would be cheaper for the FSAE team because they already have the carbon fiber in stock. However, the material Cal Poly FSAE possesses is not ideal for a tension-compression tube so some of the major advantages of composite materials are lost.

5.2.2 Custom Made Aero Tube

A custom made aero tube has many of the same advantages and disadvantages of a custom made round tube. What really separates this choice from the round tube is the reduction in drag from the aero profile. However, this method is exceedingly more expensive, difficult and time consuming. The shape of the tube is more complex, requires more material, and takes longer to produce than a round tube. Furthermore, the estimated drag reduction that would result from the shape is virtually negligible considering the size of the airfoil and the relatively low speeds the car operates at.

5.2.3 Roll Wrapped Tube

A roll wrapped tube is a prefabricated carbon fiber part that has approximately 95 % of the fiber aligned along the axial direction. The final 5% is wrapped around the tube to reduce the possibility of delamination from an impact. The advantage of a roll wrapped tube is that it is simple to work with and is lighter than a custom made tube.

5.2.4 Decision Matrix

Custom made aero profile tubing had the lowest total rating on the tube decision matrix because of its high weight, high cost, and poor manufacturability. Laying up a complex aerodynamic tube requires many molds which are inherently expensive. Custom made round tubing was rated second because tubes not manufactured professionally tend to weigh more and are harder to manufacture without mass production techniques. Roll wrapped tube was rated highest on the decision matrix because of its low weight. Also, because the tubes will be pre-manufactured, manufacturing the final part was easier and more consistent.

Table 2: Tube Decision Matrix

		Roll Wrap		Custom Made Round		Custom Made Aero Profile	
	Weight Factor	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Weight	5	1	5	-1	-5	-1	-5
Cost	3	0	0	1	3	-1	-3
Stiffness	4	-1	-4	1	4	1	4
Strength	5	1	5	1	5	1	5
Aesthetics	1	1	1	-1	-1	1	1
Manufacturability	2	1	2	-1	-2	-1	-2
			9		4		0

5.3 A-arm Assembly Joints

5.3.1 Composite

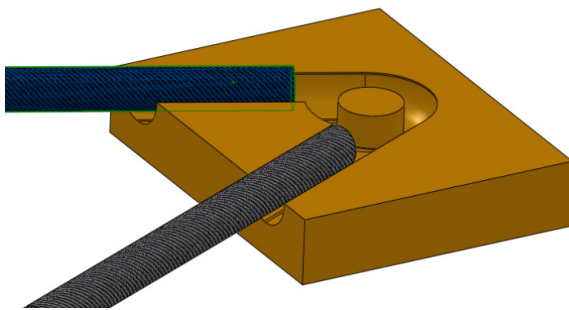


Figure 5: Composite Joint Mold with Carbon Fiber Tubes

One way to construct the A-arm joint is to manufacture it from carbon fiber. It would be constructed using a two part mold process. Each half of the part is constructed from carbon fiber cloth and resin in a mold like the one shown in Figure 5. The composite tube is inserted into one mold and the two halves are combined. The parts are then cured together in a vacuum bag that applies pressure to the carbon fiber while it cures.

5.3.2 CNC Aluminum

The basic premise of an aluminum joint is that it transfers the load from the composite tubes to a bearing through an adhesive bond. There are a few options for a CNC Aluminum joint such as the one shown in Figure 6. In each case, the bearing is press fit into the aluminum. The most complex joint would be a single piece of aluminum having cylindrical machined male

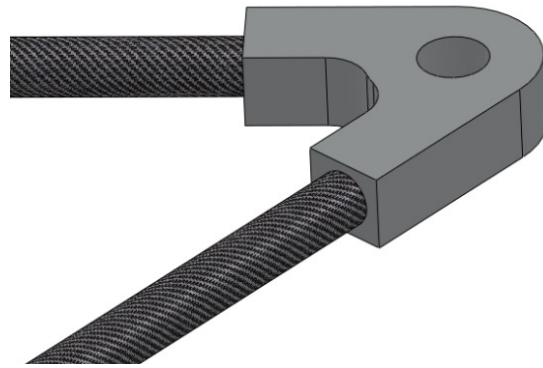


Figure 6: Aluminum Joint Design

studs inserted in the carbon tubes. Alternatively, instead of machining male studs out of fatigue-prone aluminum, holes can be bored into the joints to mate with press-fit steel dowels. These dowels would be inserted into the carbon tubes and would provide the most strength but also weigh the most. The lightest and simplest solution would involve boring holes in the joint that the whole carbon tube can slip into. In all of these designs, properly bonding the two pieces is vitally important.

5.3.3 Cast Aluminum

Casting is a very efficient way to mass produce a metallic part. However, the Formula SAE car is considered a prototype vehicle and does not need joints produced in mass quantities. The shape of the joint would be very similar to a CNC aluminum joint. The major difference would be in the size of the joint and the drafts needed for a cast part.

5.3.4 Decision Matrix

Table 3: Joint Decision Matrix

		CNC Aluminum		Cast Aluminum		Composite Joint		Previous Design (steel components)	
	Weight Factor	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Weight	4	0	0	-1	-4	1	4	0	0
Cost	2	0	0	1	2	-1	-2	0	0
Stiffness	4	1	4	0	0	1	4	0	0
Strength	5	1	5	-1	-5	1	5	0	0
Aesthetics	1	0	0	-1	-1	1	1	0	0
Manufacturability	2	1	2	-1	-2	-1	-2	0	0
			11		-10		10		0

Composite joints are rated second on the decision matrix due to the high cost of molds and the complexity of manufacturing. Composite joints would have to be manufactured in-house and require several expensive molds. Cast aluminum joints are rated lowest due to their high weight, low strength due to potentially inconsistent metallurgy, low aesthetics, and high complexity of manufacturing. CNC aluminum joints are rated highest because they offer the acceptable stiffness and strength and are significantly easier to manufacture than the other options.

6. Design Process and Development

To determine how much weight we needed to eliminate, we weighed the current steel components. Appendix C. *Actual Composite Suspension Weights (in lb)* shows the weight of the components. The total weight is 4.9 pounds. Therefore, to reduce the weight by our stated goal of 20%, we needed to reduce the mass by .4 pounds. The strength and stiffness to weight ratio of composites is great enough that it is possible to cut the weight of the tubing alone by 50%. Assuming the joints weighed the same, this would allow us to reach our desired weight savings.

The estimations were made using CAD models of preliminary designs of aluminum joints for each A-arm and pushrod. The tube sizing calculations were made using tubes of the same diameter and thickness of the steel tubes. This is a conservative estimate because carbon fiber is much stronger and the tube diameters will most likely be reduced significantly. However, it is a good initial estimate that gives the team a goal to shoot for during the design and manufacturing processes.

The best choice for the A-arms is a CNC machined aluminum part bonded to the carbon fiber tubes. An aluminum joint has many significant advantages over a two part molded composite joint. The manufacturing process of a composite joint is potentially prohibitively difficult because constructing composite parts is a difficult, time consuming and inexact science. It requires detailed part and mold design, trial and error, and attention to detail. Perhaps most importantly though is the interaction between the bearing and the composite. Bearing holes require very tight diametrical and cylindrical tolerances that are difficult to achieve with composite materials.

A CNC aluminum part can be machined to meet bearing mounting tolerances relatively easy. A properly designed aluminum joint can meet Cal Poly FSAE's weight, strength and stiffness requirements while still being cheaper and easier to manufacture than a composite joint. A design study between a basic composite and a basic aluminum front A-arm joint showed that the aluminum joint weighed only .06 lbs more than the composite joint. The total difference in weight would be approximately .25 pounds over

the entire car. The trade study in Appendix E. *Trade Study for Joint Type* shows the difference in weight is not worth the extra cost and manufacturing difficulties of a composite joint.

The joint designs were finalized using Pro/Engineer Mechanical. It is a Finite Element Analysis package that works in conjunction with the solid modeling package of Pro/E. It converts solid models to FE models quickly and easily. Modifying parts to be stronger and lighter is more efficient than a standard FEA package such as ABAQUS CAE. Each joint was modeled by constraining the bearing hole and modeling a composite tube that was bonded to the joint. Applying the load to the tube is more accurate than just applying a force to the joint. The force applied to the tube transfers to the joint and produces a stress and deflection. The results are shown using a stress contour plot with blue being the least stress and red the most. The deformation of the part is scaled by a factor of ten to show how and where the part will deflect the most.

6.1 A-arms

6.1.1 Upper A-arm

The majority of the weight of the composite part is in the aluminum joint. Therefore, reducing the weight of the joint was the major focus. Because it is a CNC part, complicated features can be constructed to remove excess material that does not add strength to the part. However, CNC parts are extremely difficult to analyze with hand calculations. Therefore, Pro/Engineer Mechanical FEA was used during the design process to ensure that the part is as strong, stiff and light as possible. Appendix H. *Tube Sizing Results* shows the final size of each composite component, the load through each component and the safety factors.



Figure 7: Upper A-arm

The final loads from Appendix H. *Tube Sizing Results* were used to analyze the upper A-arm joint in Pro/Engineer Mechanical. The aluminum joint will experience a maximum force of 410 pounds from one tube and 135 pounds from the other. The estimated maximum stress in the part is 24.5 ksi which is well below the 76 ksi yield strength of 7075-T6 aluminum

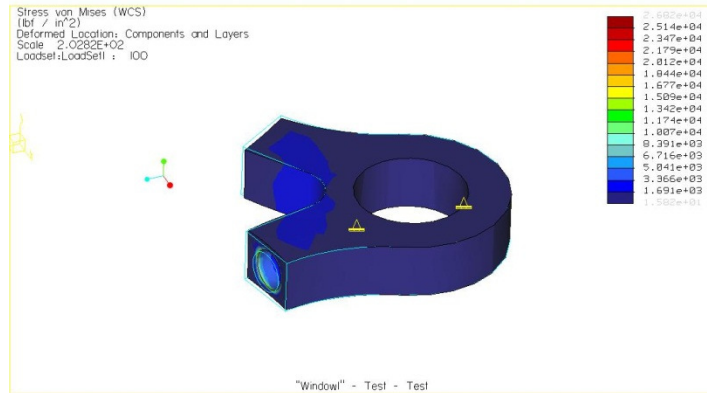


Figure 8: Upper A-arm Joint FEA

that the joints are machined from. If they do fail, the most likely section will be the radius between the two arms. However, the safety factor is high enough that any stress concentration factors will not be a problem over the life of the part. Appendix C. *Actual Composite Suspension Weights (in lb)* shows the final weight value of each upper A-arm.

However, the FEA cannot analyze the strength of the bond between the carbon and aluminum. That was found using the tested shear strength of the epoxy which was approximately 1500 psi. The bonding process is so unpredictable that high factors of safety were used for each joint. The bond length for each arm is one inch which gives an estimated bond failure load of 3000 pounds. The safety factor on the bond is approximately 6.8. Also, a significantly stronger epoxy will be used in the final manufacturing process to improve the bond.

6.1.2 Lower A-arm

The lower A-arms are significantly larger than the upper A-arms because they experience a much higher load. Each will experience a maximum force of 1800 pounds on one tube and 880 pounds from the other. The joint will also take 1100 pounds of force from the pushrod. Another major difference is that the tubes in the lower A-arm are in compression, not tension. Therefore, buckling is a potential failure mode for the tubes. Analysis of both tubes showed that they are prone to

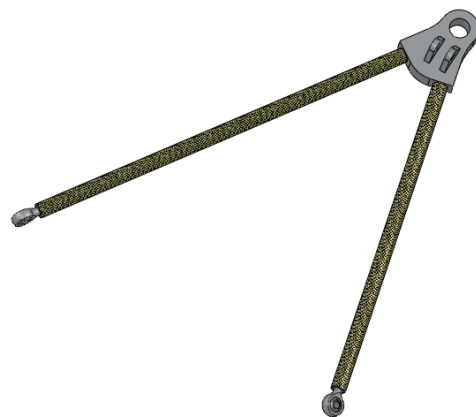


Figure 9: Lower A-arm Design

buckling and therefore the tube diameter had to be increased beyond the yield strength criteria of the composite tube.

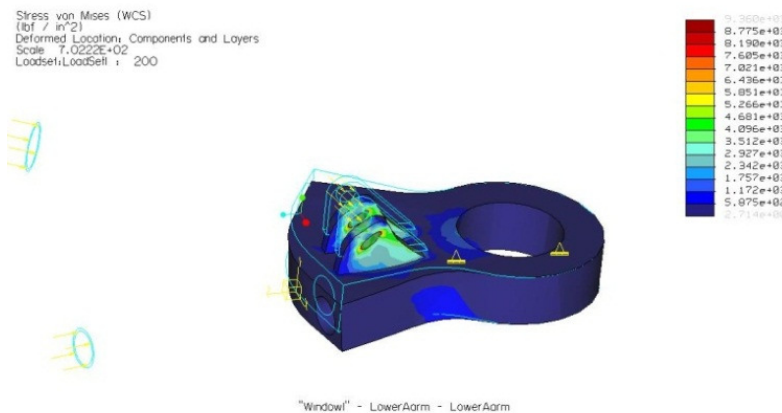


Figure 10: FEA Results of Lower A-arm Joint

The lower A-arm joint is significantly more difficult than the upper joint. Not only does it experience more load from the A-arm tubes but it has to resist the load from the pushrod as well. It is a significantly heavier part than the lower joint due to the increased loading. The final FEA results of the joint are shown in Figure 10. The maximum stress on the part is 8400 psi which is significantly

lower than the 76 ksi yield strength of the 7075 T-6 aluminum the part is made from.

As with the lower joint, the most difficult section of the A-arm to predict is the bond between the carbon fiber and the aluminum. Once again, a bond strength of 1500 psi was used with a bond length of one inch. The estimated failure load for the bond is 3500 pounds. This gives a safety factor with the ultimate load of approximately 2. However, as with the lower joint, the epoxy used is approximately twice as strong as that which was tested so the strength is significantly higher.

6.2 Two-Force Members

The design process is very similar for each two-force member. The loads were found for each set of components and the sizing was based off buckling and tension-compression yield calculations. The insert was sized to fit the tube and ¼" rod end. From there, simple load calculations were done to ensure each part will be strong enough. The pushrod experiences a load of 1100 pounds and the safety factor on the failure of the tube is 1.13. The steering arm has 120 pounds of force applied to it and has a safety factor of 1.38. Both are most likely to fail in buckling.

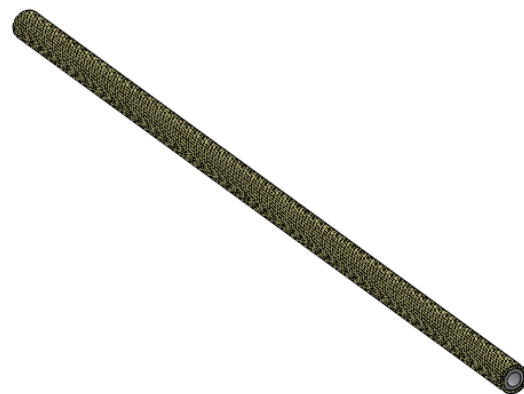


Figure 11: Pushrod/Steering Arm

7. Cost

The cost of this project came in significantly lower than expected. In total, \$120 was spent on tubing for the components and \$150 on strain gages. We avoided extra cost such as bolts, material, and bearings by using the material available to the Formula SAE team. This included sheet steel, 7075-T6 aluminum, ¼" rod ends and bolts. If Composite Suspension Solutions had been forced to purchase this material, the cost would have been significantly higher.

The most important factor for the Formula SAE team to consider though is the cost of the product according to SAE rules. The cost of material and manufacturing operations changes on a yearly basis and therefore no direct comparisons could be made between the cost of the steel components versus that of the composite ones.

8. Product Realization

The manufacturing process required a lot of problem solving because similar construction had never been done on a Cal Poly Formula SAE car. The most difficult issue for each part was the best way to bond the carbon fiber with the metal. The biggest question mark was the amount of clearance to give the tube and the metal joint. Too much clearance would create room for the tube to shift off axis and too little would cause the epoxy to be displaced when the tube was inserted into the joint. Creativity in design and experimentation solved both problems.

8.1 A-arms

8.1.1 CNC Aluminum Joints

The manufacturing processes for the upper and lower joints are very similar. For the lower joint, design was limited by the size and shape of the stock available. The Formula SAE team had a very large 2" by 4" block of aluminum at its disposal and in order to save the team money, some components were redesigned so that they would fit in this material requirement. The lower joint wasted a significantly larger amount of

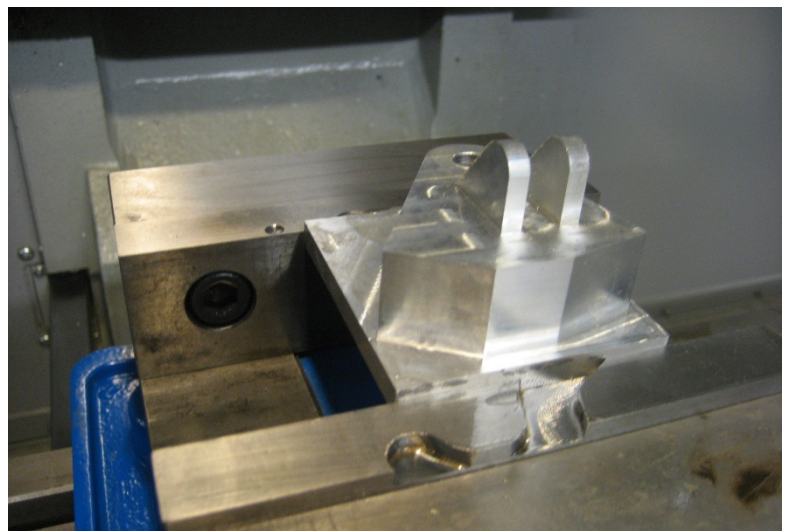


Figure 12: First Setup for CNC Joint

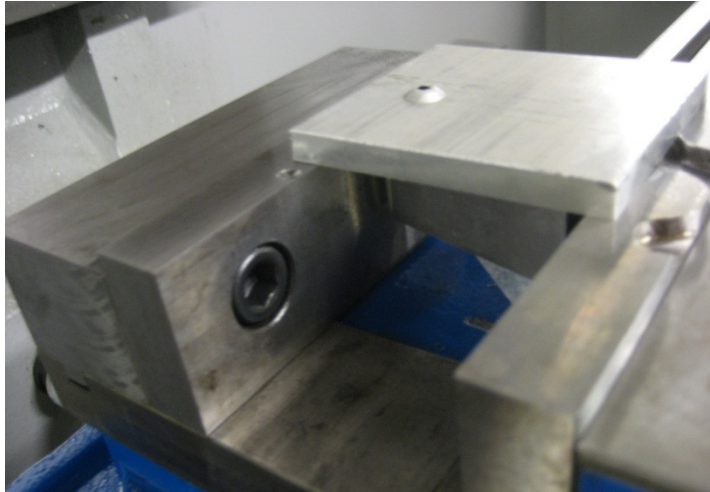


Figure 13: Second Setup for CNC Joint

material due to the pushrod mount that is machined out of the top. One 3" long section of aluminum produced one lower joint while the same length section produced two upper joints.

Both joints were made using the same five step manufacturing process. While five steps in a machining process is a significant amount, each step was short and relatively easy to setup. The first step was to

machine the outside shape of the joint which produced the part shown in Figure 12. A ½", 3-flute end mill was the primary tool used during this setup. It was chosen because it can be ran at both a high feed rate and spindle speed which provides a good balance of low run time and a high quality surface finish. For the lower joint, a 3/8" end mill was also used to machine the section between the pushrod mount located on top of the joint. In addition, a ball end mill was used to create the profile shape of the pushrod mount. The ball end mill has a rounded end that allows it to create 3-Dimensional surfaces by making machining passes at relatively small increments (approximately .003".)

The next step for each joint was to flip it so that the side initially on the bottom became the top. In order to clamp the part in a vice during the first setup, the stock material had to start out thicker than the actual part. The first machining setup left approximately .100" of material that had been clamped in the vice. The second setup removed this material using a 3" facing tool known as the "aluminator." This tool can remove significant amounts of material in a very short time and was ideal for the second setup.

The third and fourth steps in the process created the holes for the carbon fiber tubes to be inserted into. While the machine time

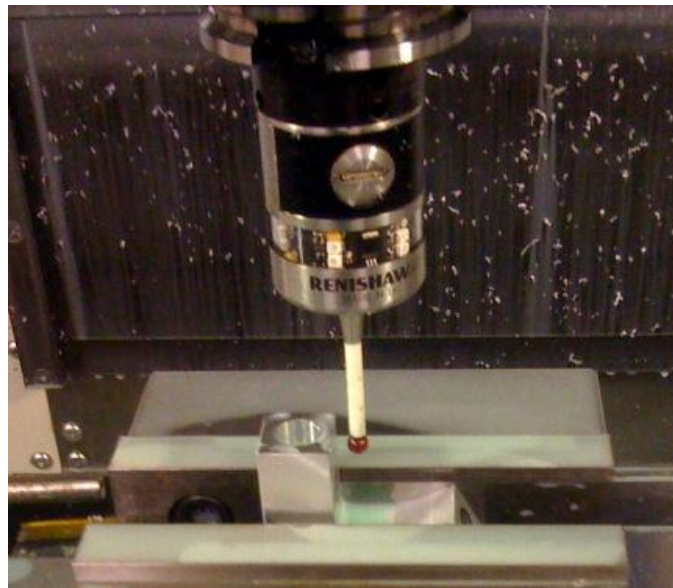


Figure 14: Spindle Probe Zeroing Part

is extremely short for each setup, approximately one minute, the setup time was much more significant. The part was oriented so that one arm was vertical and clamped in the vice. To ensure the part was as vertical as possible, a 1-2-3 block was used. 1-2-3 blocks are precisely machined setup tools that are 1"x2"x3". The block was then removed so that it didn't interfere with the machining process. One final check to ensure the part was facing 90 degrees from horizontal was made using a precise digital level gage. The hole was then machined using a ½" 3-flute end mill like the first setup. Figure 14 shows a spindle probe taking accurate measurements on the location of the part.

The final setup rotated the part approximately 270 degrees so that the tube holes were facing down. A slot was machined into the joint to allow for the bearing to fit into the joint and a bolt to pass through both. The only way to achieve this setup was to design the part so that the opposite side of the slot was completely flat when resting on parallel setup tools in the vice. Setup was relatively easy for this feature and machining time was short as well.

8.1.2 Steel End Joints

The steel end joints that connect the A-arm tubing to the spherical bearing on the monocoque required three lathe operations, a sheet metal cut using the plasma cutter, tooling designed to increase the accuracy while bending and a welding operation to finish it all off. In order to increase the precision and similarity between each end joint, we made extensive use of templates, jigs and CNC machinery.

The most difficult and time consuming process was the round steel insert bonded into the carbon fiber tube. Each was manufactured using a CNC lathe that theoretically could hold tolerances of under .001". However, due to the geometry of the part, such tolerances were very difficult to manufacture. While the machine was turning down the



Figure 15: Final Preparation of Steel End Joint

outside diameter, the part would deflect some because of its small moment of inertia and a significant section would be oversized. Therefore, multiple passes at the same final diameter had to be made in

order to make the part the correct dimension. The next two steps were to drill a hole through the part to reduce the weight and cut it off to the correct length.

The other half of the steel end joint was sheet steel bent into a C-cross section. The bearing from the tub slides into this C-section and a bolt goes through each to secure them. The sheet steel was first cut out using the automatic plasma cutter in the hangar. A 2-D pattern was drawn to slightly larger dimensions than the part and the plasma cutter followed that

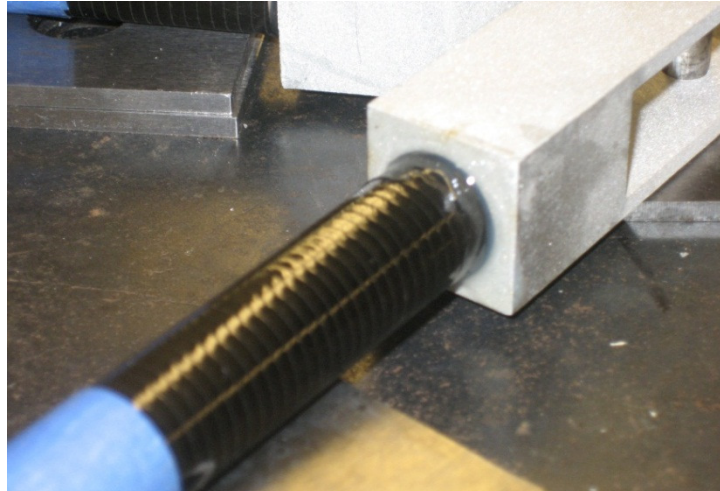


Figure 16: Bond Between Carbon Fiber and Aluminum Joint

pattern. The remaining piece was then ground down to size. Once ground down, one bend was made to 90 degrees using the large sheet metal bender at the hangar. Next the sheet was placed in a jig and hammered down to complete the final 90 degree bend. A $\frac{1}{4}$ " hole was drilled through for the bearing hole and the C-section was welded to the insert.

8.1.3 Bonding Components

Often the most difficult part of working with composites is finding the best way to attach two components. For this particular project, we used epoxy to join carbon fiber to aluminum and steel. The most important part of the process is the surface preparation of the material, especially aluminum. Research and testing led us to etch the aluminum prior to bonding.

The process for etching aluminum was relatively straight forward. First, we sandblasted the hole to give it a rough bonding surface, then cleaned it with a solution specifically designed to prepare it for the etching process. The etching process involved combining the etching fluid with water and soaking the part. Once soaked it was cleaned with water



Figure 17: Bonded and Assembled Lower A-arm in Jig

and isolated so that it could not be contaminated with dirt or oils.

The carbon fiber was sanded to rough up the surface then cleaned using acetone. This removed any oil or dust on the top layer of the part and prepared it for bonding. The steel inserts were prepped in the same way. Like the aluminum, they were isolated prior to the bonding process to ensure that they were uncontaminated.

The bonding process starts with the A-arm jig. It is a set of holes on a large steel plate that located the bearing holes for each component. The composite A-arm was first fitted to the jig to ensure that everything fit as intended. Next, the bonding surfaces were coated with epoxy and put together component by component. This step required very meticulous application of epoxy. Too much and it would be difficult to insert the part into its respective hole. Too little and it would not guarantee coverage on the bonding surface. The final step was to bolt each component to the jig and let it sit for 12 hours.

8.2 Two-Force Members

Because the goal of this project was a proof of concept for manufacturing and structural properties of composite materials, only one pushrod was. The two-force members were built from a carbon fiber tube and steel threaded insert. The carbon tubes were cut using the tile saw in the same manner as the A-arm tubes. The inserts had



Figure 18: Bond between Steel joint and Carbon Fiber Tube

to be manufactured to slip perfectly into the carbon fiber tube so that the axis of the threaded hole would be concentric with the tube.

The initial design for the steel insert required a jig to center it in the tube. The major problem is that there needs to be enough room for the epoxy to sit between the tube and the insert and not displace

when the steel part is inserted. However, if there is any room between the insert and the tube the axes will not be aligned. The solution was to leave a $\frac{1}{4}$ " of the insert on each side the exact inside diameter of the tube and machine the rest down .100" to create room for the epoxy to settle. The final design required no jig to assemble the inserts and the tube. The epoxy was applied to the groove on the insert and slid into the tube. The part then cured for 12 hours.

8.3 Strain Gage Installation

Strain gages were installed on the carbon tubes to be later used for load analysis and possible damage calculations after a high stress event such as a crash or loss of vehicle control. The carbon fiber tubes were first sanded to remove the rippled surface caused by epoxy flow during the wrapping of the tube's single transverse ply. Also, the roughened tube provided an ideal surface for bonding the gages due to the similarity of the epoxy used to manufacture the tubes and the epoxy used to bond the gages. Using a straight edge, the axial positions of the four gages were scribed into the tube for positioning. A strip of tape was then applied around the diameter of the tube to be used as a guide to scribe the circumferential location of the gages into the tube. The intersection of the axial and circumferential positioning marks corresponded to the exact center of the active gage area, not the geometric center of the gage itself. After roughening the surface and marking the gage locations, the bonding area was thoroughly cleaned with isopropyl alcohol to remove any oil from handling the tubes and debris freed during sanding. The gages were then laid out on a clean glass plate, and strips of clear cellophane tape were stuck down over the gages. This allows the gages to be held tightly against the tubes when the glue was applied. A normal two-part epoxy was chosen for bonding due to its resilience against fatigue. After the epoxy was mixed, the tape was carefully peeled off the glass plate, bringing the gage up with it. A small amount of epoxy was applied to the back of the gage, and each pair of axial gages were bonded to each tube. After adequate curing time, the tape was peeled off, leaving the bonded strain gage behind. The same procedure was used to bond each pair of transverse gages, being sure that the positioning points on the active area of the gages corresponded to the intersection of the guides scribed into the tubes. After the epoxy cured, a small terminal strip was super glued below the band of gages. This provided a secure location to attach the lead wires connecting the gages to the data acquisition system. The gages were then wired in a full bridge configuration using low diameter enamel coated magnet wire. When viewed with the terminal strip on the bottom and gages on top, the four terminals from left to right correspond to (+), (-), (A), (B), respectively. The gages can be excited by a 3-5V DC signal across the + and - terminals of the gage bridge. This voltage can be from conventional batteries, making sure that the capacity of the battery is high due to the high number of gages dissipating power. The A and B

terminals provide the differential voltage signal and should be wired to the data acquisition system accordingly.

9. Testing and Design Verification

The most important part of this project was the testing conducted to validate the design. It's extremely difficult to accurately predict how a composite part will react under load because the manufacturing process for composites is extremely variable. Errors are often made manufacturing the material, during the resin impregnation process, cutting the material to size and the final assembly. Strength and modulus values from material manufacturers can vary by as much as 20% from published values. Epoxy varies from its published bond strengths as well. For those reasons, it is extremely important to test everything.

The most variable part of the manufacturing process is the bond between the carbon fiber and aluminum. Therefore, extensive testing was conducted to determine at what shear stress the bond would fail. In addition to that, each component was tested before it was put on the car to ensure that it will withstand the load applied when on the vehicle. The tests are broken up between destructive and non-destructive testing below.

9.1 Destructive Testing

9.1.1 Flat Plate Bond Line Shear Stress

The flat plate bond line shear stress test was conducted as per the specifications of ASTM D905. The test is intended to determine the approximate shear strength of the DP110 epoxy when bonding carbon-epoxy plates to machined aluminum, the intended joint material. Three test coupons were manufactured to obtain the average shear strength. The coupons were approximately six inches in length and two inches wide to ensure they were small enough to fit in the test clamps. The tests were performed using an Instron servo-hydraulic load tester. The tester was programmed to pull the specimens apart at a constant rate of .002 in/sec, and a load cell in series with the pull grips provided the load data for the duration of the test. The results for a carbon-epoxy/aluminum bonded coupon tested to failure are seen below in Figure 19.

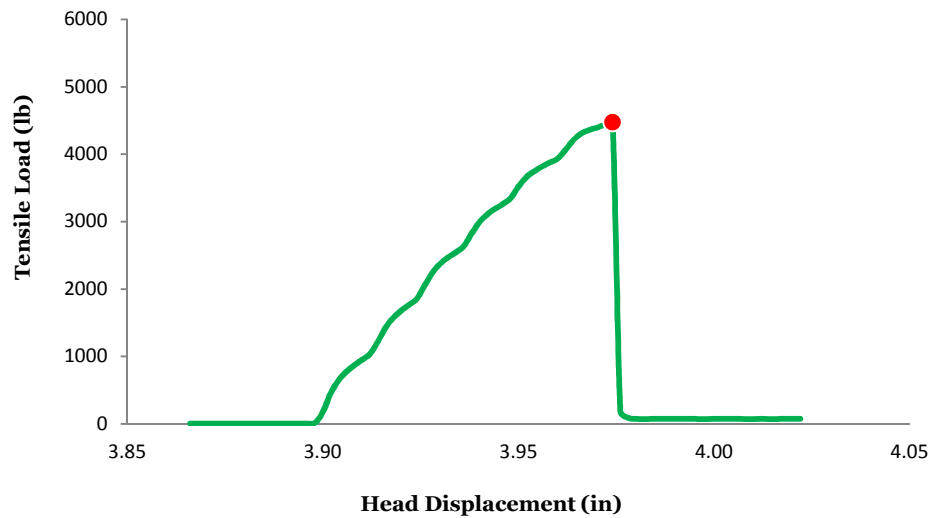


Figure 19: Breaking load of flat plate Carbon-Epoxy/Al joint.

For this particular specimen, the bond failed at a load of 4476 lb. After unloading from the test fixture, the bond area was carefully measured as 2.8 in². Dividing the failure load by the area gives the bond strength per unit area and allowed the team to calculate the required bond area and size of inserts bonded into the tubes. This particular specimen yielded bond line strength of 1592 lb/in². The advertised shear strength of the DP110 epoxy is 2000 lb/in², however the substrate to be bonded is not specified. As mentioned previously, aluminum is difficult to bond with epoxy so steps have been taken to increase this bond strength, including proper surface roughing and use of the West System 860 Aluminum Etch kit. Using the average bond line strength from several batches of coupons will give a representative average strength used to size the bond area needed for containing the inserts bonded into each tube.

9.2 Non-Destructive Testing

9.2.1 Final Strength Verification

Carbon fiber is an extremely difficult material to manufacture without variation. It's easy for voids to form, delamination to occur or just have fiber that isn't as stiff or as strong as designed. Joining the carbon fiber to metal components is difficult as well which has been discussed extensively throughout



Figure 20: Lower A-arm on Instron Force Tester

this report. For that reason, each component was tested to its ultimate failure load to determine if it could withstand any unexpectedly high forces. Figure 20 shows a front upper A-arm being tested on the Instron Force Tester.

All the tests were conducted using the Instron force and length measurement system. The most important thing to consider when using the Instron is safety. The machine can apply 20,000 pounds of force and if used incorrectly it is potentially deadly. One of the primary safety restrictions is the method in which the force is applied to the test piece. The controller can ramp up the machine using force as the driver or length. Force control is incredibly dangerous because if

the part breaks and no longer resists the applied force, the system will rapidly shift to try and apply more load. Therefore the distance control must be used.

Composite components are so stiff that under the loads experienced on the Formula SAE vehicle, the deflection of each component is very small. As a result, the distance controller cannot be used because it will apply too much force in trying to displace the part. Therefore, the test had to be conducted using a manual control. The manual control opens a valve that applies a pressure load to the Instron test fixture and the part.

Another major difficulty in the testing process was the jig used to connect the A-arms to the Instron. Initially a block was machined that fit both the Instron clamps and the A-arm joints. However, we found that the tube not being tested would contact the side of the Instron with this setup so testing wasn't possible. Therefore, a secondary design used a round tube machined flat in one section and a threaded hole on the other end. A ¼-28 rod end was inserted into the threaded hole and the A-arm was bolted to the rod end. This allowed us to rotate the A-arm in any direction and also mitigated any torsional effects from incorrect alignment of the Instron clamps.

As Table 4 shows, each part passed the ultimate failure load criteria. There was no evidence of buckling, plastic deformation or stretching of the bond during any test. The only failure seen during testing was the bolts that connected the test fixture to the actual part. The bolts deflected significantly and accounted for the majority of the displacement of the part as shown in the graphs of Appendix XX.

Table 4: Test Results for Strength of Each Component

Suspension Member	Load Applied (lbs)	Results	Failure Mode
Front Upper A-arm	410	Pass	N/A
Rear Upper A-arm	135	Pass	N/A
Front Lower A-arm	1800	Pass	N/A
Rear Lower A-arm	880	Pass	N/A

9.2.2 Stiffness Measurement

We attempted to compare the stiffness between the steel and composite suspension components but were unable to get reliable data. As mentioned in the previous test section, the bolts connecting the Instron test fixture to the part deflected significantly under high load. This introduces an unexpected and unaccounted for variable in the determination of the stiffness of the part. Even under lower loading conditions, the bolt would deflect more than the carbon fiber component and the data would be incorrect.

This problem could be corrected through the use of strain gages which were applied to the composite components. However, due to the FSAE team's switch to the 2008 vehicle, we were unable to apply strain gages to the steel components. Therefore, accurate tests could not be conducted to determine the stiffness of the steel components. Comparing the stiffness of the composite components using strain gages and the steel components using the Instron's head displacement tool would have inaccurate and misleading. Therefore no stiffness comparison tests occurred.

9.2.3 Strain Gage Calibration

Many supporting equations have been developed to predict the nature of the signal produced from a full bridge of strain gages as a means of establishing ballpark figures for planning purposes. Strain gages are very precise instruments and many variables can affect the very low amplitude differential voltage signal needed for analysis. The largest factors affecting the signal output by the full gage bridges are the alignment of the bridges and the thickness/completeness of the bond line between the rear face of the gage and the steel tubes. Variation of these two factors may cause errors in determining the theoretical equations dictating the calibration constant of a full bridge, as they are based on the gages being seamless with the material and perfectly aligned. Because of these concerns, the calibration constant of each gage bridge will be determined experimentally to achieve the most accurate measured strain values. To accomplish this task, a regular 6V lantern battery (same that will be used during real testing) was connected to the voltage input on each bridge. The differential voltage output of the bridge was be attached to the DAQ, at which point a suitable gain for the signal was chosen. A series of weighted plates was hung from each member, and the data was imported to a table. The stresses experienced by the tubes were well within the linear range, so a simple graph plotting force against differential voltage (as seen in Figure 21) produced the calibration constant, in lb/V. This value will is multiplied by the voltage signal taken during testing to output the loads in each member.

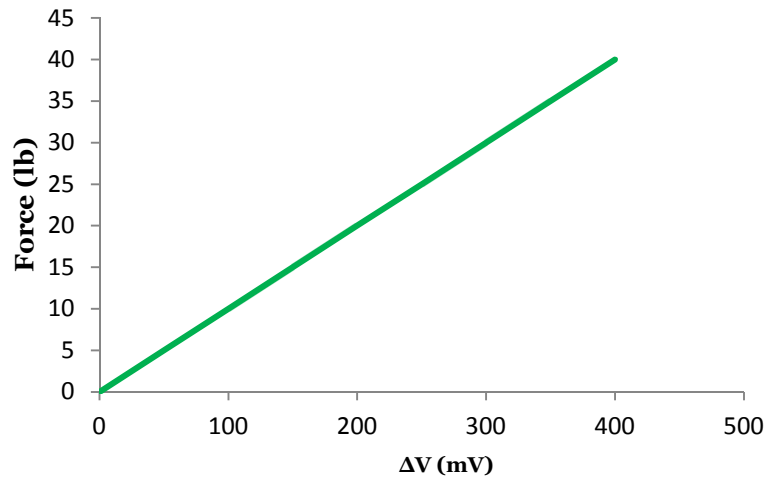


Figure 21: Calibration constant is the slope of the Force-Voltage curve.

9.2.4 Electromagnetic Interference Investigation

Several bridges of gages, especially those mounted on the rear control arms and the rear pushrod, are in close proximity to the engine. As the electronic ignition discharges each spark for the engine, electromagnetic interference is produced due to the thousands of volts traveling between the coil and the spark plug. The voltage signal produced by the gages is extremely small in amplitude and will potentially be affected by the electromagnetic interference from the engine. Tests will have to be performed testing the effect of interference on the signal, and can be accomplished without the vehicle moving. As the engine is running, a preliminary test will simply involve examining the steady-state signal from an unloaded member placed close to the engine. If large fluctuations are seen in the signal, the issue of interference will have to be addressed further. Also, long lengths of lead wire act as antennas in the presence of a fluctuating magnetic field, so methods of braiding or shielding the wire by grounding a braided steel sheath to the chassis may be necessary for a clean signal.

10. Conclusion

As the requirements of this project evolved over time, the goals of Composite Suspension Solutions changed as well. Initially, it was our goal to provide the Cal Poly Formula SAE team with a competition ready platform that would improve the vehicle this year. However, their decision to scrap work on the current vehicle and revert back to the 2008 vehicle changed this aim. Our primary goal became to build a platform that the team could use to determine in future years what type of suspension they will use.

Therefore, it was not necessarily our goal to provide a polished product but instead one that was strong enough to withstand the pressure put on suspension components over the course of a testing year.

As shown in the testing section of this report, the composite components passed tests well beyond the expected ultimate failure load. The factors of safety are significantly higher than what would be found on a competition vehicle. Despite the added material required to achieve higher safety factors, the final parts came were approximately 40% lighter than the steel suspension components. This result exceeded both our goals and expectations for the project and is an extremely encouraging sign for the viability of carbon fiber suspension on a Formula SAE vehicle. Another significant upgrade over the steel suspension is the increase in stiffness of a composite suspension. While we were unable to get reliable stiffness data from the tensile and compressive tests, as mentioned in the testing section, the increased stiffness is apparent in handling the two different components.

We expected the cost of the components to be greater as well and they were but not to the extent we expected. The total cost of the project came out to approximately \$500. A significant amount of this came from strain gages that were applied to the steel components and would not be factored into any cost analysis at competition. However, to determine the cost of each component in terms of the SAE cost report, more analysis must be conducted using the cost tables published each year. The aluminum and carbon may be significantly more expensive in those tables than steel is.

The manufacturability of the carbon fiber components came as a welcome surprise as well. They were significantly easier to manufacture than expected. We planned to spend an extensive amount of time testing different bonding procedures between aluminum and carbon fiber. However, the cheapest and easiest option worked the best and we did not have to pursue other aluminum preparation methods. The most difficult part of the process was the CNC machine work. Each part required five setups which is time consuming considering the number of parts that need to be produced.

Due to the significant weight savings and increase in both strength and stiffness, Composite Suspension Solution strongly recommends the 2010 Formula SAE team pursue the use of composite suspension components. As shown in the QFD from Appendix A. *Quality Function Deployment*, weight, strength and stiffness are the three most important factors in suspension design. Carbon fiber components improve the overall performance of the car so dramatically that the extra costs incurred by the team are far outweighed. This is especially true considering the manufacturing process is no more difficult than steel components.

Regarding potential changes to Composite Suspension Solutions' design, we feel there are a few areas for improvement, primarily in the joints. The 2008 vehicle uses a very inefficient method to mount the A-arms to the rest of the car with the bearing being on the tub/upright side. We believed this added a significant amount of weight to our suspension and is something to be avoided in the future. Using aluminum inserts with aluminum rod ends threaded into the A-arm would mean both a decrease in weight and an increase in manufacturability. We also believe that welded steel joints bonded to carbon tubes should be considered at the upright. The CNC aluminum part, while not being extraordinarily heavy, was extremely bulky in shape due to the tube sizes. A smaller, and potentially lighter part could be made with a welded steel joint.

Appendices

Appendix A. Quality Function Deployment

Grouping	Customer Requirements	Item No.	Importance	Weight	Strength	Stiffnes	Cost	Manufacturability	Aesthetics	Customer Ratings					
				Specifications						Bad				Good	
				A	B	C	D	E	F		1	2	3		4
	Acceleration		4	9	9	3	0	0	0						x
	Skidpad		5	6	9	3	0	0	0	x					
	Endurance		1	9	9	9	0	0	0	x					
	Autocross		2	9	9	9	0	0	0	x					
	Cost		6	0	0	0	9	6	0					x	
	Design		3	6	3	6	3	6	3		x				

Appendix B. Steel Suspension Weights (in lbs)

Component Weight			
Weights in [lb]	Per Each Side		
	Right	Left	Total
Upper A-arm*	.643	.641	1.550
Lower A-arm*	1.403	1.407	2.810
Pushrod	.31	.31	.62
		Total Weight	4.98

*Due to the cross-bracing present on the steel suspension components but not on the composite, we were unable to make an accurate comparison between the steel and composite components. Therefore, we estimated the weight of this cross bracing and removed it from the total weight of each A-arm component.

Appendix C. Actual Composite Suspension Weights (in lb)

Component Weight			
Weights in [lb]	Per Each Side		
	Right	Left	Total
Upper A-arm	.378	.378	.756
Lower A-arm	.618	.622	1.40
Pushrod	.130	.131	.261
		Total Weight	2.417

Appendix D. Trade Study for Tube Type

		Roll Wrap		Custom Made Round		Custom Made Aero Profile	
	Weight Factor	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Weight	5	1	5	-1	-5	-1	-5
Cost	3	0	0	1	3	-1	-3
Stiffness	4	-1	-4	1	4	1	4
Strength	5	1	5	1	5	1	5
Aesthetics	1	1	1	-1	-1	1	1
Manufacturability	2	1	2	-1	-2	-1	-2
			9		4		0

Appendix E. Trade Study for Joint Type

		CNC Aluminum		Cast Aluminum		Composite Joint		Previous Design (steel components)	
	Weight Factor	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Weight	4	0	0	-1	-4	1	4	0	0
Cost	2	0	0	1	2	-1	-2	0	0
Stiffness	4	1	4	0	0	1	4	0	0
Strength	5	1	5	-1	-5	1	5	0	0
Aesthetics	1	0	0	-1	-1	1	1	0	0
Manufacturability	2	1	2	-1	-2	-1	-2	0	0
			11		-10		10		0

Appendix F. Bill of Materials

The following parts list is for one side of the car. For each final part there is a quantity value of two. This is to indicate that there is one of each part on both sides of the car. However, each part is not the same for both sides of the car. For example, part number 204 may have to incorporate a different attachment method on the right side than the left side due to asymmetry in the bearing blocks on the FSAE car.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	103	Bearing Cup, Front A-arm Upper	1
2	101	Front Tube, Front A-arm, Upper	1
3	102	Rear Tube, Front A-arm, Upper	1
4	104	Rear Insert, Front A-arm, Upper	2
5	203	Bearing Cup, Front A-arm, Lower	1
6	201	Front Tube, Front A-arm, Lower	1
7	202	Rear Tube, Front A-arm, Lower	1
8	204	Front Insert, Front A-arm, Upper	2
9	301	Tube, Pullrod	1
10	302	Insert (RHT), Pullrod	1
11	303	Insert (LHT), Pullrod	1
12	401	Tube, Steering Arm	1
13	402	Insert (RHT), Steering Arm	1
14	403	Insert (LHT), Steering Arm	1
15	60685K721	1/4 inch Rod End	4

Appendix G. Cost Analysis

Carbon Fiber Tube Cost Breakdown*	
TUR-07A (.500" Inside Diameter x .030" Wall Thickness x 60" Length)	
Quantity	1
Total Cost	\$23.75
TUR-08A (.555" Inside Diameter x .033" Wall Thickness x 58" Length)	
Quantity	1
Total Cost	\$27.50
TUR-08 (.555" Inside Diameter x .033" Wall Thickness x 28.5" Length)	
Quantity	1
Total Cost	\$15.50
TUR-10A (.625" Inside Diameter x .043" Wall Thickness x 70" Length)	
Quantity	1
Total Cost	42.50
Total Composite Tubing Cost (Includes S&H)	\$119.36

*All tubes are purchased from ACP-Composites.com

Appendix H. *Tube Sizing Results*

Tube Sizing Results					
Suspension Member	Load (lbs)	OD	Wall	SF	Faliure Mode
Fornt Upper A-arm	410	0.5	0.03	5.583	Yield
Rear Upper A-arm	135	0.5	0.03	10.525	Yield
Pushrod	1100	0.55	0.033	1.133	Yield
Front Lower A-arm	1800	0.625	0.033	1.1396	Buckling
Rear Lower A-arm	880	0.5	0.03	1.05	Yield
Tie Rod	120	0.55	0.033	1.38	Buckling

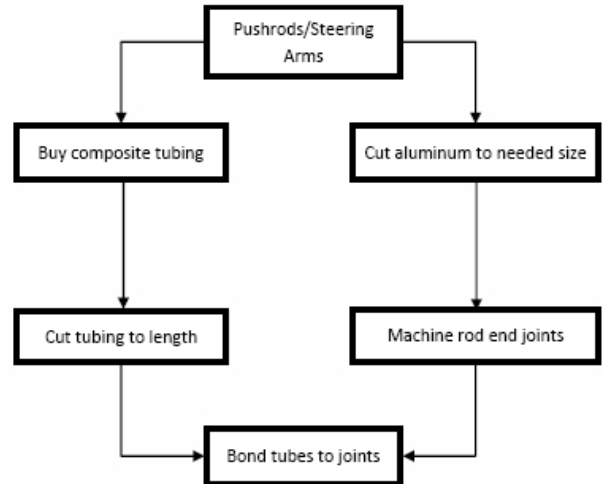
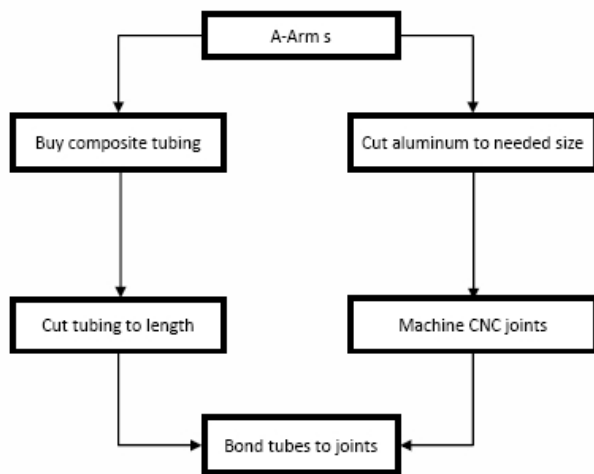
Appendix I. Mechanical Properties of Carbon Roll Wrapped Tubes

Carbon Roll Wrapped Tubes

Tensile Strength (ksi)	275
Tensile Modulus (Msi)	20
Compressive Strength (ksi)	132
Compressive Modulus (Msi)	14.5
Torsional Strength (Msi)	15
Torsional Modulus (Msi)	1.3
Fatigue Strength (10^9)	90
Coefficient of Thermal Expansion (in/in/°F) (10^{-6})	-.24 Axial
Density (g/cm ³)	1.52

Appendix J. Manufacturing Flow Charts

Manufacturing Flow Chart



Appendix K. Design Verification Plan and Report

DESIGN VERIFICATION PLAN AND REPORT									
CUSTOMER		Cal Poly Formula SAE							
TEST PLAN					TEST REPORT				
Item No	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	TEST RESULTS			Quantity	NCES
					Test Result	Quantity Pass	Quantity Fail		
1	Measure forces applied to each suspension member on 2009 vehicle using strain gages	None	Andrew Bookholt	Pre-prototype	N/A	N/A	N/A		This is not a pass/fail test. It simply determines the amount of load that each suspension member experiences. This test was not conducted due to the Formula SAE team's switch in focus from the 2009 vehicle to the 2010 vehicle.
2	Lap shear test of adhesive	Shear strength of at least 1000 psi for adhesive	Reid Olsen	Pre-prototype	Pass	100%	0%		Each test sample met the required shear strength. The maximum was approximately 1700 psi while the minimum was 1300 psi.
3	Measure dimensions of rough cut for lathe parts	Adequate clearance (+/-125) & material for facing	Reid Olsen	Manufacturing	Pass	100%	0%		
4	Measure dimensions of final cut for lathe parts	Same thickness around perimeter, adequate L & W dimensions	Reid Olsen	Manufacturing	Pass	60%	40%		Improper measurements were taken during the lathe process which resulted in an incorrect OD dimension. The errors were fixed in the processes following.

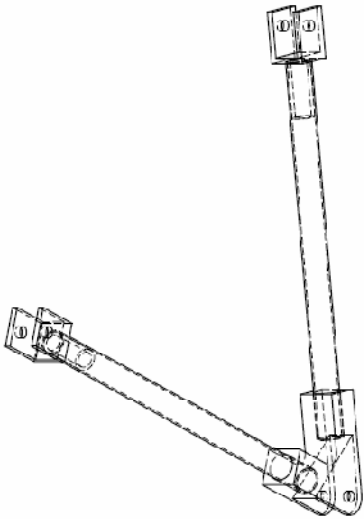
DESIGN VERIFICATION PLAN AND REPORT							
CUSTOMER:		Cal Poly Formula SAE					
TEST PLAN				TEST REPORT			
Item No	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	TEST RESULTS		NOTES
					Test Result	Quantity Pass Quantity Fail	
5	Inspection of CNC cut & boreholes	Tube hole $\pm .005$	Reid Olsen	Manufacturing	Pass	66%	33%
							Of the four CNC components that were made, 3 had to be remade to due failures in the CNC machining process.
6	Proper inner tube hole surface finish	200 grit sand, sandblast, visual inspection	Andrew Bookholt	Manufacturing	Pass	100%	0%
							This visual inspection was done to ensure that the adhesive would bond properly to the carbon fiber. It was specifically installed as a test due to the unexpected failure of the adhesive bonded to the carbon fiber during the initial testing phase.
7	Visual inspection of bond coverage	Tube to Joint & Tube to insert bond fails if inadequate adhesive coverage	Andrew Bookholt	Manufacturing	Pass	100%	0%
							Parts fit on vehicle except for manufacturing defect on lower right A-arm. Hole drilled incorrectly while part was on car and part rendered unuseable.
8	Test Components fitment on vehicle	Adequate if all components fit on the vehicle	Eric Melchiori	Prototype	Pass	90%	10%
							Each component passed the static load required of it. Only failure was the bolt which cannot be controlled by Composite Suspension Solutions
9	Load testing of each component	Bond strength is within safety factor for component	Eric Melchiori	Prototype	Pass	100%	0%

Appendix K. *Part Drawings*

Each final part is treated as an assembly and as such there is a BOM for each final part. The components for each final part follow in order of part number.

Table of Contents for Drawings

1. Front Upper A-arm Assembly	43
a. Front tube	
b. Rear tube	
c. Joint	
d. Front Insert	
2. Front Lower A-arm Assembly	48
a. Front tube	
b. Rear tube	
c. Joint	
d. Front Insert	
3. Pushrod	53
a. Tube	
b. RHT Insert	
c. LHT Insert	
4. Steering Arm	57
a. Tube	
b. RHT Insert	
c. LHT Insert	



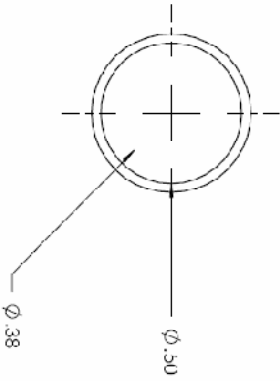
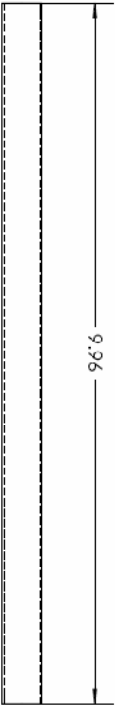
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	103	Bearing Cup, Front A-arm, Upper	1
2	101	Front Tube, Front A-arm, Upper	1
3	102	Rear Tube, Front A-arm, Upper	1
4	104	Rear Insert, Front A-arm, Upper	2

UNLESS OTHERWISE SPECIFIED:
 DIMENSIONS ARE IN INCHES
 TOL. FRACTIONS:
 TWO PLACE DECIMAL ±.01
 THREE PLACE DECIMAL ±.005

DESCRIPTION
**Front A-arm
 Assembly, Upper**

SIZE PART NUMBER REV
A 100

SCALE: 1:3 WIDTH: SHEET 1 OF 1

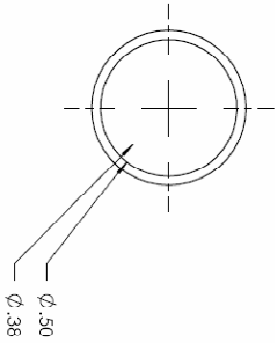
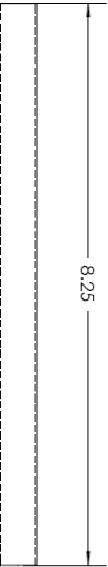


UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONS DECIMALS
THIRD PLACE THIRDS

DESCRIPTION
Front Tube, Front A-
arm, Upper

SIZE	PART NUMBER	REV
A	101	

SCALE: 1/4" = 1" WEIGHT: SHEET 1 OF 1

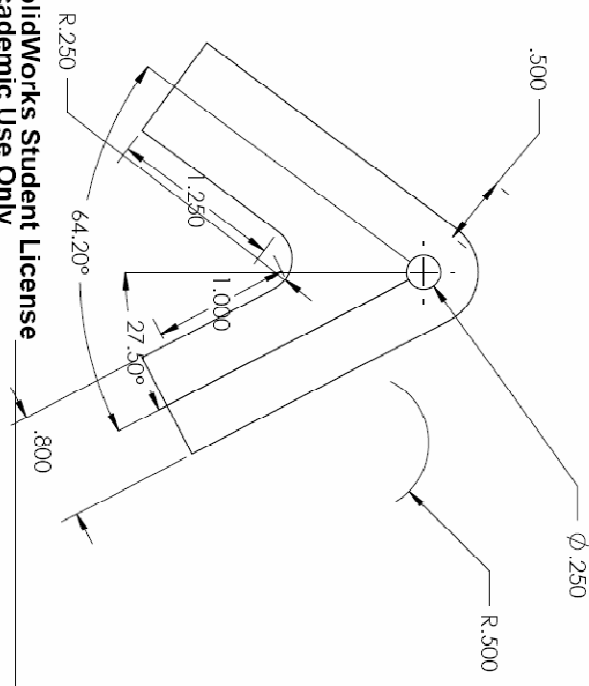
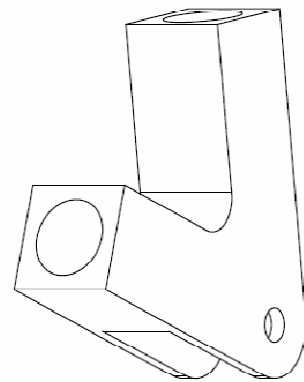
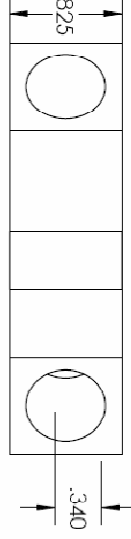


UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES
TWO PLACES DECIMAL: $\pm .01$
THREE PLACES DECIMAL: $\pm .005$

DESCRIPTION
Rear Tube, Front A-
arm, Upper

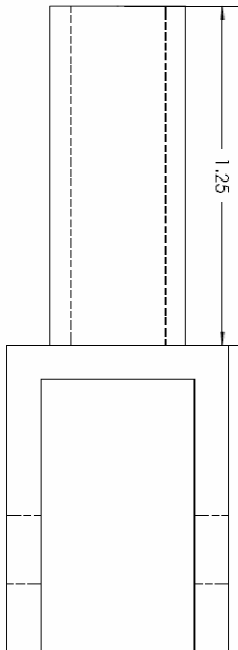
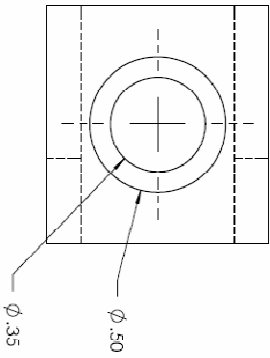
SIZE	PART NUMBER	REV
A	102	

SCALE: 1/4" = 1" WEIGHT: SHEET 1 OF 1

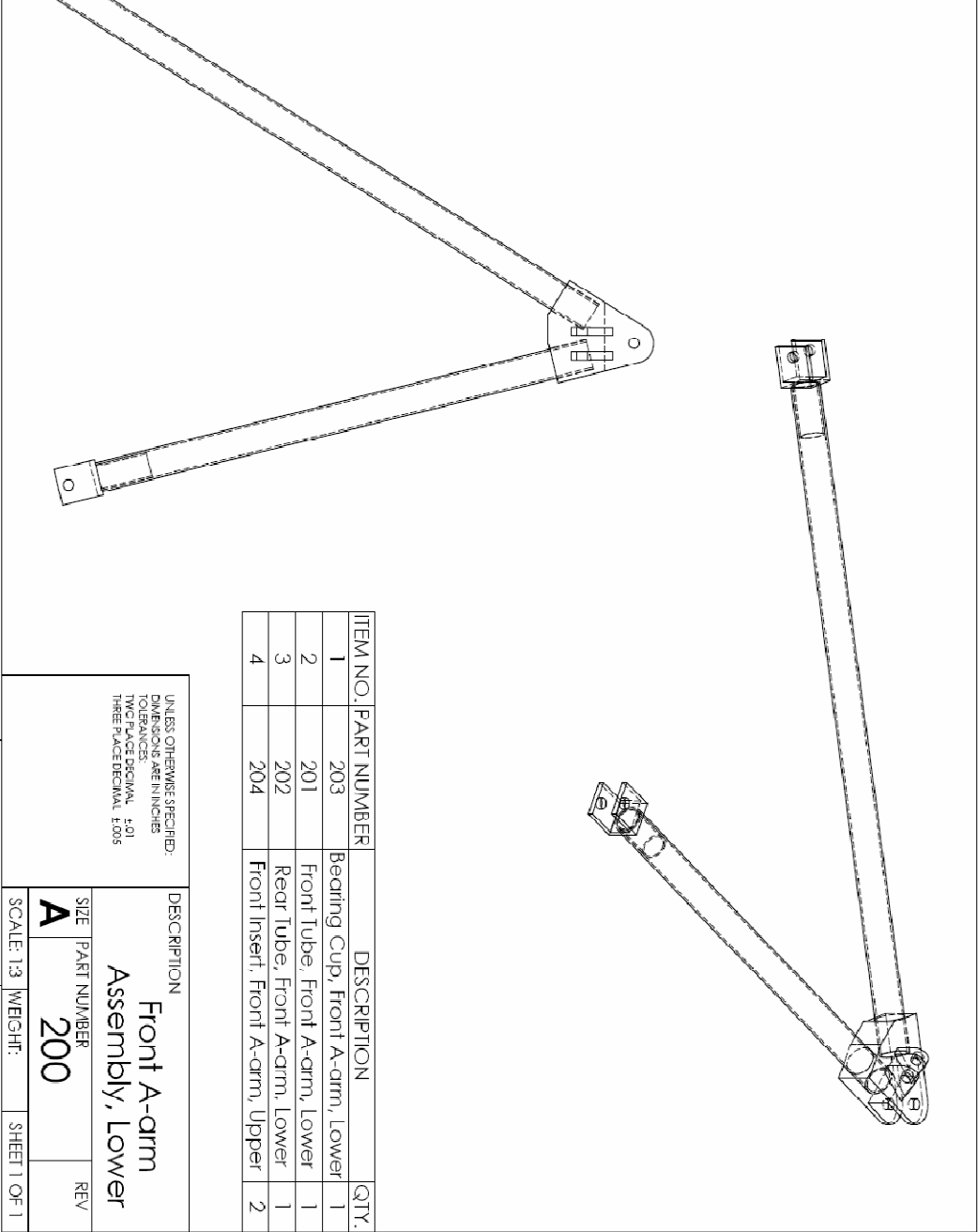


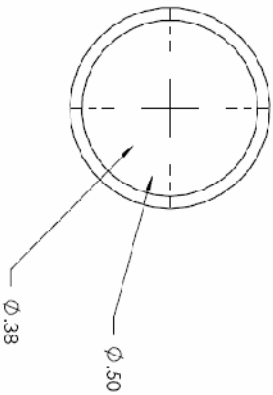
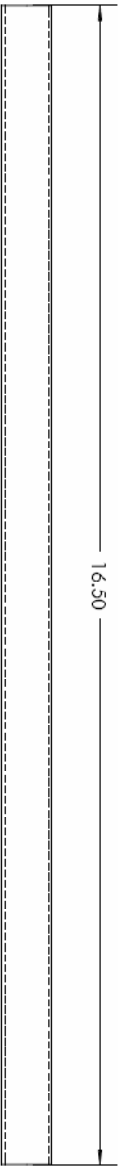
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UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL .4 .01 THREE PLACE DECIMAL .1 .005			
DESCRIPTION Bearing Cup, Front A-arm Upper			
SIZE	PART NUMBER	REV	
A	103		
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.005			
DESCRIPTION Rear Insert, Front A- arm, Upper			
SIZE	PART NUMBER	REV	
A	104		
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1	



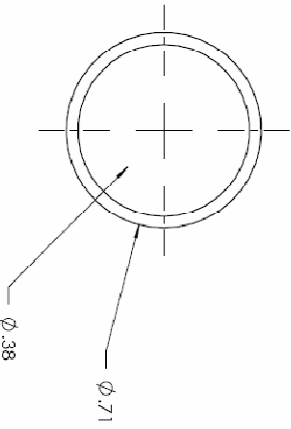
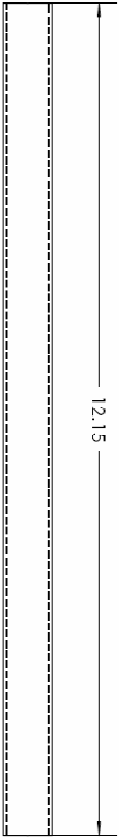


UNLESS OTHERWISE SPECIFIED,
DIMENSIONS ARE IN INCHES
TOLERANCES
TWO PLACE DECIMAL $\pm .01$
THREE PLACE DECIMAL $\pm .005$

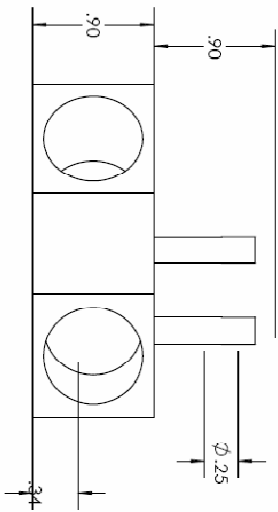
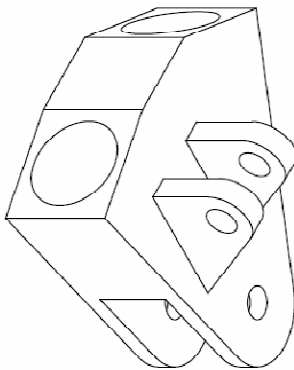
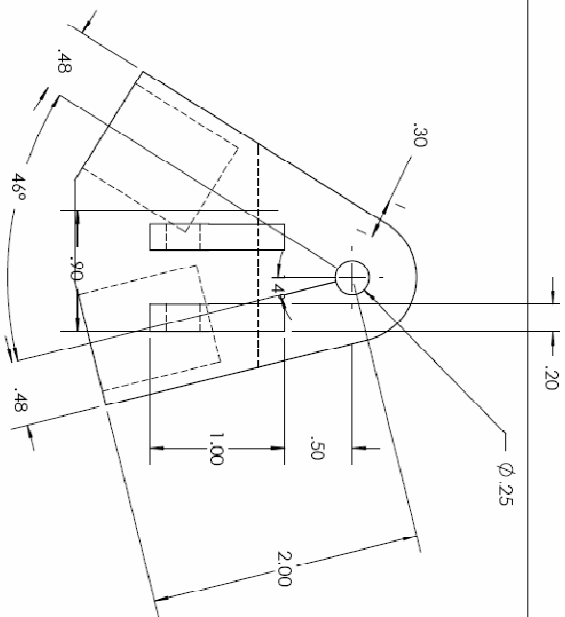
DESCRIPTION
**Front Tube, Front A-
arm, Lower**

SIZE PART NUMBER
A 201 REV

SCALE: 1/4" WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL $\pm .01$ THREE PLACE DECIMAL $\pm .005$			
DESCRIPTION Rear Tube, Front A- arm, Lower			
SIZE	PART NUMBER	REV	
A	202		
SCALE: 1:4	WEIGHT:	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES
FRACTIONS
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005

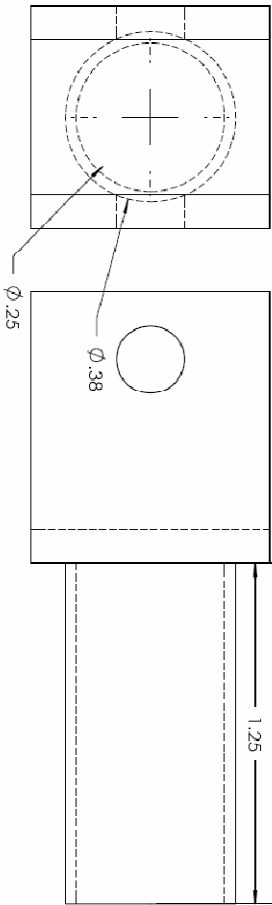
DESCRIPTION
Bearing Cup, Front
A-arm, Lower

SIZE	PART NUMBER	REV
A	203	

SCALE: 1:1	WEIGHT:	SHEET 1 OF 1
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2

1



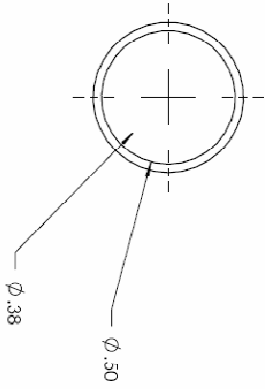
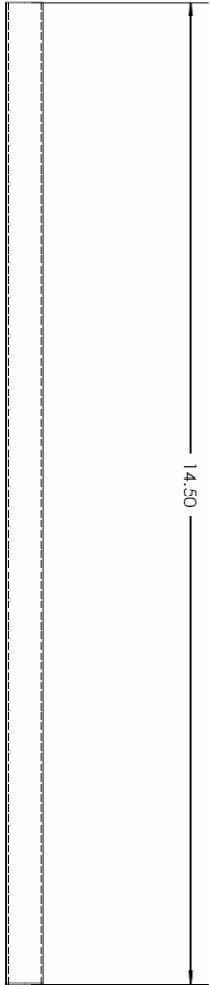
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.005			
DESCRIPTION Front Insert, Front Arm, Upper			
SIZE	PART NUMBER	REV	
A	204		
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1	



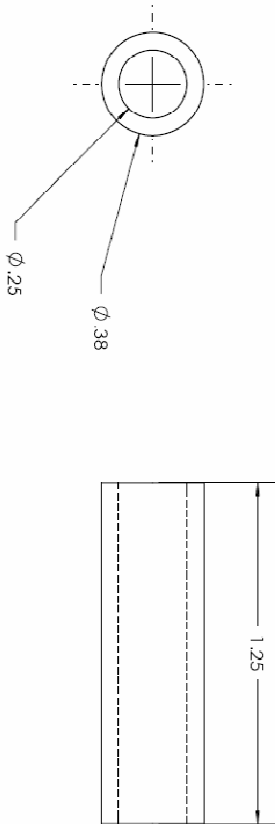
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	301	Tube, Pullrod	1
2	303	Insert (LHT), Pullrod	1
3	302	Insert (RHT), Pullrod	1
4	6068SK721	1/4 In Rod End	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES UNLESS
SPECIFIED:
TWO PLACE DECIMAL .01
THREE PLACE DECIMAL .005

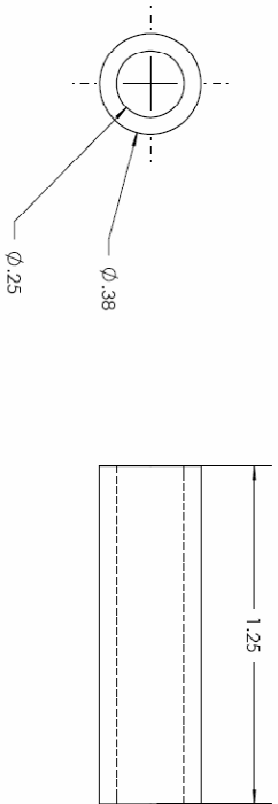
DESCRIPTION			
Pullrod			
SIZE	PART NUMBER	REV	
A	300		
SCALE: 1/2	WEIGHT:	SHEET 1 OF 1	



DESCRIPTION			
Tube, Pullrod			
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL $\pm .01$ THREE PLACE DECIMAL $\pm .005$			
SIZE	PART NUMBER	REV	
A	301		
SCALE: 1/4"	WEIGHT:	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.005		DESCRIPTION Insert (RHT), Pullorod	
SIZE	PART NUMBER	REV	
A	302		
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES DECIMAL ±.01 THIRDE PLACE DECIMAL ±.005			
DESCRIPTION			
Insert (LHT), Pullrod			
SIZE	PART NUMBER	REV	
A	303		
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1	

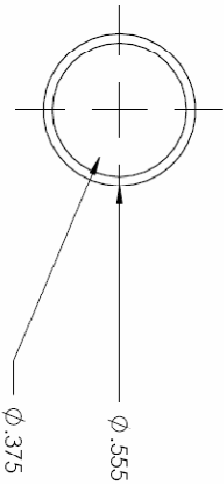
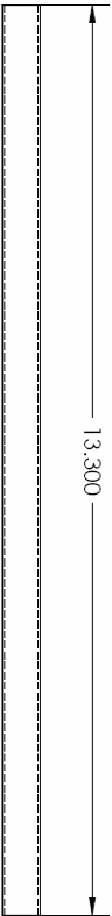


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	401	Tube, Steering Arm	1
2	402	Insert (RHT), Steering Arm	1
3	403	Insert (LHT), Steering Arm	1
4	60685K721	1/4 in Rod End	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL +.01
THREE PLACE DECIMAL ±.005

DESCRIPTION
Steering Arm

SIZE	PART NUMBER	REV
A	400	
SCALE: 1/2	WEIGHT:	SHEET 1 OF 1

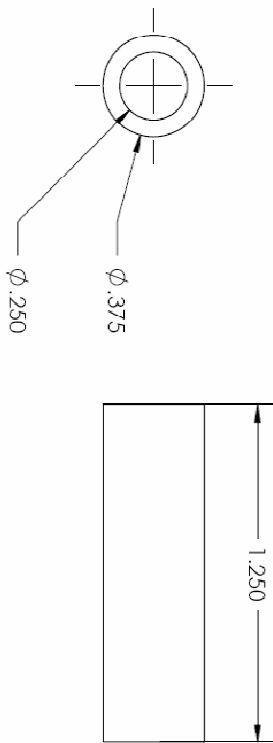


UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL: $\pm .01$
THREE PLACE DECIMAL: $\pm .005$

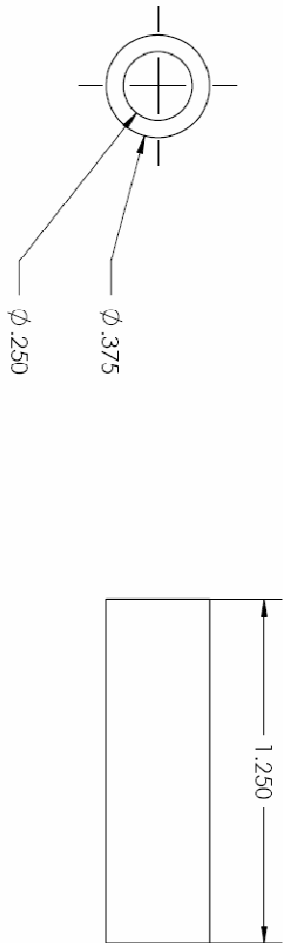
DESCRIPTION
Tube, Steering Arm

SIZE	PART NUMBER	REV
A	401	

SCALE: 1:2	WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL $\pm .01$ THREE PLACE DECIMAL $\pm .005$		DESCRIPTION Insert (RHT), steering Arm	
SIZE	PART NUMBER	REV	
A	402		
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL .01 THREE PLACE DECIMAL .005			
DESCRIPTION Insert (LH), steering Arm			
SIZE	PART NUMBER	REV	
A	403		
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1	