

Design of a Carbon Fiber Suspension System for FSAE Applications

by  
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by  
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## ABSTRACT

Reducing weight while maintaining structural integrity is one of the key challenges Formula SAE teams face as they try and design the suspension of the formula car. The purpose of this paper is to present experimental data on designing and optimizing a carbon fiber suspension system for formula cars. The reason carbon fiber suspensions are favored over the current steel suspensions is because of they can reduce the weight of the suspension by 50%. Pull tests on an Instron machine were performed on over 15 specimens composed of a carbon fiber tube with an aluminum insert bonded to each end. Loctite E-120HP epoxy was used and the surface preparation, bond gap, and bond length were varied to find the optimal bond strength. An average bond strength of 2,382.6 pounds per square inch was determined for specimens with surface preparation. Furthermore a bond gap of 0.0065 to 0.008 inches was found to give the strongest bond.

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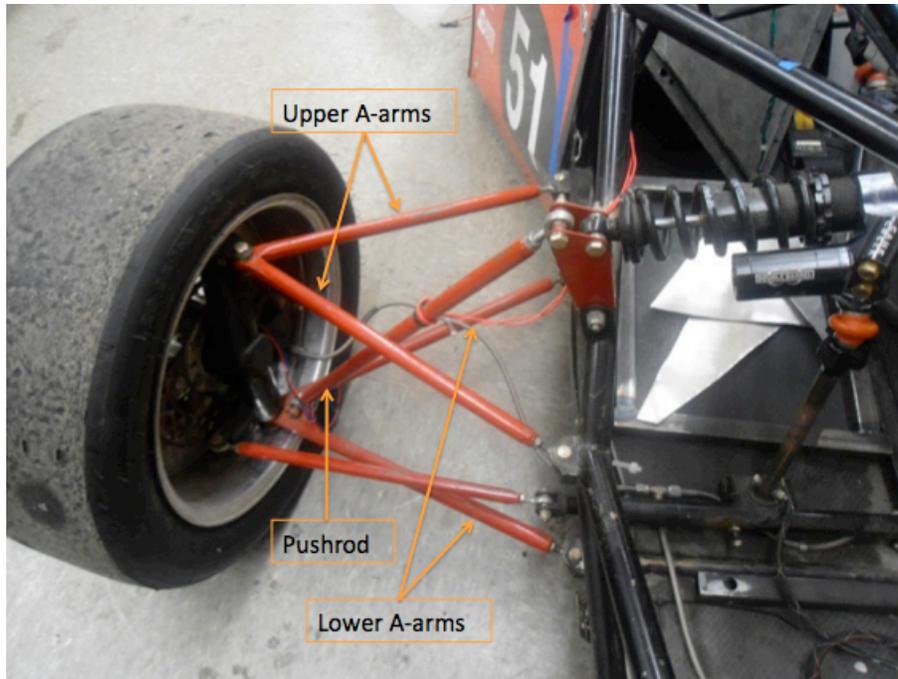
## **1.0 What is FSAE?**

FSAE, short for Formula SAE is a worldwide collegiate competition hosted by the Society of Automotive Engineers (SAE). Teams composed of undergraduate and graduate students design, build and compete a formula style racecar in the FSAE series. In competitions, teams score points by delivering in four main events: design, cost, marketing, and performance events. Competitions are held in over ten countries spanning all the continents of the world.

Since its birth in 2001, the MIT FSAE team has historically attended FSAE West in California (to move to Nebraska in 2013) and FSAE Michigan. In 2010, MIT placed 8<sup>th</sup> overall in FSAE West and in 2012 they placed 16<sup>th</sup> overall in FSAE Michigan, two very good finishes considering that there were over 80 teams in FSAE West and over 120 in FSAE Michigan. In order for teams to be successful in these competitions, their cars must be built to very strict specifications or else they will be disqualified from the competition. These specifications can be found in the official most up-to-date FSAE rules on the web. [1]

## **2.0 Background on Suspension Systems**

There are various geometries that suspension systems can take in formula one cars. The most widely-used suspension geometry, even in professional-sized formula cars and the one consistently used by MIT since the birth of MIT's FSAE team is the double wishbone design. The double wishbones, shown in figure 2-1 on the following page are most commonly called A-arms because of their resemblance to the letter "A".



**Figure 2-1: Front A-arms on MIT's 2010 formula car**

It is also important to understand the concepts of sprung and unsprung masses in order to design and engineer an effective suspension system. In a suspension system, the sprung mass is the part of the car that is supported by the car's suspension system. The engine, the frame, and everything within the frame of the car are part of the sprung mass system of the car. The unsprung mass on the other hand is the part of the car that is not supported by the suspension. This generally includes the wheels, brakes, tires, and a few other components outside the frame of the car.

The A-arm design uses a total of 16 tubes, 4 on each wheel of the car. These tubes, historically made of steel on formula car suspensions and especially on MIT formula cars make up a significant portion of weight of the car. MIT's 2011 car's A-arms weighed a total of 6.49 lbs. See Appendix A for the specific weight of each A-

arm. In a competition where the weight to power ratio matters significantly, FSAE teams always strive to design and engineer a car that is as light as possible yet still structurally sound and that delivers maximum power to the wheels. By using carbon fiber tubes to replace the 16 steel tubes the total weight of the A-arms can be reduced by at least 50% and the overall stiffness of the tubes can be maintained or even increased.

While the A-arms act as structural members of the suspension, the push rod, also shown in figure 2-1, acts as the spring-damper component of the car's suspension. The A-arms, push rod, and sprung and unsprung masses of the suspension system all need to be carefully designed so that optimal car performance is reached on the race track.

## **3.0 Carbon Fiber Tubes**

### **3.1 Types**

Carbon fiber tubes are most commonly manufactured using two methods: pultruding and roll-wrapping. [2]

Pultruded – 100% of the fibers are aligned with the axis of the tube. These tubes are prone to delamination and must be protected from exterior damage. Delamination is a condition where the bonds between the fibers break. An example of a pultruded tube is shown in figure 3-1 on the left, on the following page. It is barely noticeable but you can see that the fibers are aligned along the axis of the tube.



**Figure 3-1: Pultruded tube (left) and roll-wrapped tube (right)**

Roll-wrapped – multi-directional fiber alignment. These tubes have excellent torsional strength, axial strength, and lateral strength, but they are more expensive. An example of a roll-wrapped tube is shown in figure 3-1 above on the right. You can notice thin lines perpendicular to the axis of the tube that show that the fibers are wrapped around the circumference of the tube. Roll-wrapped tubes can have fibers aligned in multiple directions and angles with respect to the axis of the tube.

### **3.2 Advantages**

The main advantage of using carbon fiber tubes in suspension design as opposed to steel or other metals is their weight. A manufacturer of carbon fiber tubes lists the properties of its tubes and gives that the density of carbon fiber is about 5 times less than that of steel. [3] Therefore, a significant amount of weight

can be cut from a formula car by using carbon fiber tubes, while maintaining the stiffness of the tubes similar to that of steel tubes.

### **3.3 Disadvantages**

The main disadvantage of carbon fiber is that it does not yield but rather shatters when loads greater than it can handle are applied to it. While most carbon fiber tubes are really strong in tension, they are not as strong in compression and that can sometimes be a disadvantage. One very important factor to keep in mind however, when choosing what kind of carbon fiber tubes to choose for any type of design is that the material properties of the tubes vary from manufacturer to manufacturer. A pultruded tube from one manufacturer may have significantly different properties from another manufacturer, and same goes with roll-wrapped tubes. Carbon fiber does not behave as nicely as some common metals like aluminum or steel in the manufacturing process so any type of tube choice needs to be carefully thought out and experiments on the specific tubes are highly recommended.

## **4.0 Mechanical Design**

### **4.1 Tube Size**

Tests to find appropriate tube sizing were not performed but it is important to note that when carbon fiber tubes fail, most of the time it is under compression. Therefore, sizing your carbon fiber tubes for suspension members needs some testing. Fracture and fatigue testing is necessary for sizing the tubes appropriately. A study was performed by a few CalPoly FSAE members and they determined

appropriate sized tubes for certain axial loads their models were giving them, but further tests may be necessary depending on the manufacturer the tubes are purchased from, and the alignment of the fibers in the tube. For further information regarding their study, see their report in the bibliography section of this paper. [2] For the design of a suspension roll-wrapped tubes are recommended because of their combination of axial and lateral strengths.

## 4.2 Aluminum Inserts

The aluminum inserts are a critical part of suspension design. The inserts are the pieces that connect the A-arm tubes to the frame of the car and they are responsible for transmitting forces to the A-arms. For testing purposes, inserts like the one shown below in figure 4-1 on the left were used. These inserts were designed with an extended shoulder length so that an Instron machine can grip them for pull tests. Actual A-arm inserts look more like the one in figure 4-1 on the right and they should be designed that way to save weight. The hole in the middle is threaded so a bearing insert can screw in and attach to the frame of the car.



**Figure 4-1: Insert used for experiments (left) and actual A-arm insert (right)**

The experimental inserts were also machined out of aluminum alloy 6061-T6 because of its low cost. It is important to note that Al 6061-T6 was just used for

testing, whereas in the actual suspension design, aluminum 2024 or 7075 alloys are recommended because of their higher strengths. A detailed drawing of the experimental inserts can be found in Appendix B.

### 4.3 Aluminum Etching

Analysis on different etching kits was not performed but through some research, it was determined that etching aluminum and coating it with alodine is a good option. The benefits of an alodine coating are that it prevents corrosion, and also makes the adhesive bond to the aluminum stronger. For these tests, the West System 860 Aluminum Etching Kit was used. It is a 2-part etching kit that comes with a clear-colored cleaner and a golden-colored alodine solution as shown in figure 4-2 below.



**Figure 4-2: West System aluminum etching and alodine coating kit**

There are also other aluminum etching products like the DuPont Acid Etch and Alodine solutions, but any aluminum etching kit will do. Specific directions on how to properly etch and coat the aluminum are in section 5.1 of this paper.

#### 4.4 Bond Gap Size and Bond Length

The bond gap between the aluminum inserts and the carbon fiber tube is one of the most critical parts of the carbon fiber suspension design. Research and experimentation suggests a bond gap of 0.004" - 0.012" for hot bonding, which is when the adhesive is heated to cure faster. For cold bonding, when the specimen is allowed to cure without any external heating, a bond gap of 0.008" is recommended. Theoretically the insert and carbon fiber tube both need to be slightly tapered in so that the shear stress in the epoxy under tension is spatially constant, but experiments were not performed to confirm this. [6] Figure 4-3 below shows the effects that tapering the inserts and tubes have on the adhesive.

Figure 6.16 Different Designs for Bonded Joints

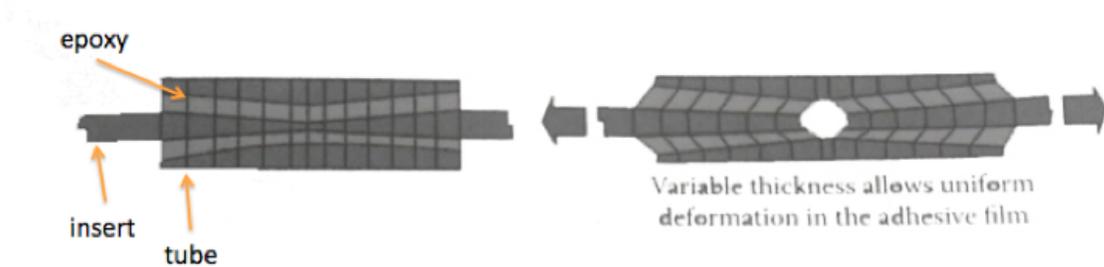


Figure 4-3: Figure showing the effect of a tapered tube/insert design

Experiments were also performed in a paper written in 2004 on the effect of bond circumference and bond length of inserts and it was shown that bond strength

scales linearly with bond circumference and approaches an asymptote with bond length. This is known as the Volkersen theory, which holds true for bonding flat surfaces together, but the experiments performed in the 2004 paper proved that the same concept is also true for cylindrical geometries. [7]

Experiments were also performed to verify this information with an epoxy adhesive, and results are shown in section 6.0 of this paper.

#### **4.5 Bond Gap Adhesive**

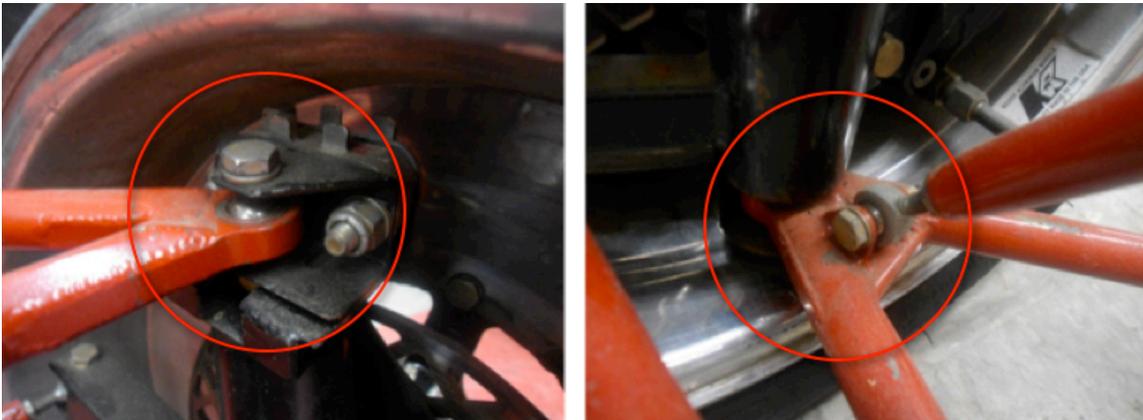
Like all other parameters in cylindrical bonding, the right adhesive must be properly chosen for the right job. In an ideal bond, the adhesive bonds tightly to the aluminum and carbon tube surfaces, and when the fracture happens it goes through the adhesive rather than detaching from the aluminum or tube surfaces. The correct way to have that failure is through surface preparation of the aluminum and carbon surfaces. A high shear strength adhesive is required for a strong bond. In a paper released by Loctite Industrial Adhesives, a comparison of different types of adhesives including acrylic based, urethane based, MMA, and epoxy was done and epoxy shows to have the toughest strength out of all the adhesives. [8] For the purposes of these experiments the adhesive used was Loctite Hysol E-120HP. It is a high strength 24 hour curing epoxy, shown in figure 4-4 on the following page.



**Figure 4-4: Loctite high strength epoxy used for pull test experiments**

## **4.6 Tube-to-Upright Attachments**

The tube-to-upright attachments are the pieces that connect the carbon fiber tubes to the uprights. A steel tube to upright attachment geometry is shown in figure 4-5 below.



**Figure 4-5: A-arm to upright attachment in MIT's 2010 car**

In a carbon fiber suspension design the tube-to-upright attachments would be made of high strength 2024 or 7075 aluminum alloys. No analysis was performed on these components of a carbon fiber suspension but the same experiments and data in the Testing and Results section of this paper are also valid for the bond strength of these

attachments to the carbon tubes. The only difference is that these tube-to-upright attachments have a different shape, the one on the left for the upper A-arm in figure 4-5 being V-shaped and the one on the right for the lower A-arm in figure 4-5 having a push rod connected to it. The part of these attachments that needs further analysis is the bearing that will connect these attachments to the upright. In figure 4-5 above, a bearing is installed into the steel attachments using a staking tool. In a carbon fiber suspension design, the bearing will be inserted into aluminum so the physics may differ, but that's not to say for sure. Design of these attachments is important and requires additional finite element analysis and testing.

## **5.0 Fabrication Techniques**

### **5.1 Aluminum and C.F. Tube Prep**

First the surface area of the aluminum inserts that will be bonded must be sanded and degreased. The inside of the carbon fiber tube that will be bonded must also be sanded and degreased. Brake cleaner or a similar type of degreaser can be used to degrease these components. After both surfaces have dried, they are ready to be etched. Pour enough West System cleaner solution in a cup so that the aluminum inserts are fully submerged. Follow instructions on the bottle and remove from the solution after 1-3 minutes. For these experiments, the aluminum inserts were left in the cleaner for 3 minutes and then removed. Now the inserts are ready to be coated with alodine. Contrary to what the directions may say on the West System Etch Kit, the inserts should be submerged in non-diluted alodine for a nice golden coating. Experiments were performed and if the inserts are not submerged

in alodine solution, they will not have a sufficient alodine coating and will not appear golden in color. For these experiments the inserts were submerged in the alodine for 5 minutes then removed, washed, and air dried. Figure 5-1 below shows what the inserts look like after being coated with alodine.



**Figure 5-1: Appearance of aluminum inserts after alodine coating**

The alodine is most effective within 2 hours of coating the insert therefore it is recommended to bond the inserts to the carbon tubes as soon as possible after they are coated with alodine and allowed to air dry. There are also several resources online on how to etch and coat aluminum, one great resource being YouTube for homemade tutorials. [9]

## **5.2 Tube to Insert Adhesion**

It is widely known that the preparation of bonding surfaces is one of the key aspects to an insert to tube bond. It is very important to centralize the insert in the carbon fiber tube so that the bond gap is uniform throughout the circumference of the insert. [6] There are several methods for centralizing the insert in the tube. One method is designing and carefully fabricating a fixture or jig. This method takes

some time to fabricate and is specialized for a specific tube size. Another method is using a tiny amount of microbeads or a similar spacer that can be mixed in with the epoxy and give you the specific bond gap you are looking for. It is suggested by some that microbeads may weaken the bond but further experimentation is required to confirm this. A third method, also the one used for these experiments is using a small amount of some kind of shim or tape to set the gap size and centralize the insert in the tube. Flashbreaker tape was used in these experiments to centralize the insert in the carbon tube, as shown in figure 4-1 on page 16. The blue strips are the flashbreaker tape.

To properly bond the insert to the carbon fiber tube first prepare the two surfaces as suggested in section 5.1 of this paper. When it's time to bond the inserts to the tubes, take epoxy and spread it evenly on the inside of the tube. Then take epoxy and spread it evenly on the outside of the aluminum insert surface. Slowly insert the aluminum insert into the tube and spin it slowly so that the epoxy spreads evenly along the surface of the bond. Once the insert is all the way in the tube, wipe off any excess epoxy and allow the tube to cure overnight for at least 24 hours.

### **5.3 Carbon Fiber Sleeve Layup**

Two methods for laying up carbon fiber sleeves over a round surface with heat shrink tubing and heat shrink tape were found in the composite materials fabrication handbook and then tested. [5] Figure 5-2 on the following page shows the tests of the two methods compared to a specimen with no heat shrink tape or tubing used on it.



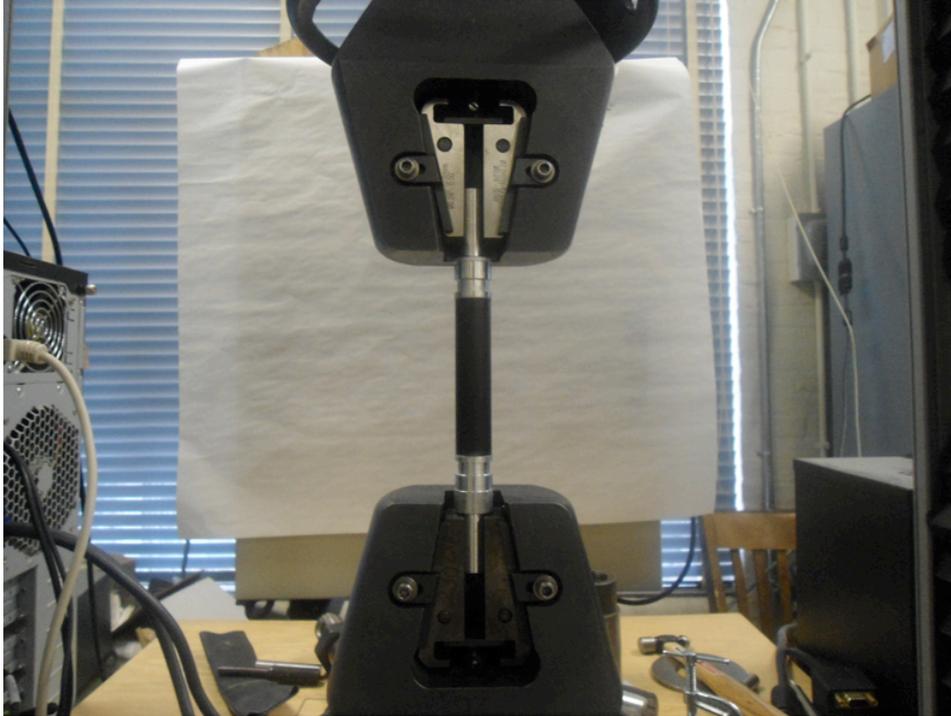
**Figure 5-2: Three methods for laying carbon fiber sleeves**

The first specimen from the top was epoxied without compressing the sleeve. The second specimen from top was epoxied and then heat shrink tape was wrapped around it to compress the fibers so that the cylindrical shape can be maintained. It has a slightly shiny surface and lines (not visible in the picture) where the edges of the heat shrink tape contacted the epoxy. The third specimen from top was layed on a tube and heat shrink tape was placed over it. It has a dull surface and it is tightly compressed onto the cylinder. These results may be useful if one decides to make their own carbon fiber tubes for suspension design. As mentioned earlier, fracture and fatigue tests must be performed on the tubes one manufactures if they are to be used in suspension design.

## **6.0 Testing and Results**

## 6.1 Pull Test Experimental Setup

The pull test experiments were all performed on an Instron machine found in the MIT 2.002 laboratory. A picture of the experimental set up is shown in figure 6-1 below.



**Figure 6-1: Pull-test experimental setup on an Instron machine**

The jaws of the Instron machine grip on the aluminum inserts and then pull the inserts apart until failure.

## 6.2 Surface Preparation Results

As mentioned earlier, surface preparation is an important part of the bond that can not be ignored. Tests were performed on 2 specimens with no surface

preparation and 13 specimens with surface preparation and the results were dramatic. The average pull force per area is shown in table 6-1 below.

**TABLE 6-1: Average force per area for surface preparation tests**

Surface Preparation	Avg Force/Area [lbs/in <sup>2</sup> ]
No surface prep	623.6
Surface prep	2382.6

The specimens that had surface preparation turned out to be about 4 times stronger than the specimens with no surface preparation. It is important to note that the flashbreaker tape used to centralize the insert in the tube covered about 0.15 inches of the bond length so in reality the effective non-taped bond length is reduced by 0.15 inches for each bond. This was not taken into account for the areas calculated for the results in Table 6-1, above, so in reality the bond for the surface prep specimens is stronger than what is listed in Table 6-1. The specimens with no surface preparation were also not centralized in the carbon tube, and the tube surface was not prepared either. The specimens with surface preparation were first sanded, then degreased, chemically etched, and then coated with alodine as recommended in section 5.1 of this paper. The inside of the carbon tube was also sanded and degreased.

### 6.3 Varying Bond Gap and Bond Length Results

Pull tests were performed on 12 specimens of varying bond gap and bond lengths. The tubes were pultruded carbon fiber tubes of average diameter 0.503 inches and a length of about 2.5 inches. The failure load per area was graphed for a range of bond gaps and is shown in figure 6-2 below.

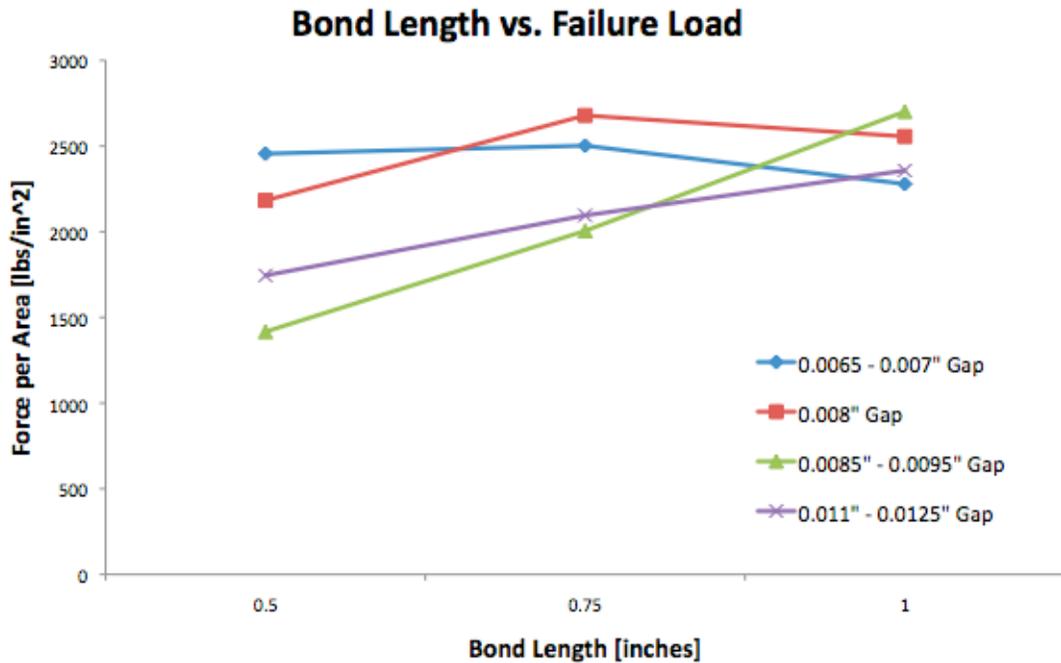


Figure 6-2: Failure load per area vs. Bond length for varying gap sizes

The data suggests that at 0.5 - 0.75 inch bond lengths a bond gap of 0.0065-0.008" is strongest with bond strengths between 2200 and 2700 pounds per inch squared. However, for the 1-inch bond length the data is a bit mixed and does not give an optimal bond gap. It is important to note that all of these specimens failed at the surface of the epoxy to tube or epoxy to insert interface. This means that the data

does not give any information about the shear strength of the epoxy itself but rather how well the epoxy bonded to the aluminum and carbon fiber surfaces, which can include human errors. As mentioned in section 6.2 it is also important to note that the flashbreaker tape used to centralize the insert in the tube covered 0.15 inches of the bond length. The forces per area calculations in Figure 6-2 on the previous page, did not take this reduction in area into account. More detailed pull forces on each specimen can be found in Appendix C.

## **7.0 Conclusion**

Through experimental data, a relationship between bond length and force per area to pull out an aluminum insert from a carbon fiber tube was determined. Methods for surface treating, centralizing and bonding the aluminum to the carbon fiber tubes were also developed. This data could prove useful for designing the suspension members of a formula SAE car out of carbon fiber tubes. The parameter that was kept constant in all the experiments was the adhesive used, however it was not chosen at random, but rather chosen for its high shear strength.

The aluminum inserts and carbon fiber tubes were surface treated for better adhesion to the epoxy and it was shown that with the correct surface treatment the bond strength can increase by 400% compared to no surface treatment at all. An average bond strength of 2,382.6 pounds per inch squared was determined for the specimens that had surface treatment. Furthermore, a bond gap of 0.0065 to 0.008 inches gave the strongest bond of about 2200 to 2700 pounds per square inch for bond lengths between 0.5 to 0.75 inches.

Experiments or research on carbon tube sizing was not provided in this report, however it remains as an area that needs further research and testing for the design of carbon fiber suspension members. Further research, testing, and finite element analysis is also required for designing the tube-to-upright elements of the suspension system.

## **7.1 Future Recommendations**

Further analysis such as fatigue and fracture testing on carbon fiber tubes is recommended for proper tube sizing. As mentioned earlier carbon fiber tubes vary greatly from manufacturer to manufacturer and therefore one cannot assume that all tubes will have the same or even similar properties. Another area of future experimentation and analysis is the tube-to-upright attachments. A method to install bearings to these attachments must be developed and tested under appropriate loading conditions that these bearings will see on the race track.

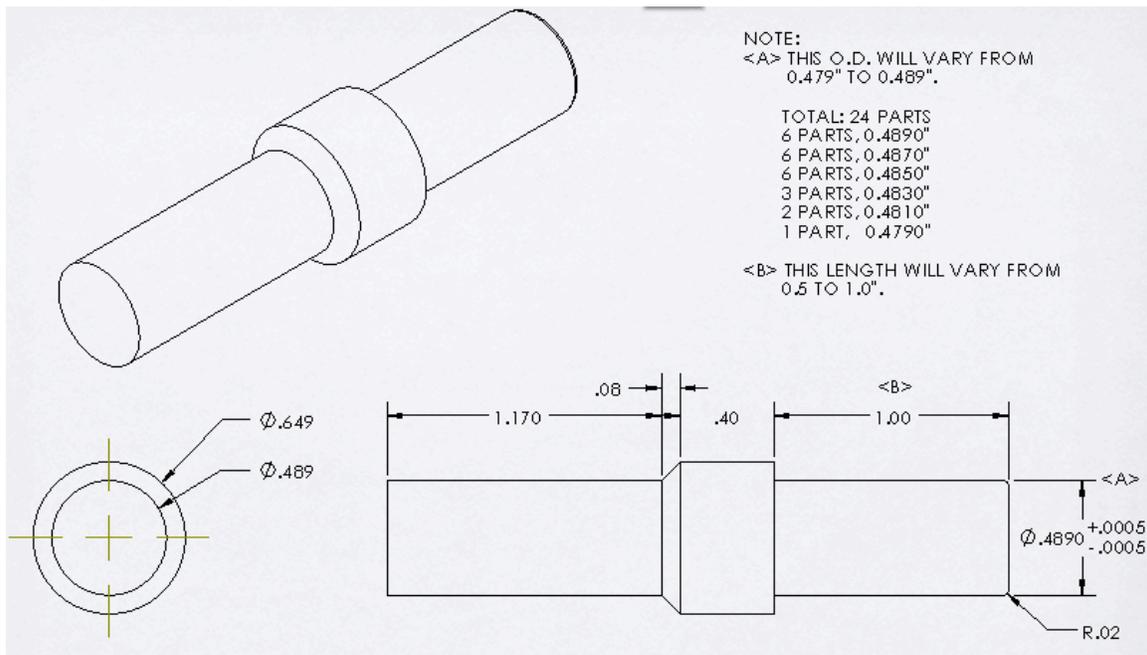


## 8.0 Appendices

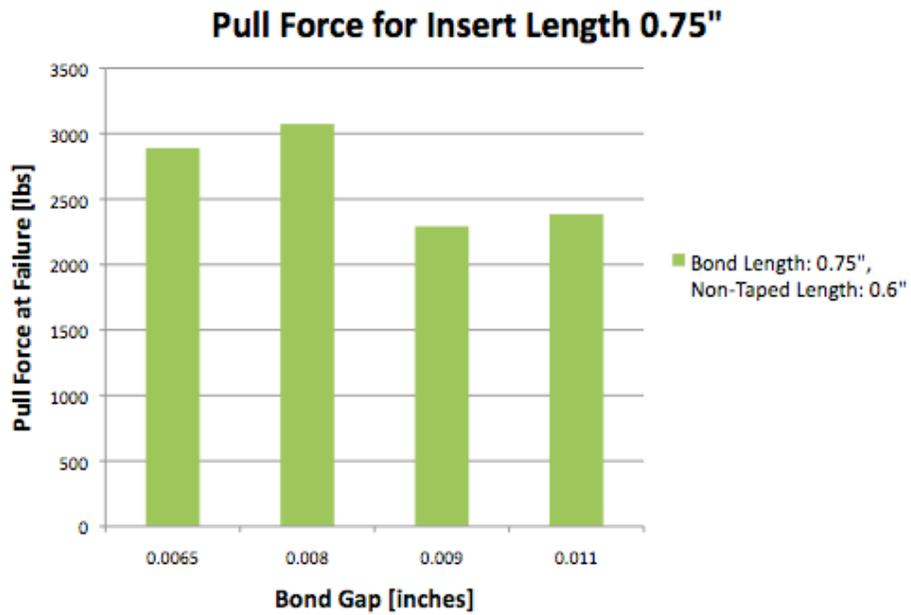
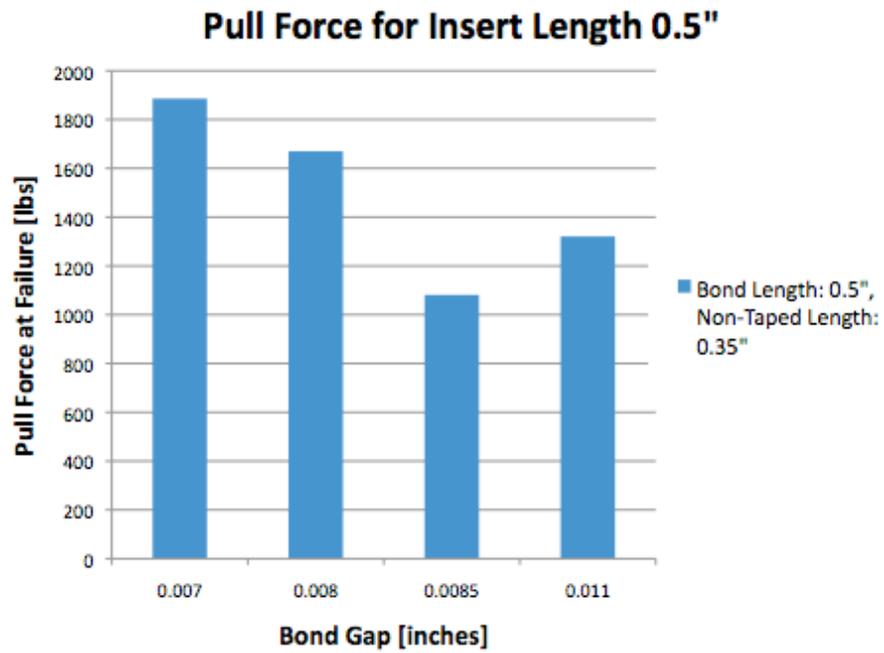
### Appendix A: MIT's 2011 Car A-arm Weight

Suspension Member	Weight [lbs]
Front Left Upper A-arm	0.670
Front Left Lower A-arm	0.980
Front Right Upper A-arm	0.670
Front Right Lower A-arm	0.895
Rear Left Upper A-arm	0.772
Rear Left Lower A-arm	0.860
Rear Right Upper A-arm	0.776
Rear Right Lower A-arm	0.855
<b>TOTAL</b>	<b>6.490</b>

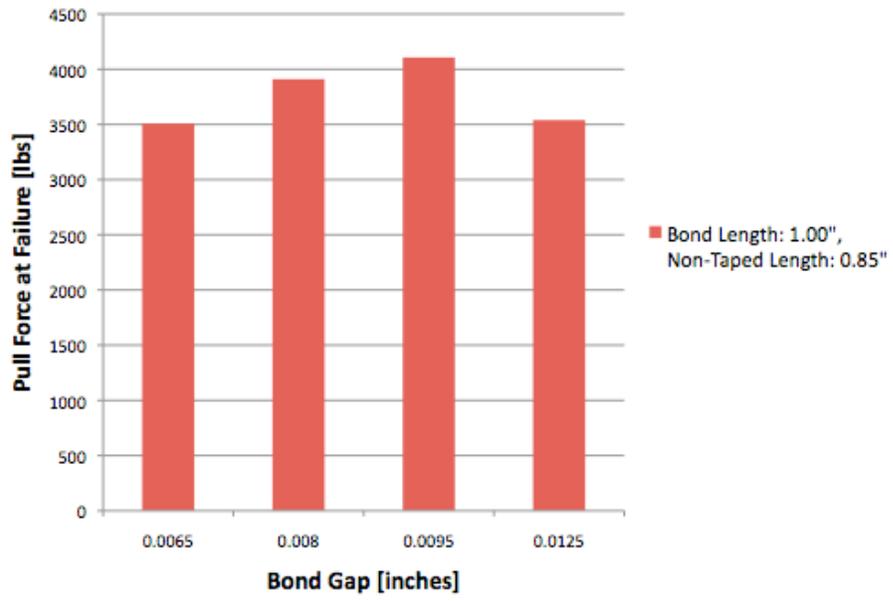
### Appendix B: Insert Used for Experiments



## Appendix C: Pull Force for Each Specimen Tested



### Pull Force for Insert Length 1.00"





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