# Structural Carbon Fiber Research and Design for uses in Baja SAE

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## ABSTRACT

The Michigan Baja Racing team is a part of the Baja SAE Design Series that designs, builds, tests, and competes a single seat off-road race car in various competitions across North America. In order to further improve the success of the team in the overall competition, research and design of carbon fiber components was done in order to compare the potential weight and moment of inertia savings versus the increased cost of the cost report. Specifically, Michigan Baja Racing wanted to research the ability to use carbon fiber in its tie-rod, steering column, and wheels. Tests were then performed to determine ideal carbon-to-aluminum bond preparation parameters as discussed in the tie rods results section. Using the ideal bond, maximum tensile and torsional load of the carbon-to-aluminum bond were compared and correlated as discussed in the tie rod and steering column results section. Finally, computer simulations were run to determine the optimal wheel design as discussed in the wheel results section. It was found that while the carbon fiber steering column and tie rods were able to withhold the challenges of the competition while not adding a significant penalty to the cost report, the carbon fiber wheels were far too costly and risky to be implemented.

## INTRODUCTION

Successful execution of carbon fiber component design is largely rooted in advanced computational abilities of models, minimizing imperfections in the component manufacturing to limit from deviation of expected behavior in application, and copious amounts of verification and validation testing. Although the process to design and successfully implement a structural carbon fiber component onto our baja vehicle is fairly similar in process, for different applications, different amounts of work and resources are required. This paper will discuss the development of three different carbon fiber components- a carbon fiber steering column, carbon fiber tie rods, and carbon fiber wheels - to be used on the University of Michigan Baja Racing competition vehicle. A discussion of the work done developing all three components, the resources needed for implementation, and challenges faced during the implementation of each component will also be included.

### Steering Column

In order to reduce mass in the steering column, a carbon fiber equivalent was researched to replace the existing aluminum column. In order to validate components off-car, a design of experiments (DOE) was setup to determine the best bonding methods, and the relationship that exists for bond length and maximum withstandable force. Through this exploration other opportunities to save weight were analyzed to further optimize the performance of the vehicle.

### Tie Rod

The desire to develop a carbon fiber tie rod came from the weight loss and shortened manufacturing time of a carbon fiber version resulted in over the previously used aluminum design. After successful implementation of a steering column was achieved, a design for a carbon fiber tie rod would required mostly extensive verification and validation testing to confirm success in competition applications. The component itself rarely sees high loads, but in extreme cases is vulnerable to unpredictably high loading based on the nature of many competition obstacles. The need for the component for successful completion of the majority of  competition events is why extensive knowledge of the failure mode and loads of tie rods to be used on the 2018 vehicle is required for implementation. In order to validate the tie rods full tensile testing was completed in addition to full vehicle testing.

**Wheels**

Three factors drove the decision to look into developing carbon fiber wheels for a baja vehicle. One, carbon fiber wheels would immensely impact the overall weight of the vehicle and the unsprung mass of the car allowing for better suspension handling and improved top speed capabilities. Two, the decrease in the wheel would decrease the moment of inertia of the wheel and tire assembly allowing for less driving force required for acceleration of the rear tires. Three, the research required to potentially implement a solution would help satureate the team's overall knowledge base and understanding of carbon fiber design and application. As mentioned, it was clear from the start that successful implementation of carbon fiber wheels would be a demanding project in both time and resources as well as a very difficult one. For successful completion of the project, the wheel would not only have to go under routine loading, but the occasion direct impact of a blunt object to the wheel. Due to the need for impact resistance to the shatter-prone carbon fiber meant having to increase the safety factor and thicken the material at the outer edge of the wheel. In order to try and develop a successful carbon fiber wheel, optimizations were performed to determine the optimal load paths and amount of carbon fiber needed in order for the wheel to survive all the conditions of a Baja SAE event. After these optimizations were performed, a volume analysis and cost estimation were completed to determine the feasibility of running the wheels during competition.

## METHODS

The following section is used to describe the methods performed to analyze and ensure that all components were suited for on car use. Data was collected and analyzed, parts were designed and experiments were set up to fully validate all car components.

**Steering Column**

In order to develop a steering column suitable for the constant cyclical loading seen during a competition setting, a series of tests were performed. First, data was collected using strain gauges on an aluminum column to find the loading, failure of previous designs were analyzed and then a design of experiments was performed to determine the optimal bond characteristics desired.

*Collection of Application Load Data:* An important contribution to begin a design on the carbon fiber steering column was gaining some understanding of what loads the column would experience during different competition events. The steering subsystem is designed with the goal of having the weakest component be the tie rod because of its overwhelming ease of replacing, as compared to the remainder of the steering system, if a failure were to occur during an endurance race. As this is the case, the steering column is designed to withstand the aluminum tie rod buckling force which is 9882.4 Newtons. To more adequately refine the actual load case of the steering column in a competition-like environment, we strain gaged an aluminum steering column and ran it in both routine and irregular load cases scenarios.

Although it was initially believed that the column receives the entirety of the load applied at the tie rod, data correlated from a strain gaged column and tie rod suggests otherwise. In reality, only about 90% of the load from the tie rod is transmitted to the steering column. The strain gauge test set-up seen in Fig. 1, below, was used to determine the actual loads in the steering column. Given this load we were able to determine the routine and irregular, but possible loading scenarios of the steering system

Figure 1: Strain gauged steering column used to collect maximum torsional loads seen in routine loading to develop a baseline for the required strength of a carbon fiber steering column.

*Failure of Previous Designs:* Another understanding we needed to gain in designing the carbon fiber column was the actual failure point of the manufactured aluminum column to determine if we could produce a column that would be both lighter and stronger. An aluminum version of the steering column - which has a theoretical failure point of the buckling force, 9882.4 N or 240 Nm- when tested, actually failed at the weld at a value around 180 Nm of torque as seen in Fig. 2, below.

Figure 2: Aluminum column, failed at the weld, as expected, during on-car testing. This setup was strain gauged to determine the max loading the aluminum column was capable of withstanding.

*Design of Experiments:* In order to develop the ideal bonding characteristics, a DOE was performed to analyze the best choice of bonding epoxy, surface preparation, and bondline thickness as shown in Table 1, below. For epoxies, DP 460 and DP 8410 were used to compare their ultimate tensile strengths versus their bonding characteristics. Although DP 8410 had the theoretical higher bonding strength, the DP 460 was easier to work with and allowed for a longer work life. In order for the epoxy to have a good bonding surface with the both the carbon fiber and aluminum the surface must be roughened to allow ridges for the epoxy to cling to. To determine the best method of roughening the surface, sandpaper or scratching the surface was compared with using an engraving tool to create micro dimples in the surface. Bondline thickness was also compared. A bondline thickness of 15 and 30 thousands of an inch were compared to determine how thick of a bondline was needed to allow the epoxy to ideally bond the metal and carbon fiber.

Table 1: Describes the test matrix for the DOE. A comparison between DP 460 and DP 8410 epoxy, sand paper and sand blasting for surface preparation, and a 15 or 30 thousandths bond line thickness were compared to develop the best results for applications in Baja SAE.

| **Test** | **Epoxy** | **Surface Preparation** | **Bondline Thickness** |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | -1 | -1 |
| 3 | -1 | 1 | -1 |
| 4 | -1 | -1 | 1 |
| **Key** | | | |
| + | DP 460 | sand paper | 0.015 |
| - | DP 8410 | sand blasting | 0.03 |

*Torsion Testing:* After a DOE was performed to determine the best epoxy, surface preparation, and bondline thickness, we wanted to ensure that the shear strength remained the same when pulled axially and rotated. Since the carbon-aluminum bond always fails in shear through the epoxy, theoretically the maximum bond strength will be related to the radius of the tube. In order to fully validate the system, the test samples shown in Fig. 3 and Instron test setup shown in Fig. 4 below were created to test the ultimate torsional strength of a mock steering column. Slugs of the desired bond length were made and welded to aluminum blocks to fit into a torsional Instron machine at Ford Motor Company.

Figure 3: Shows the test samples with shortened versions of the steering column tube size for torsion testing in their fixtures.

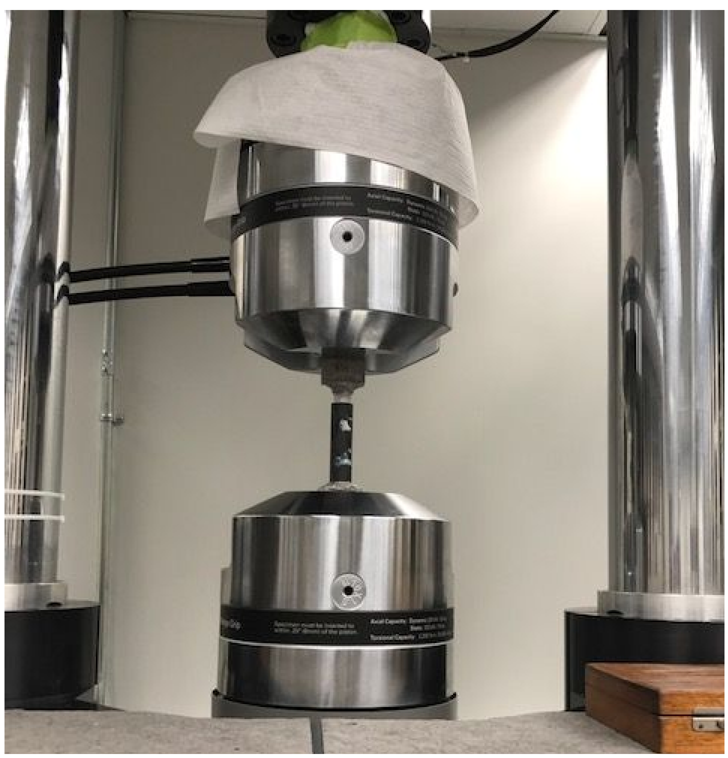


Figure 4: Test set-up of torsion testing at Ford Motor Company.

**Tie Rod**
In order to develop a carbon fiber tie rod able to withstand the rigor of a Baja SAE competition, the following methods were performed. First, to determine the design loads, data was collected to determine the stresses, the ideal bond preparation methods were determined through a DOE, validated through tensile testing, and then fully validated by driving for 4 continuous hours in an off-season competition.

*Collection of Application Load Data:* To determine the worst case loading aluminum tie rods were outfitted with axial strain gauges. Impact loads were tested to determine the highest loads in competition and rough obstacles. The maximum force was used to develop carbon tie rods theoretical failure point. Overall the worst load case that was able to be achieved in testing was 4000N in compression.

*Bond Preparation and Tensile Tests:* To further develop the best carbon-aluminum bonding another design of experiment (DOE) was performed to compare the different methods of bonding. The samples in Fig. 5, below, were tested according to the matrix in Table 2, below. In total, 54 samples were tested to compare use of honing, bond gap controller beads and increased curing temperature. Honing uses a special tool made for the inner diameter of the carbon fiber tube to help roughen the inner surface of the carbon tube. The rougher surface helps allow the epoxy to bond with the carbon fiber by creating a greater surface area for the adhesive. Adhesive beads or bond gap controller beads help keep the bond line thickness consistent around the slug and theoretically increase the bonding strength by limiting inconsistent loading of the bond. Some epoxies cure better at higher temperatures and can increase the bond strength, so a low temperature cure was also tested. Since a tie rod's primary point of failure is in tension/compression, all of the samples were tested in tension to approximate the maximum possible force the carbon tie rod would be able to withstand during a competition.

Figure 5: Shows all the test samples after being bonded and failed in tension. In total 54 samples were tested to determine a strong correlation.

Table 2: The test matrix for the DOE comparing honing, adhesive beads, and the curing temperature of the epoxy.

| Test | Honing | Adhesive Beads | Curing Temp |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | -1 | -1 |
| 3 | -1 | 1 | -1 |
| 4 | -1 | -1 | 1 |
| **Key** | | | |
| + | Honing | Adhesive Beads | Low Temp Cure [~170C] |
| - | No Honing | No Adhesive Beads | Room Temp Cure |

*On Car Testing:* Before putting any components through the rigors of competition, all components are validated in on car testing. The carbon tie rods were put on the car for component verification through a series of tasks. The component was first implemented at an off-season competition in October of 2016 to verify the proof of concept and ensure that there would be no unexpected failures during competition. Following this testing, more routine and extreme loading cases were tested with the car to ensure that it could withstand a Baja SAE competition.

**Wheels**

This section describes the methods used to develop a working model for a carbon fiber wheel and how we estimated the cost of the wheel in competition.

*Topology Optimization:* To gain an idea of how to optimally design a carbon wheel we decided to utilize optimization software for topology optimization. This would provide us with a general path forward on how to design the carbon wheel and how to make it manufacturable. After discussing with industry professionals on the best way to design and optimize a carbon fiber component, it was decided we would run topology optimization on the design to get desired load paths and a general design shape, and then would run composite optimization to determine the optimal direction of plys in the lay-up. For topology optimization, we used Optistruct optimization solver available as part of Altair Hyperworks. Optistruct optimizes based on different design responses. An optimization model can have a variety of drivers to push the model to a desired result. For our model we used driving constraints of volume fraction and mass. The constraint set on the optimization run was a volume fraction constraint of 0.3. This would not allow the optimization to take away more than 30% of the volume. The objective set on the model was to minimize mass. We did not set a constraint on stress, as we did not have a clear definition of what the maximum stress could be as it would change based on the quality of the layup and the final properties of the full lay-up. The optimization then ran through iterations of the design until converging on one that was feasible based on the criteria of the optimization. The resultant of the optimization provided a guide of where material needed to stay and where it could be taken away so that the design would still pass when run in finite element analysis (FEA) with the same load cases.

*Cost Estimation:* Before completing the modeling, design, and analysis of the carbon fiber wheels was completed, a cost analysis was performed. A part of the Baja SAE competition is a cost event to encourage being able to cost effectively build a vehicle. According to the series rules, carbon fiber composites made in house are costed at $150.76 per cubic inch. A volume estimation based on the results of the optimization results and comparisons using carbon fiber wheels was then performed.

**RESULTS**

This section is intended to detail the results of the methods section above. After months of performing simulations, collecting data, and testing samples, these are the results from the performed experiments.

**Steering Column**

This section is intended to detail the results of the steering column testing. The final steering column for the 2017 competition vehicle can be seen in Fig. 6, below. For complete calculations on how the carbon tie rod and steering column bond lengths and mass saving were determined, please see Appendix A.2.

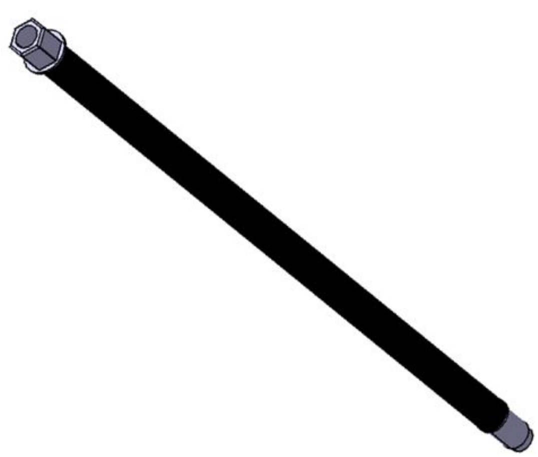


Figure 6: Computer aided design (CAD) of the final iteration of the carbon fiber column.

*Design of Experiments:* After completion of testing all tensile samples for the steering column, it was determined that the column could be designed to meet and exceed functional requirements of previous components. The peak forces achieved in the small tensile samples tested correlated to a required bond length that guaranteed a strong enough component that would also be 21.2% lighter than the previous design. The full calculation to determine the desired bond length of the column slugs can be reviewed in Appendix A.2.

*Torsion Testing:* The results of the torsion testing provided verification of the design as well as information on the failure mode of the carbon aluminum bond in torsion. The three samples tested were all designed to represent the final design for the vehicle component, excluding the fact that the length of the carbon tube was significantly shorter due to a restriction in the size limit of the Instron machine. In testing, samples were constrained with clamping force and one slug was kept stationary while the other was put into torsion application. The angle of rotation increased at a consistent rate until maximum torque appeared to be reached and maintained as seen in FIg. 6 below. The samples also appeared to maintain a portion of their original strength even after failure as the torque load did not automatically go to zero at the theoretical failure point of the bond. This was most likely due to high friction between the bond surface, even after failure.


Figure 6: Torsion testing results demonstrating the bond converging to a maximum withstandable load (~200 Nm) and maintaining that load until breaking at 40 degrees of relative twist.

**Tie Rod**

This section is intended to detail the results of the tie rod testing. Fig 7, below, shows the carbon fiber tie rod used in competition. For complete calculations on how the carbon tie rod and steering column bond lengths and mass savings were determined, please see Appendix A.2.

Figure 7: The tie rod used in competition. The tie rod was able to maintain its tensile strength when compared to the aluminum version, while saving 50% in weight and being 18% thinner in diameter to improve packaging.

*Bond Preparation and Tensile Testing:* The tensile tests were performed to compare honing, adhesive beads, and curing temperature using carbon tubes and aluminum slugs to determine the desired bond length for the tie rod slugs and the effectiveness of the different surface preparation and curing characteristics. In terms of consistent failure, samples failed pretty consistently. As seen in figure 8, below, in some cases when samples were not prepared to specification, the failure point and method differed from the expected. In the specific example shown below, the entry hole for the adhesive was too close to the end of the tube and caused a stress riser at that point in the tube. As a result, the carbon tube failed before the bond. Samples prepared out of specification were ignored in data analysis of the peak force held by the bond. Of the honing, adhesive beads, and low temperature curing, the honing had the greatest effect on the bond strength. The low temperature curing and adhesive beads had a minimal but positive effect on the bond strength.

Figure 8: Shows the failure method of the carbon aluminum differing from the expected failure mode of the sample at the bond.

*On Car Testing:* In order to fully validate the tie rod before a Baja SAE competition, a test tie rod was made to be run at an off-season competition and in numerous heavy loading events at the test track to simulate routine loading. During the competition the vehicle endured a rollover which broke the lower control arm, but left the tie rod intact as well as lots of hard testing specifically loading the tie rod. It was in the 12th hour of testing that the carbon tie rod finally failed to to an extreme roll over scenario, that was determined would also have buckled an aluminum tie rod. Through this testing it was determined that the tie rod would be robust enough to handle the constant loading in a Baja SAE competition.

**Wheels**
This section is intended to detail the results of the carbon fiber wheel design.

*Optimization Analysis:* After running topology optimization on the carbon fiber wheel with a load representing the worst loading case - a direct impact to the wheel as seen in Fig. 9 below - the resultant models provided information on how material would need to be distributed. The optimization results suggested we would want a bulk of material around the rim of the part- as expected- and would also tend to a design including spokes as is commonly seen in industry. The optimization see Fig 10. below did not turn out to be overwhelmingly insightful in determining the design of the wheel, but did provide a standard of where and where not to remove material for a successful final part.


Figure 9: Load case for the finite element analysis (FEA) was picked to represent a load case seen in real life. Pictured an aluminum wheel with a sizeable dent after a day of testing.

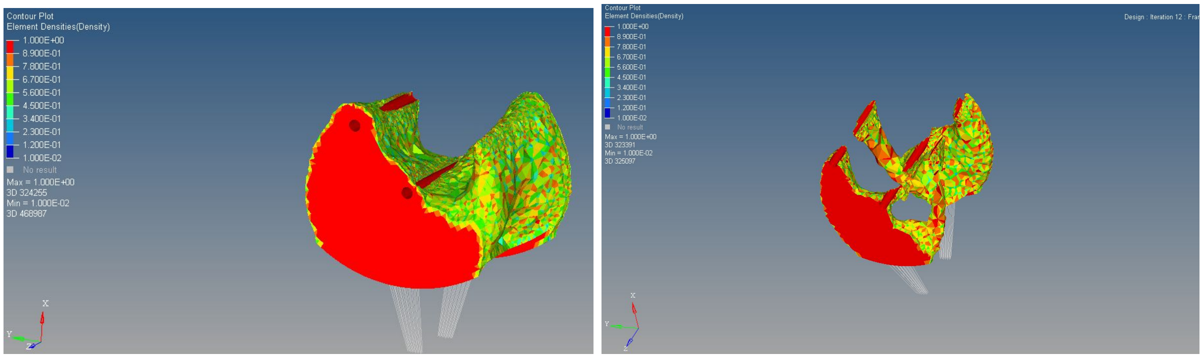



Figure 10: The upper limit for volume fraction constraint of the optimizations equals 0.3. To see all optimizations, please refer to the Appendix A.1.

*Cost Analysis:* After analyzing the optimization results, an estimation was made as to the cost report cost of the overall vehicle. It was estimated that with an average thickness of 60 thousandths of an inch for the carbon fiber wheel would have a volume estimation of 6.4 cubic inches and a resulting cost of $805.16 per wheel.

## DISCUSSION

The results from the experimentation showed many promising results for the uses of carbon fiber in Baja SAE. Through the use of carbon fiber it was proven to be an effective way to reduce mass from the vehicle and increase the overall performance of components like the tie rod and steering column. After further analysis, carbon fiber wheels were not identified to be a viable option for competition due to their massive increase to cost and resultant loss of point in competition.

### Tie Rod

The carbon fiber tie rod was able to reduce the mass of the system by 50% as well as help improve the packaging for the front corner. Due to the higher strength to weight ratio of the carbon fiber tube, the OD of the tube was able to be reduced in order to improve the clearance between the upper and lower control arm over travel. By determining the ideal bonding methods between aluminum and carbon fiber allows for extrapolation for future innovations. After fully testing the system for 12 hours, tensile testing past the maximum force recorded in testing, and comparing different bonding methods with one another the system was validated to have complete confidence in their ability to perform successfully at competitions.

### Steering Column

In developing the steering column we were able develop a correlation between tensile and torsional carbon to aluminum bonding. In order to maintain reverse compatibility, a carbon column the same OD as the aluminum column was used, but resulted in a 21.2% mass savings by switching to the carbon column over aluminum. By comparing epoxy, bondline thickness, and the surface preparation we were further able to determine the best bonding methods and ensure a repeatable bond. After developing a desired bond and torsion testing the samples to ensure consistent reporting with tensile and torsional data it was determined that the carbon fiber steering column would be able to withstand competition loading.

**Wheels**
The carbon fiber promised a lot in their ability to reduce weight and moment of inertia, but lacked in their ability to manufacture and their high cost. Optimizations were completed to determine the optimal load path and the layers of materials needed. Although design was not fully finished, this data was used to create a cost benefit analysis. The wheel was estimated that at minimum a 50 thousandths of an inch average ply thick around the wheel ended in a minimum volume of carbon fiber to be approximately 5.34 cubic inches. Due to Baja SAE's rules dictating that carbon fiber parts be priced at $150.76 per square inch, the estimated total cost of a singular carbon fiber wheel would be $805.16. The aluminum equivalent wheel is $64, resulting in an increase of 12.5 times the amount for the carbon fiber wheel or nearly half the price of the entire 2017 competition vehicle for a set of the carbon fiber wheels. At this point, it was determined that further time designing the wheels was not effective and would not make a suitable option to replace the current aluminum wheels and the time was better spent optimizing and improving other components.

## RECOMMENDATIONS

This research provided many important things for the Baja Racing team. Not only did it allow the team to dedicate resources and time into researching challenges with implementing lightweight carbon fiber components onto our car, but it also resulted in the successful implementation of different components onto the car and created a beginning knowledge center to reference for future carbon fiber designs. Although the research provided the team with many resources, there were limitations and research that could be expanded and improved upon. In retrospect, improvements to be made include:

- An exponential increase in sample size and bond characteristics tested
- More consistent sample preparation procedure
- More access to torsion instrons for further torsion testing

These recommendations will be discussed in the following paragraphs.

One recommendation that would have immensely improved our data and certainty in designs being representative of reality would be an increased sample size for all testing and an increased range of bond characteristics tested. In the time we had, we were able to test four unique bond characteristics, but in research were able to identify many other characteristics that could have a significant effect on the strengths of our aluminum-carbon bonds. Things especially of interest to look into would be the effect of honing the carbon tube, the use of adhesive beads for consistent bondline thickness, and low-temperature curing on bond strength. Although this testing would be very interesting, at this point it requires a large amount of time and money for little increase in weight savings as the only decrease in weight would be the minimal weight savings from shortening the slug.

Another recommendation that would be of interest to investigate in the future is a continued evaluation of the component manufacturing process and quantifying the standards needed to create a reliable and consistent part. In preparing the samples for testing, we learned a lot about standardizing preparation and how the process could be improved. Some of these process improvements include:

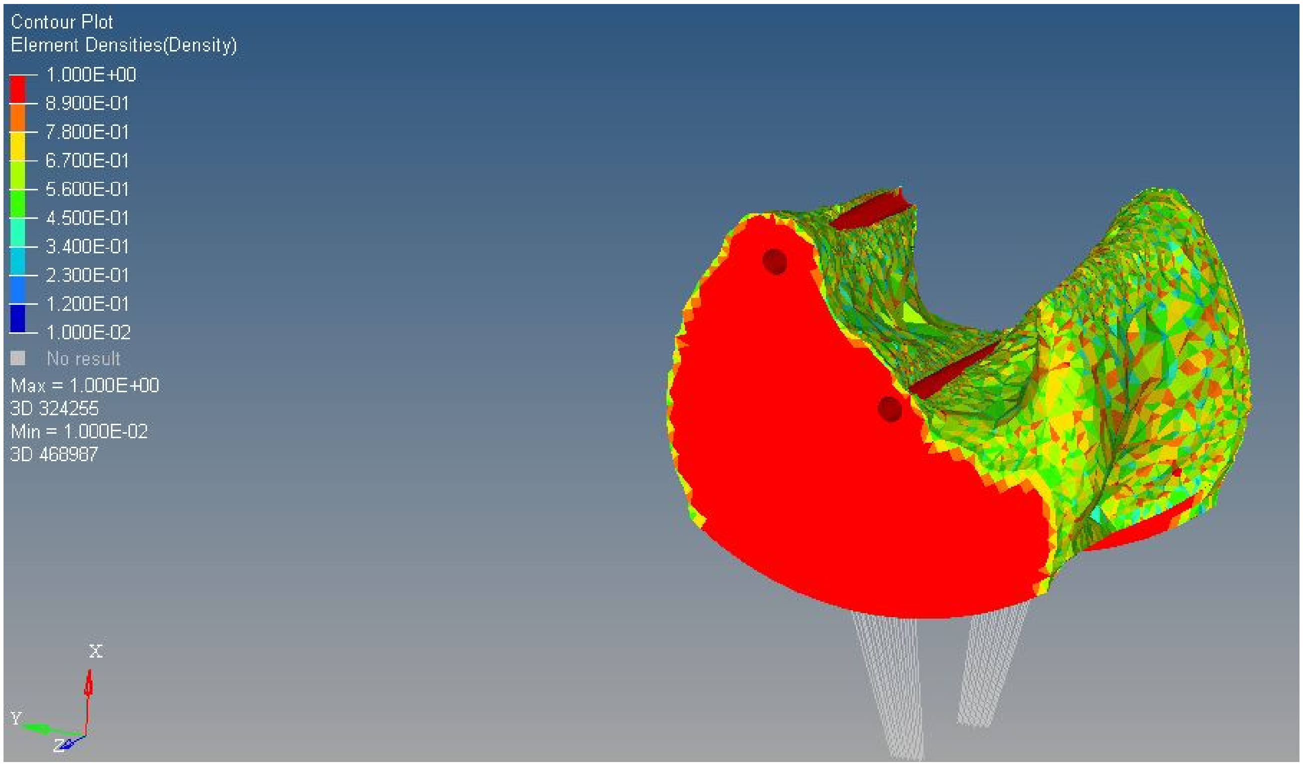
- A consistent way to evaluate the bonding surface to produce a replicated bonding surface
- A clean-room to manage bonding surface contamination
- Documented procedures to provide standard instruction to make the samples all the same

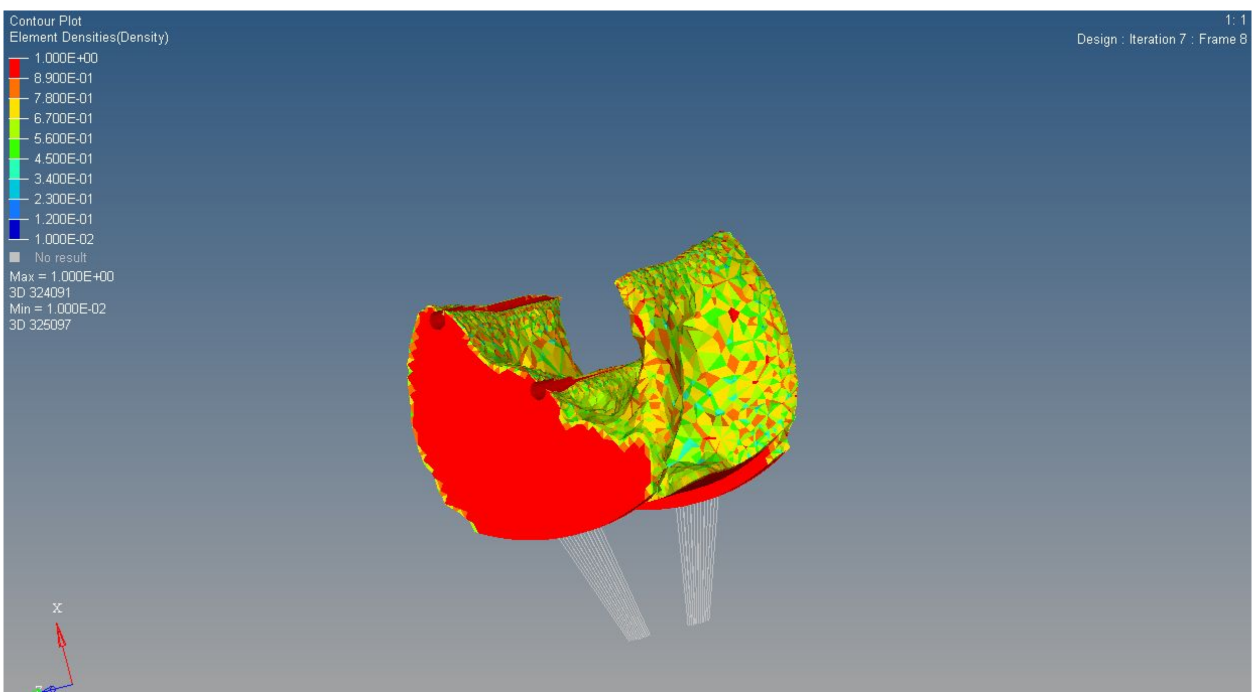
Increased access to torsion testing resources would have increased our data where it is lacking the most which is in torsion testing. Ford Motor Company provided us testing time on a torsion Instron machine. However; this machine had very strict length and fixturing requirements. The test samples that were able to be tested in the torsion Instron were not ideal representations of the column and required a lot of material and time to make. As a result, generating a large sample size was not feasible in the time we had to prepare test samples for torsion testing. If more time and access was available to the torsion Instron, the team's ability to predict results of carbon fiber-aluminum bonds in torsion applications would be greatly increased.

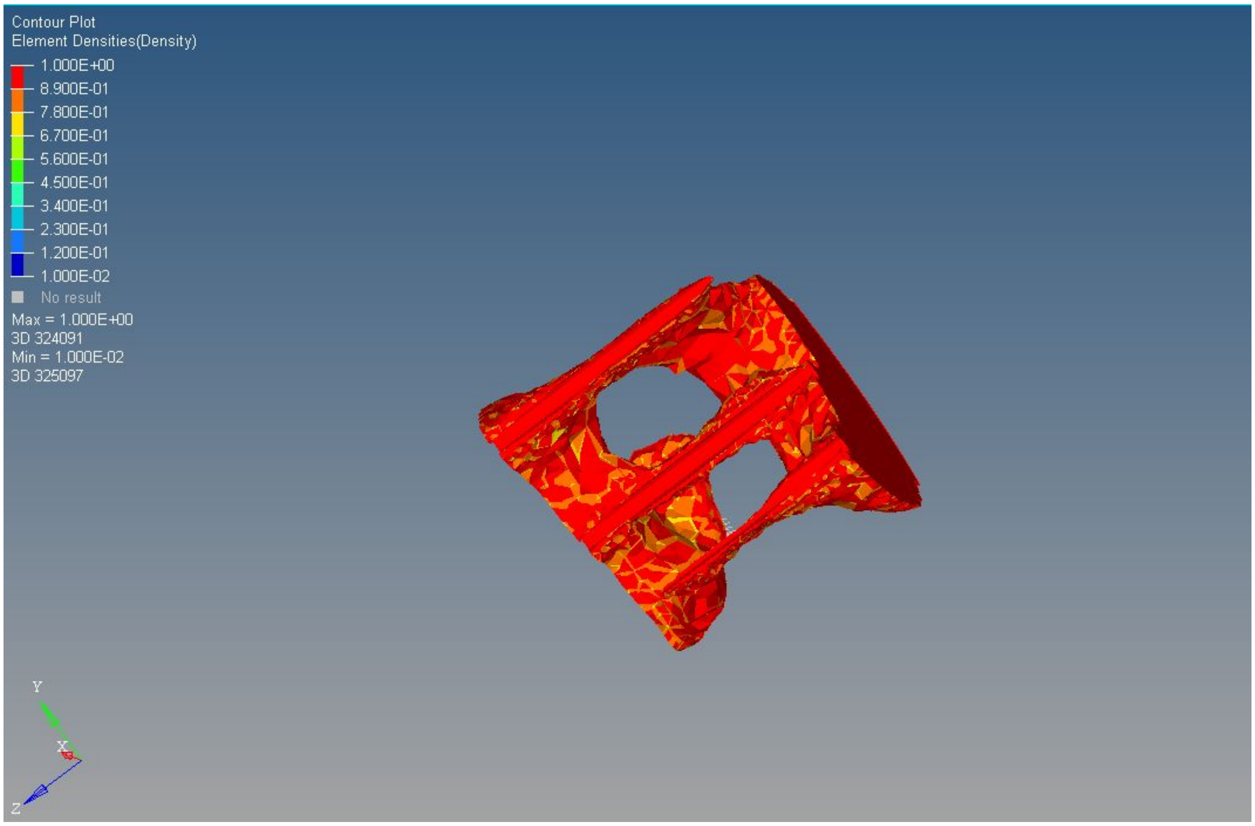
While many of the carbon fiber projects undertaken were successful in the goals of reducing weight and and increasing strength, the carbon fiber wheel project was deemed too risky and expensive to complete. After optimizing the shape of the wheel, running a cost analysis, and a risk assessment, the wheels were deemed to be too risky of a project to undertake and efforts to further improve the car were best used in other areas. In an analysis of the increase in the vehicle cost report it was determined that the carbon fiber wheels would increase the cost of the wheels by approximately four times that of an aluminum wheel. Coupled with the increase in the risk of fracture versus denting the rims it was decided to currently be unfit to use carbon fiber wheels for our applications in Baja SAE.

**APPENDIX**

A.1 - Carbon Wheel Optimization Iterations

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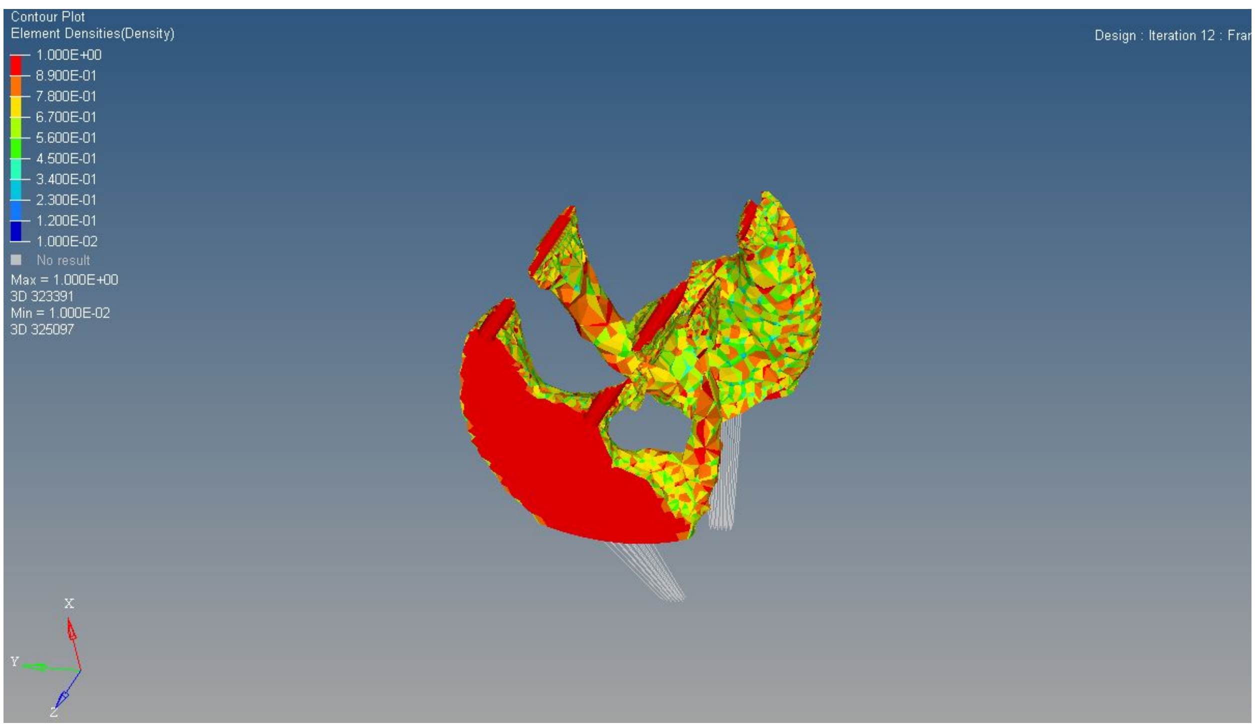
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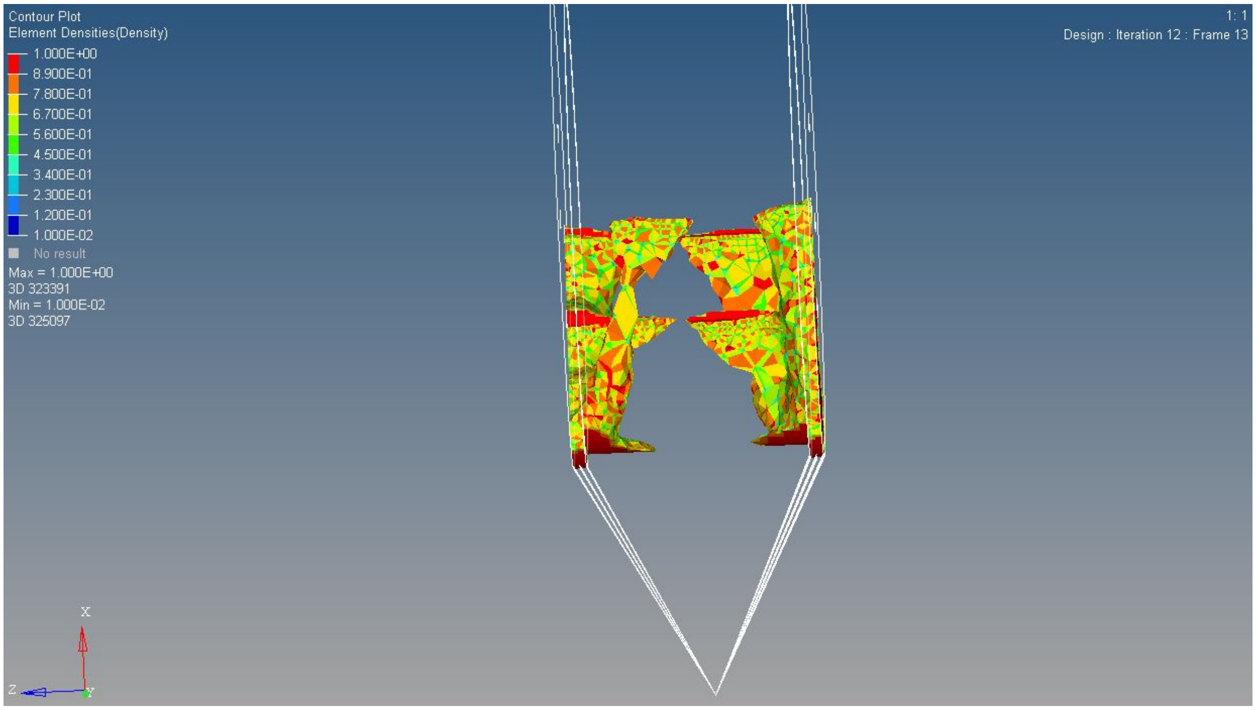
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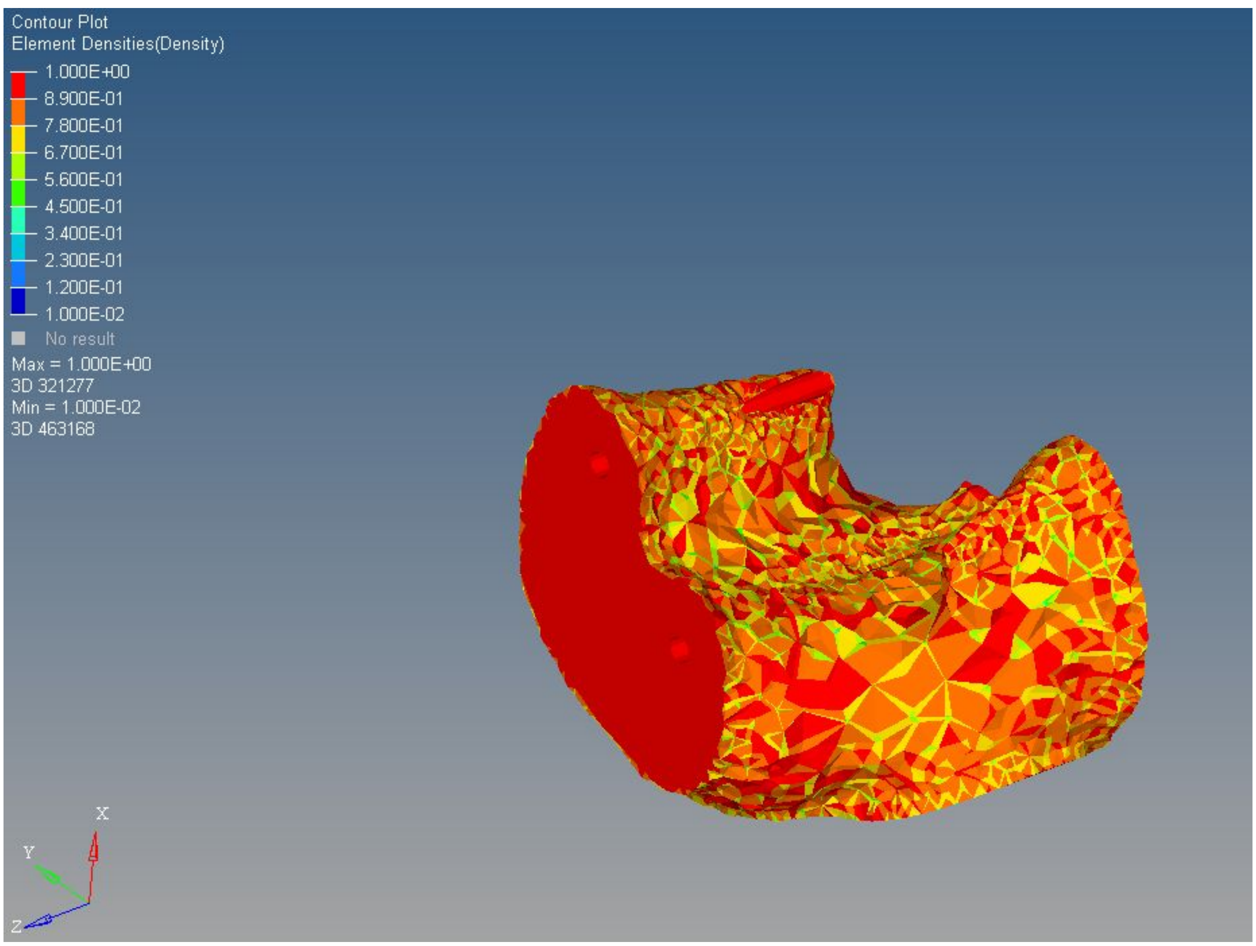
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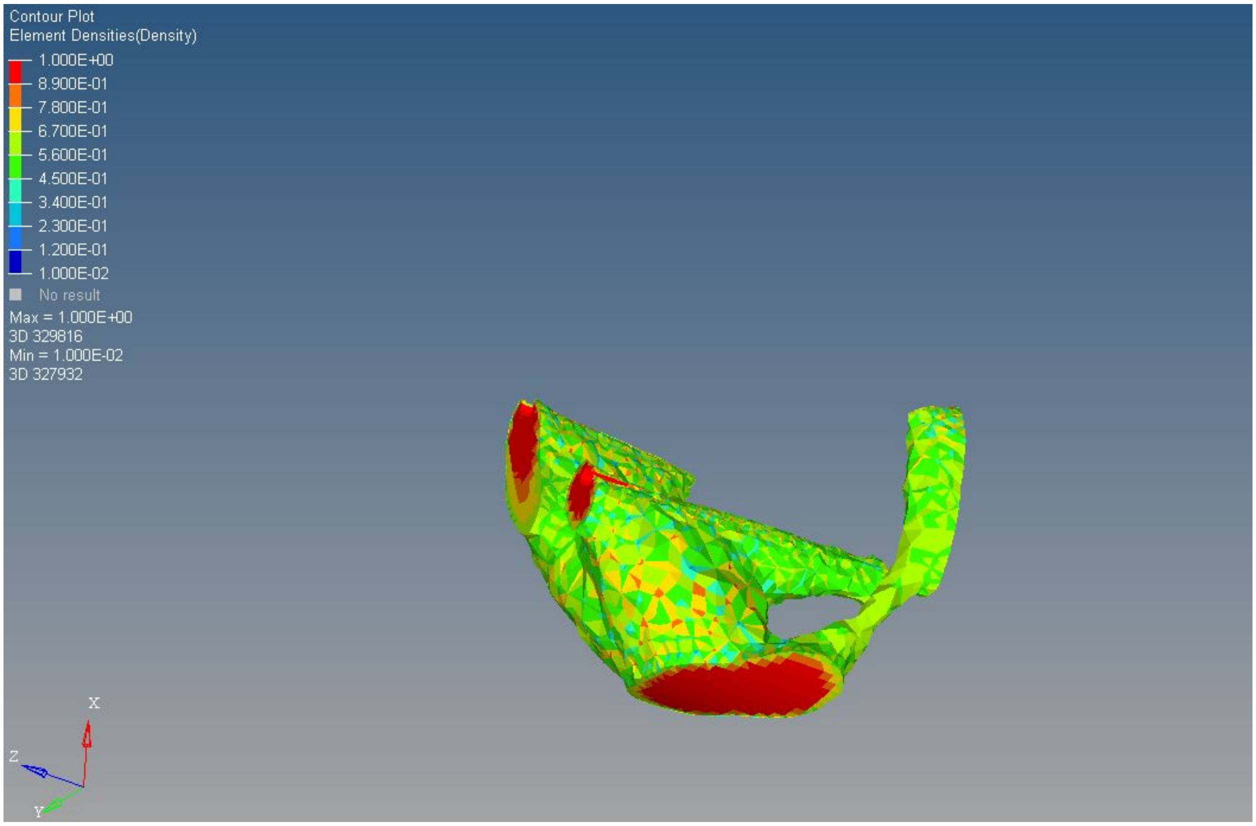
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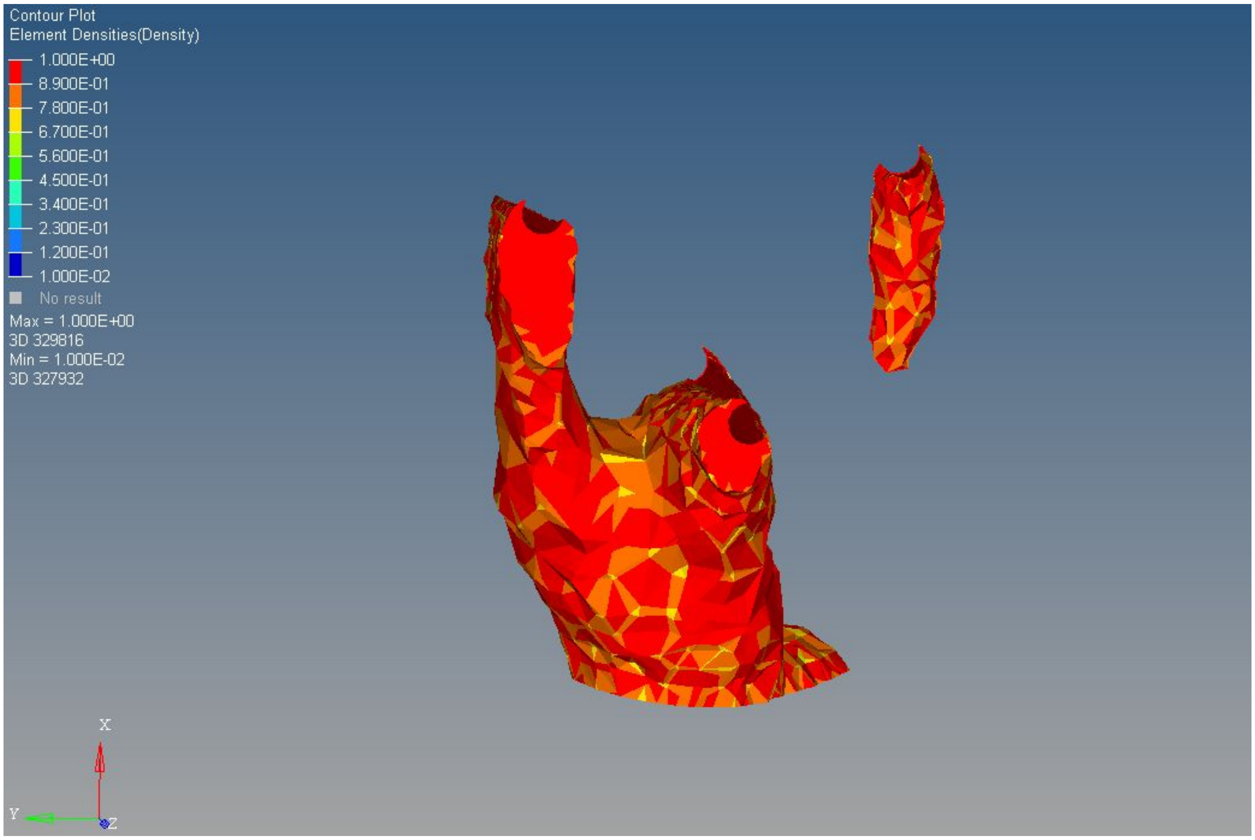
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## A.2 - Carbon Column Calculations

**COPIED FROM Z:\2016-2017\2017 CAD\Composites\Instron Testing\Results from testing**

| Test #_Sample # | Epoxy | Surface Preparation | Bondline Thickness (in) | Peak Force (kN) |
|---|---|---|---|---|
| 1_1 | DP460 | sp | 0.015 | 7.888 |
| 1_2 | DP460 | sp | 0.015 | 13.35 |
| 1_3 | DP460 | sp | 0.015 | 1.76 |
| 2_1 | DP460 | sp + etch | 0.03 | 9.777 |
| 2_2 | DP460 | sp + etch | 0.03 | 10.34 |
| 2_3 | DP460 | sp + etch | 0.03 | 10.66 |
| 3_1 | DP8410 | sp | 0.03 | 6.882 |
| 3_2 | DP8410 | sp | 0.03 | 5.295 |
| 3_3 | DP8410 | sp | 0.03 | 5.891 |
| 4_1 | DP8410 | sp + etch | 0.015 | 5.698 |
| 4_2 | DP8410 | sp + etch | 0.015 | 4.675 |
| 4_3 | DP8410 | sp + etch | 0.015 | lost value < 8 |

| **DOE** | | | | |
|---|---|---|---|---|
| 1_1 | 1 | 1 | 1 | 7.888 |
| 1_2 | 1 | 1 | 1 | 13.35 |
| 1_3 | 1 | 1 | 1 | 1.76 |
| 2_1 | 1 | -1 | -1 | 9.777 |
| 2_2 | 1 | -1 | -1 | 10.34 |
| 2_3 | 1 | -1 | -1 | 10.66 |
| 3_1 | -1 | 1 | -1 | 6.882 |
| 3_2 | -1 | 1 | -1 | 5.295 |
| 3_3 | -1 | 1 | -1 | 5.891 |
| 4_1 | -1 | -1 | 1 | 5.698 |
| 4_2 | -1 | -1 | 1 | 4.675 |
| 4_3 | -1 | -1 | 1 | 5 |

| | | | |
|---|---|---|---|
| 1 | **DP460** | sp | 0.015 |
| -1 | DP8410 | **sp + etch** | **0.03** |

**Conversion Factors**

| | |
|---|---|
| in to m | 0.0254 |
| in^2 to m^2 | 0.00064516 |
| N*m to in*lbf | 8.850745792 |
| N to lbf | 0.224809 |
| pa to psi | 0.000145038 |

| **Torque and Bond Length Calculations** | **Standard** | | **Metric** | |
|---|---|---|---|---|
| Bond area on all slugs in this testing batch: | 0.5761 | in^2 | 0.000371677 | m^2 |

| | | | | |
|---|---|---|---|---|
| lowest max tensile from this batch with set of variables to be used with steering column bonds: | 2197.957593 | lbf | 9777 | N |
| Max strain measured from Al stering column F16 MM (average of two half-bridges) | 7.00E-04 | strain | 7.00E-04 | strain |
| MM column OD | 1 | in | 0.0254 | m |
| MM column ID | 0.87 | in | 0.022098 | m |
| E column 6061 | 9.99E+06 | psi | 6.89E+10 | pa |
| Nu column 6061 | 0.33 | | 0.33 | |
| max stress calculated from MM | 5259.535895 | psi | 36263157.89 | pa |
| Polar modulus of section Zp | 0.083861358 | ___ | 1.37424E-06 | ___ |
| Torque calculated | 441.0718235 | in*lbf | 49.83433445 | N*m |
| Force calculated | 882.143647 | lbf | 3923.963343 | N |
| Load safety factor | 5 | | 5 | |
| Design force with safety factor (from MM) | 4410.718235 | lbf | 19619.81671 | N |
| Area needed for force seen with safety factor | 1.156079982 | in^2 | 0.000745855 | m^2 |
| Tube ID | 0.875 | in | 0.022225 | m |
| Bondline thickness | 0.03 | in | 0.000762 | m |
| bond surface ID | 0.815 | in | 0.020701 | m |
| Length needed for area | 0.451523543 | in | 0.01146868 | m |
| Tie rod buckling force | 2221.652462 | | 9882.4 | N |
| Distance from column centerline to rack | 0.958 | in | 0.0243332 | m |
| Torque calculated | 2128.343058 | | 240.4704157 | N*m |
| Bond surface ID | 0.815 | in | 0.020701 | m |
| Force calculated | 5222.92775 | lbf | 11616.36712 | N |
| Load safety factor | 2 | | 2 | |
| Force with safety factor | 10445.8555 | lbf | 23232.73423 | N |
| Area needed for force seen with safety factor | 2.737931511 | in^2 | 0.000883202 | m^2 |
| Length needed for area | 3.359425167 | in | 0.0426647 | m |

| | | | | |
|---|---|---|---|---|
| **Weight Calculations** | | | | |
| Density of 6061 | 0.0975 | lb/in^3 | 2.7 | g/cc |
| 2017 column length | 23 | in | | |
| Volume of al tube (MM al dimensions) | 4.391396751 | in^3 | | |
| Mass of al tube | 0.428161183 | lb | | |
| mass of upper slug for al (CAD) | 0.05 | lb | | |
| mass of lower slug for al (CAD) | 0.109 | lb | | |
| Mass of weld beads for al (guess) | 0 | lb | | |
| Mass of al system | 0.587161183 | lb | | |
| Carbon tube ID | 0.875 | in | | |
| Mass of carbon tube (website) | 0.239583333 | lb | | |
| Mass of upper slug for carbon (CAD) | 0.052 | lb | | |
| Mass of lower slug for carbon (CAD) | 0.097 | lb | | |
| Mass of epoxy for carbon (guess) | 0 | lb | | |
| Mass of carbon system | 0.388583333 | lb | | |
| | 0.19857785 | | | |
| % weight diff (carbon vs Al) | -33.8199894 | % | | |

| | | | | |
|---|---|---|---|---|
| Mass of upper slug for carbon LONG (CAD) | 0.079 | lb | | |
| Mass of lower slug for carbon LONG (CAD) | 0.119 | lb | | |
| Mass of carbon LONG system | 0.437583333 | lb | | |
| | 0.14957785 | | | |
| % weight diff (carbon LONG vs Al) | -25.4747511 | % | | |

| | | | | |
|---|---|---|---|---|
| **Bond Torsion Test Info - added F17** | | | | Plan: break |
| Torsion sample bond length | | | | |
| Torsion sample bond ID | | | | |
| Torsion sample bond area | | | | |
| Torsion sample 1 max load | 197.91 | N*m | | For these r |
| Torsion sample 2 max load | 196.01 | N*m | | |
| Torsion sample 3 max load | 191.02 | N*m | | |
| Torque to break 6061-t6 column | 196 | N*m | | |
| | | | | |
| Shear strength 6061-t6 | 207000000 | pa | 30000 | psi |
| J (of column we torqued to failure) | 1.74529E-08 | [metric] | 0.041930679 | [standard] |
| radius (of column we torqued to failure) | 0.0127 | m | 0.5 | in |
| Predicted failure torque | 284.4679788 | N*m | 2515.840745 | |