4-14-2020

Design of a Carbon Fiber Composite Monocoque Chassis for a Formula-Style Vehicle

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Recommended Citation

Carline, Alexander, "Design of a Carbon Fiber Composite Monocoque Chassis for a Formula-Style Vehicle" (2020). *Honors Theses*. 3235.
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Design of a Carbon Fiber Composite Monocoque Chassis for a Formula-Style Vehicle

ME 4800 – Senior Design Project

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Faculty Advisor: Dr. Kujawski

Spring 2020

Disclaimer

Abstract

Western Michigan University's Formula SAE team, Bronco Racing, designs and manufactures a formula-style vehicle to compete annually at an international collegiate design and racing competition. In order to remain competitive, Bronco Racing required a lighter chassis for the 2021 vehicle. To achieve this, the full 2020 carbon fiber monocoque chassis system was redesigned to be lightweight while considering packaging constraints, the Formula SAE rules, and design parameters set by Bronco Racing. The monocoque geometry was modeled using SolidWorks and the carbon composite was simulated, tested, and verified using ANSYS and quasi-static load frame testing. The newly designed 2021 monocoque chassis when compared to the 2020 decreases weight by 8.24 kg and cuts cost by $3,442.57. Also, a comprehensive manufacturing plan was then produced, allowing Bronco Racing to manufacture the monocoque to design specifications.

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Nomenclature

BR20 – Bronco Racing’s 2020 Formula SAE car

BR21 – Bronco Racing’s 2021 Formula SAE car

Chassis - The fabricated structural assembly that supports all functional vehicle systems. This assembly may be a single fabricated structure, multiple fabricated structures or a combination of composite and welded structures.

Spaceframe – Chassis made from steel tubes

Hybrid Monocoque – Chassis made from both carbon fiber and steel tubes (excluding roll hoops)

Frame Member - A minimum representative single piece of uncut, continuous tubing.

Monocoque – A type of Chassis where loads are supported by the external panels

Main Hoop - A roll bar located alongside or just behind the driver’s torso.

Front Hoop - A roll bar located above the driver’s legs, in proximity to the steering wheel.

Roll Hoop(s) – Referring to both the Front Hoop AND the Main Hoop

Roll Hoop Bracing Supports – The structure from the lower end of the Roll Hoop Bracing back to the Roll Hoop(s).

Front Bulkhead – A planar structure that provides protection for the driver’s feet.

Impact Attenuator – A deformable, energy absorbing device located forward of the Front Bulkhead.

FBH – Front Bulkhead

FBHS – Front Bulkhead Support

VSIS – Vertical Side Impact Structure

HSIS – Horizontal Side Impact Structure

MHBS – Main Hoop Bracing Support

SES – Structural Equivalency Spreadsheet

1 Introduction

1.1 Background

In 2019, Western Michigan University's Formula SAE Team, Bronco Racing, changed the vehicle chassis from a steel spaceframe to a hybrid monocoque chassis. This chassis begins at the impact attenuator anti-intrusion plate and continues through to the main roll hoop.

As seen in Figure 1, after the main roll hoop, a steel subframe is used to connect the rear wheels and engine assembly to the rest of the vehicle. This setup was chosen as it provided the easiest entrance to a carbon composite chassis. The hybrid monocoque design shown was carried over to the 2020 Bronco Racing vehicle (BR20) without changes.

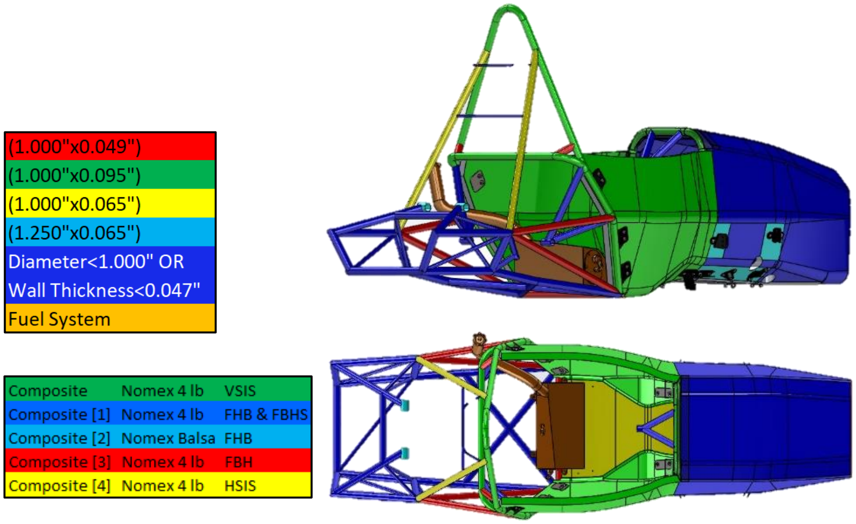


Figure 1 - 2020 monocoque laminate details

2 BR20 Drawbacks

Due to BR20 being a first iteration design, there are multiple areas of issue or lack of development. These areas are laminate design and simulation, packaging considerations, and manufacturing quality.

2.1 Laminate Design

The BR20 composite chassis only utilizes four different laminate designs. This was done for simplicity and ease of testing. However, doing this results in an extremely overbuilt chassis. The BR20 chassis was designed in ANSYS ACP. The initial conducted simulations were not properly conducted to represent the “as built” chassis used in the vehicle.

As seen when comparing Figure 2 to Figure 3, the BR20 chassis simulation is not representative of the actual structure. The simulation assumes that balsa wood inserts are able to be molded to match the surface of the chassis. Realistically, these balsa pieces must remain flat. Additionally, the location of the beginning of the vertical side impact structure (VSIS) is not consistent between the two versions. For the actual manufactured unit, the VSIS begins after the front roll hoop and continues to the end of the chassis. Finally, the Front Bulkhead (FBH) laminate is shown to match that of the Front Bulkhead Support (FBHS). To pass front impact testing, this laminate is much thicker, however it was only shown in a more local simulation, and not carried into the full chassis simulation.

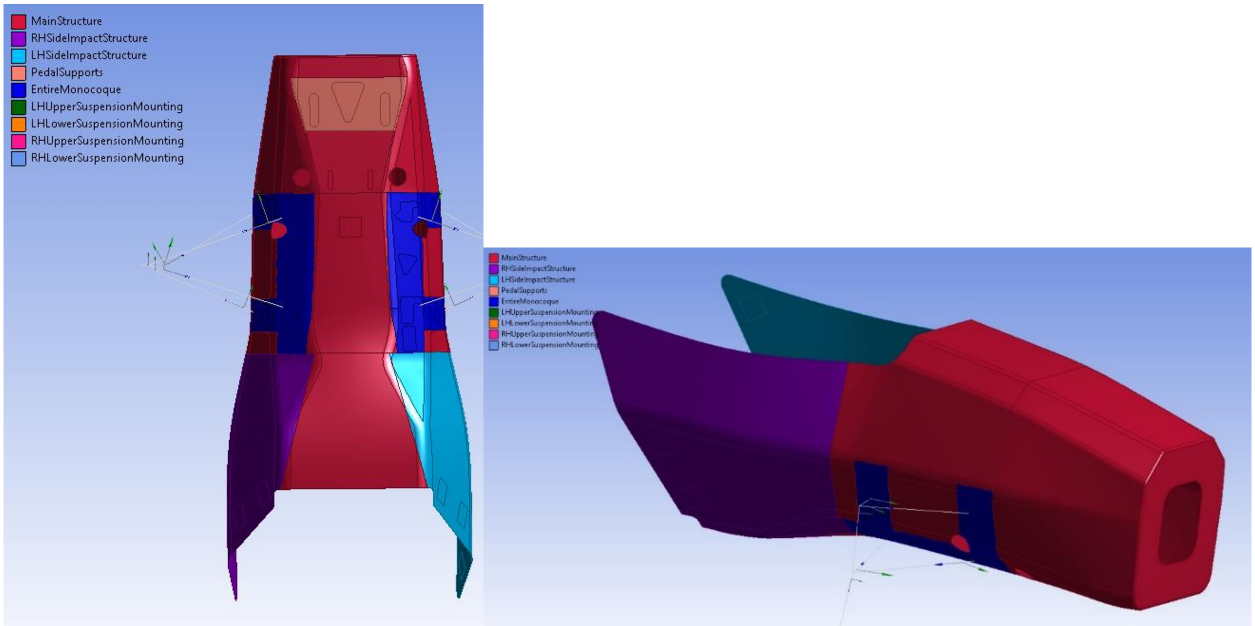


Figure 2 - BR20 incorrect laminate simulation

The beforementioned issues with the laminate simulation was corrected to provide a functional foundation to compare the BR20 to the BR21 platform.

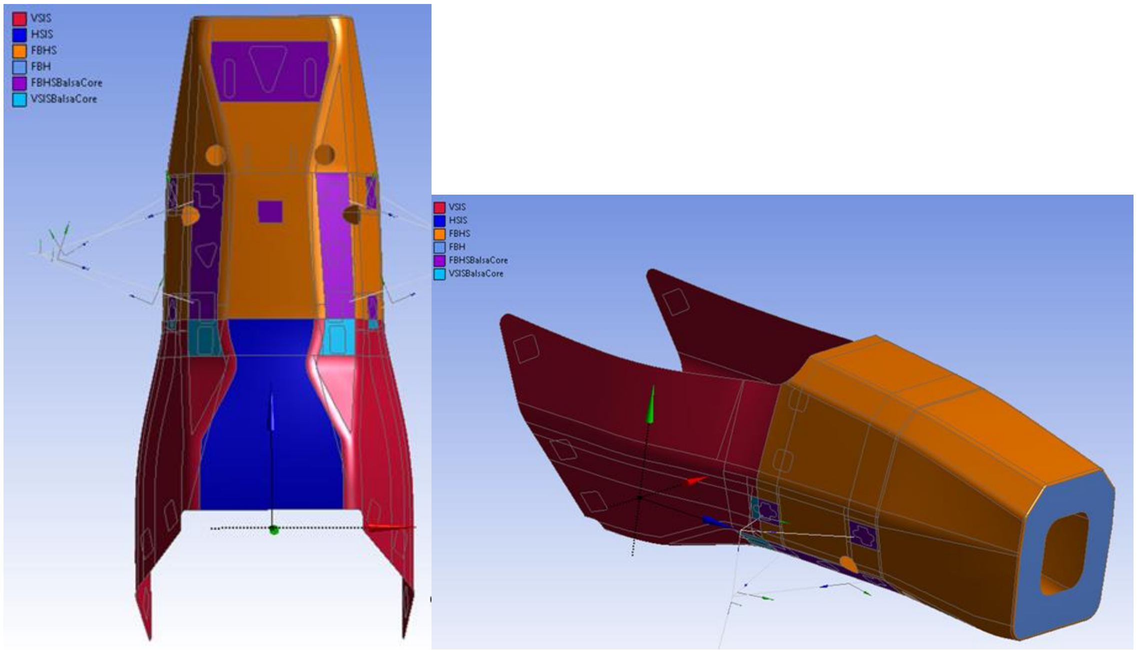


Figure 3 - BR20 corrected laminate simulation

Figure 3 above shows the updated simulation layout. The laminates are corrected to show the as built and designed intention layout of the chassis.

Due to the lack of variation in the laminates, the chassis is overbuilt. However, the poor simulation quality previously misdirected the actual factor of safety. The targeted FOS is 1.65 for the BR20 chassis.

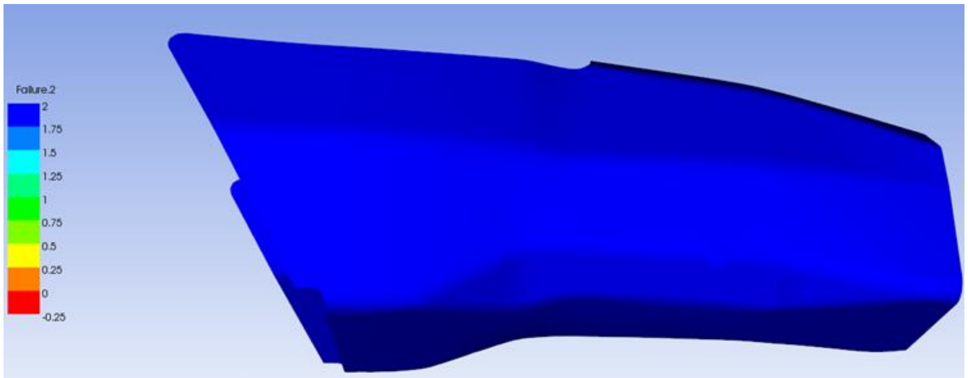


Figure 4 - BR20 incorrect laminate factor of safety

Figure 4 shows the factor of safety (FOS) of the low quality and incorrect simulation. Through viewing this, it appears as that the structure is significantly overbuilt in all parts of the vehicle. The minimum FOS found from this study was 1.991.

However, using the updated simulation, the structure is not built to meet the minimum 1.65 FOS.

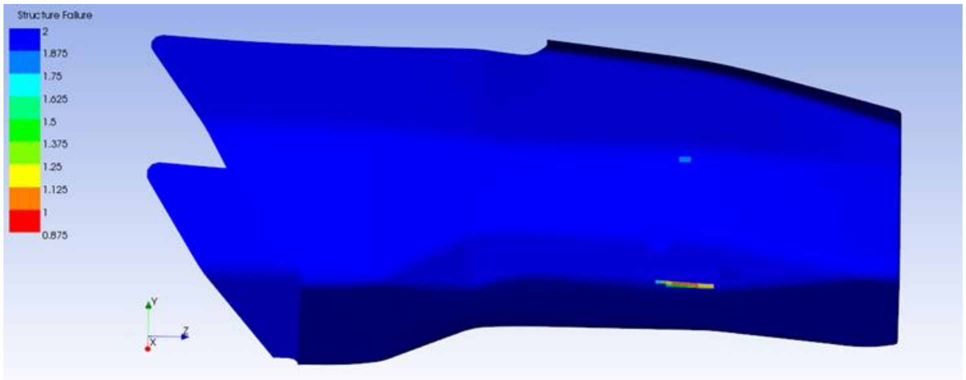


Figure 5 - BR20 corrected laminate factor of safety

Figure 5 shows that the fillet directly above the front lower control arm is a high stress concentration. This is due to the balsa no longer supporting this region, instead replaced with

Nomex honeycomb. The updated simulation shows a minimum FOS of 1.014, while the rest of the structure is still overbuilt.

To prevent an overbuilt chassis, the Formula SAE (FSAE) ruleset must be understood. In BR20, multiple regions were overbuilt when they were not in fact regulated.

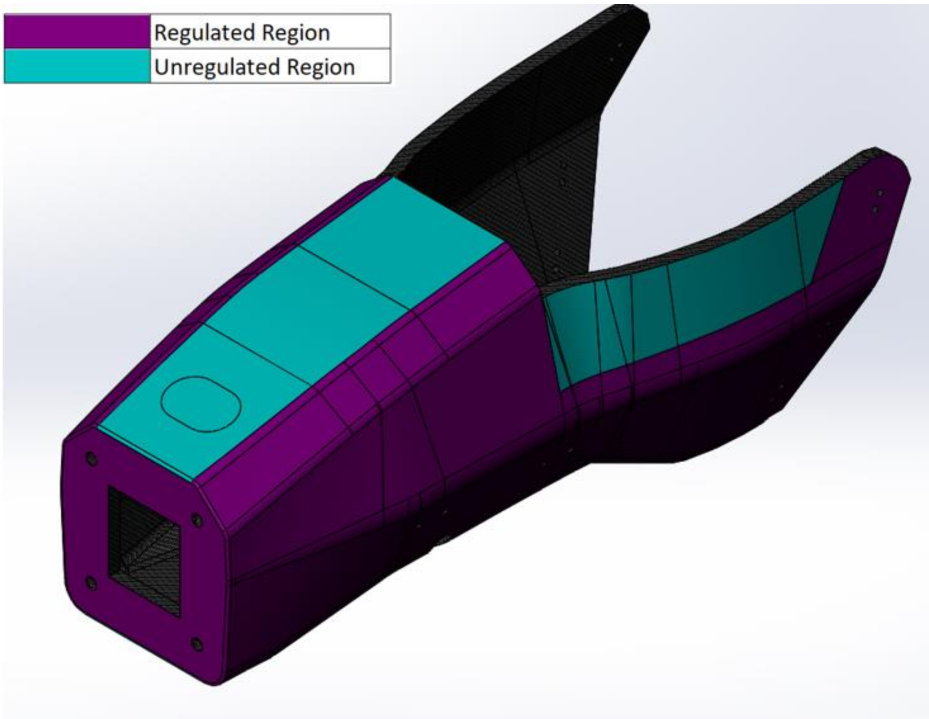


Figure 6 - Unregulated regions isometric view

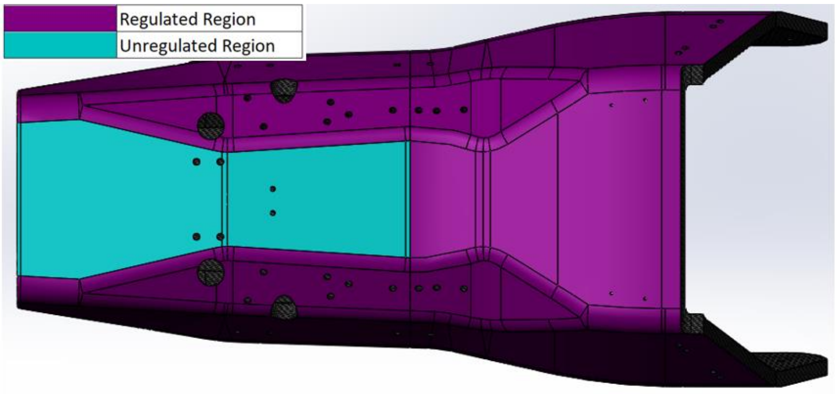


Figure 7 - Unregulated regions bottom view

Figure 6 and Figure 7 show three additional regions of the BR20 chassis that could have been used as a separate laminate. These regions are considered unregulated and could have been significantly downsized. The FBHS upper and lower regions are deemed unregulated due to wording in the FSAE rules that allows for horizontal areas in these regions to not have a ruleset applied to them. Additionally, the area above the VSIS is not required to meet structural equivalency requirements.

2.2 Packaging Considerations

The BR20 monocoque has areas of potential packaging improvement. The driver cockpit area is overly large, creating a need for excess material and weight.

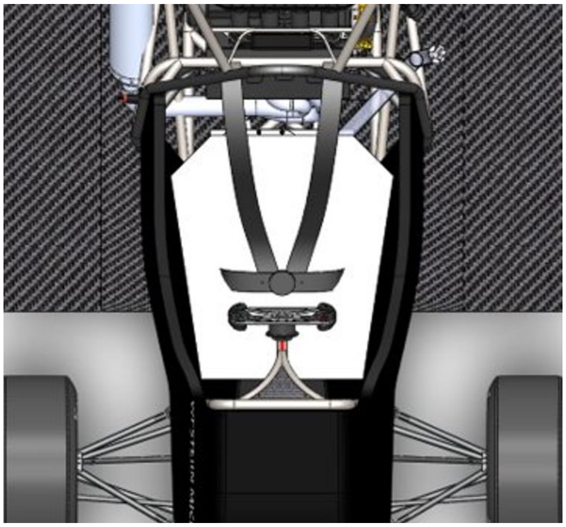


Figure 8 - BR20 cockpit opening

The driver cockpit opening only needs to be large enough to fit the required cockpit template shown in Figure 8. The BR20 cockpit is far larger, giving an appearance of a very large overall structure.

Additionally, the front roll hoop is far higher than needed. Height of the front roll hoop is determined by the driver knee height clearance, as well as the height of the steering wheel. For safety, the driver must be able to egress the vehicle in under five seconds. A low knee height will make this requirement difficult to achieve. The steering wheel, at maximum height, must also remain under the front hoop to prevent the driver's hand from being crushed in the event of a rollover. Finally, the overall height of the front roll hoop can also affect driver visibility.

Figure 9 - Excessive front roll hoop height

Figure 9 shows the unnecessary space between the driver's knees and front roll hoop. This space shows that the monocoque is larger than needed.

Figure 10 - BR20 visibility

BR20 has an excessively high front roll hoop. Due to driver position, visibility is good on the sides of the vehicle, but not the front. A reduced front roll hoop height will allow for better visibility. The driver visibility can be seen in Figure 10 above.

2.3 Manufacturing Quality

The BR20 monocoque manufacturing process was not efficient. BR19 and BR20 both use the same molds, reducing cost of the vehicle manufacturing. However, the molds created have inherit issues due to construction type and use. This section of the report covers the manufacturing quality issues of the BR20 vehicle,

The manufacturing of the monocoque occurred in five steps. These steps are outlined below.

2.3.1 Tooling Board

The male molds of the monocoque are manufactured using polyurethane tooling board. Due to sponsorship limitations, the tooling board received was acquired in multiple pieces and adhered together. Using correct cut tolerances, the gaps in the mold was able to be kept to a minimum. Due to the monocoque construction, two different molds were created. One mold was used for the top of the chassis, and one for the lower.

2.3.2 Male Molds

The male molds were designed in CAD, then created using a 3-axis CNC mill. This is the ideal construction of the male molds as the Formula SAE team has access to many sponsors that have this machinery. Unfortunately, a drawback to the polyurethane tooling board is the weight of the overall structure. Each mold weighs approximately 300lbs, requiring a forklift or pallet jack wherever the part is moved.

Once the tooling board was cut on a mill, it was then sprayed with automotive primer, and wet sanded to a mirror finish to allow for easy demolding and good surface finish of the fiberglass mold. The male molds were then waxed and prepared with mold release.

2.3.3 Fiberglass Molds

The fiberglass molds were created by using a multiple part layup procedure. First, the male mold was brushed and rolled with a gel coat system. Next, a thicker layer of fiberglass was used followed up with a layer of chop strand fiberglass. The outside of the mold was thickened using structural putty to prevent warping of the mold under vacuum and heat.

When the molds were eventually used, and the final part demolded, it was found that the above-mentioned manufacturing method led to a very poor surface finish seen in Figure 11.

Figure 11 - BR19 monocoque bottom view after demolding

Unfortunately, the fiberglass layups were created in such a way that give less than desirable surface finishes. The thick layer of fiberglass used after the gel coat should be substituted with a thin veil layer of fiberglass, then a much thicker layer. Additionally, between each layer of fiberglass resin should be brushed onto the fabric to prevent air pockets. Finally, when placing the fabric, the center of the fabric should be placed onto the mold, then the edges gradually pressed into the mold, preventing any air from becoming trapped in the layers.

In addition to the surface bubbling, the fiberglass mold was found to be warping and expanding throughout the heat cycle of the cure process. This can be seen in Figure 12, demonstrating that the carbon fiber and fiberglass were expanding and contracting throughout the heat cycle. The cooling of the sample of cure cycle led to the fiberglass mold effectively crushing the carbon fiber part, leading to the mass warping.

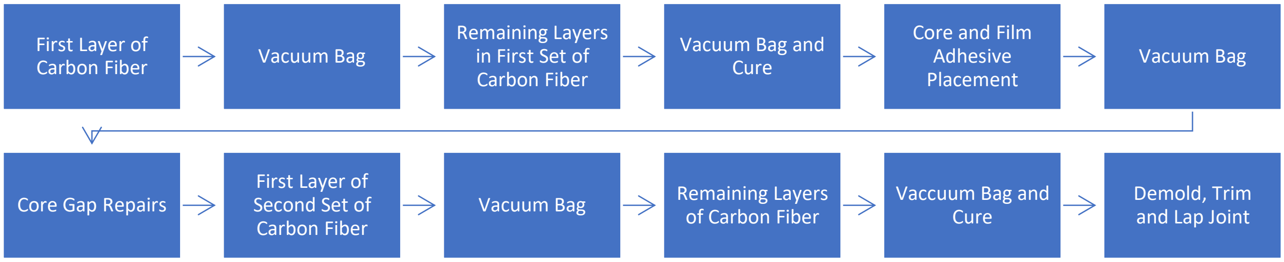
Figure 12 - Warped first iteration monocoque laminate

To mitigate this issue and the surface finish issue, the fiberglass molds were prebaked at temperatures higher than that of the carbon fiber cure cycle, to allow for effective cross-linking of the resin in the fiberglass mold before cure. During this process, the molds were vacuum bagged to pre-crush any remaining air pockets. Finally, the mold surface was repaired with body filler and wet sanded. To prepare for carbon layup, the surface was prepped with Frekote 770-NC mold release.

2.3.4 Monocoque Manufacture

The process to layup the BR19 chassis varied from that of BR21. In BR19, the process required three trips to a sponsor in Lansing to cure the part in a large autoclave. For BR21, the same part will only require two trips. This is done by not curing the core and film adhesive before applying the second layer of carbon fiber. Through testing it was found that simply vacuum bagging the molds in increased frequency can substitute having to cure the laminates.

The layup procedure for the BR21 chassis is such:



The decision to run vacuum bagging between the first layer of carbon in each set was driven by the issue of carbon fiber bridging over fillets and curves in the mold. The vacuum bagging helped decrease the bridges and showed any problems of issue through wet-spotting.

After laying up the remaining carbon fiber and curing, warping typically occurred. This warping was from the expansion and contraction of the fiberglass relative to the carbon fiber during the heat cycle. However, it was also found that thinner laminates warped at a much higher rate than that of thicker laminates. To combat this, the carbon fiber is wrapped over the lip of the mold to aid in securing the fabric. After cure, the carbon fiber was sanded to increase bond strength with the film adhesive.

Core and film adhesive were roughly placed in position by hand, then vacuum bagged to form-fit the core to the surface of the carbon fiber. This allowed the core to be set in place, and any remaining gaps to be filled. After the second set of carbon fiber, the laminate was cured for a final time under vacuum, then demolded from the fiberglass.

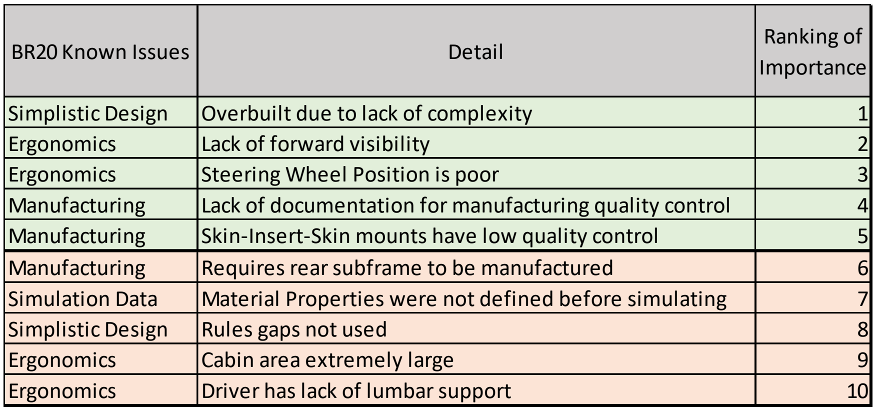
2.3.5 Trimming and Lap Joint

After demolding, the part was trimmed to specifications using mold witness lines and bonded along the trim seam with epoxy. In previous years, the lap joint was conducted using large 4” wide sections of carbon fiber along the length of the seam. However, due to poor manufacturing tolerances, the wet-layup carbon fiber was over-resined and lead to a very poor surface finish as seen in Figure 13.

Figure 13 - BR19 low quality lap joint

To mitigate this issue, the lap joint will be done in increasing widths from 2” to 4”. This will not only result in a lighter lap joint but will also distribute the stress throughout the laminates more evenly. Additionally, resin will be applied to the dry weave carbon fiber by brushing the resin on, then squeezing out excess to prevent oversaturation. The rest of the chassis will be covered in painter’s tape to allow for easy removal of dripping or excess resin, preserving surface finish. Finally, the chassis will be wet sanded before the installation of mounting structures.

The monocoque used in BR20 is a first-generation design. There are many drawbacks, and likewise many areas where design improvements can be made. To focus the directed changes of the BR21 chassis, the known issues were ranked to prioritize the required changes to be made. These issues are shown in Table 1.



BR20 Known Issues	Detail	Ranking of Importance
Simplistic Design	Overbuilt due to lack of complexity	1
Ergonomics	Lack of forward visibility	2
Ergonomics	Steering Wheel Position is poor	3
Manufacturing	Lack of documentation for manufacturing quality control	4
Manufacturing	Skin-Insert-Skin mounts have low quality control	5
Manufacturing	Requires rear subframe to be manufactured	6
Simulation Data	Material Properties were not defined before simulating	7
Simplistic Design	Rules gaps not used	8
Ergonomics	Cabin area extremely large	9
Ergonomics	Driver has lack of lumbar support	10

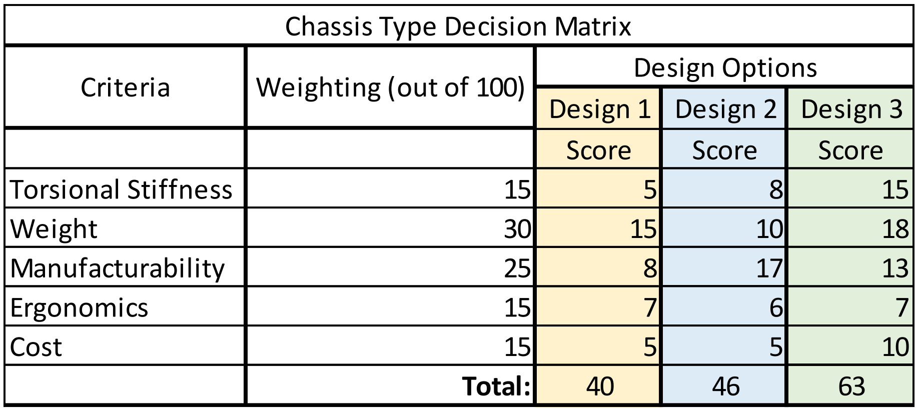
Table 1 - BR20 known issues ranked

The first five issues will be pursued, with the remaining considered if applicable. Ideally, the BR21 monocoque will resolve all known issues, however compromises must be made to ensure vehicle quality and cohesion with other Bronco Racing sub-teams.

3 BR21 Design

3.1 Initial Concepts

Initial concepts were created to capture the known issues of BR20. Three designs were made, and a decision matrix generated to decide the best design. The decision matrix is shown in Table 2. Each design can be seen in Appendix B – Initial 3 Design Sketches.



Chassis Type Decision Matrix

Criteria	Weighting (out of 100)	Design Options		
		Design 1	Design 2	Design 3
		Score	Score	Score
Torsional Stiffness	15	5	8	15
Weight	30	15	10	18
Manufacturability	25	8	17	13
Ergonomics	15	7	6	7
Cost	15	5	5	10
	Total:	40	46	63

Table 2 - Chassis type decision matrix

As seen above, Design 3, the full monocoque design, will be pursued. This design was then developed in multiple iterations to show development across each region of the vehicle.

3.2 Geometrical Constraints

To create the monocoque chassis, a geometrical surface model must be created. This model was created in SolidWorks. To ensure the chassis would be effective for the BR21 vehicle, the complete BR20 vehicle assembly was imported into an assembly with the new BR21 monocoque. Parts that are known to be changing were removed, leaving a set of design criteria components.

3.2.1 Suspension Constraints

The BR20 chassis, or half monocoque, did not mount the front suspension components perpendicular to the face of the monocoque, as seen in Figure 14. This caused the suspension loads to act primarily in shear, which in turn required the FBHS to be overbuilt to withstand the shear loads.

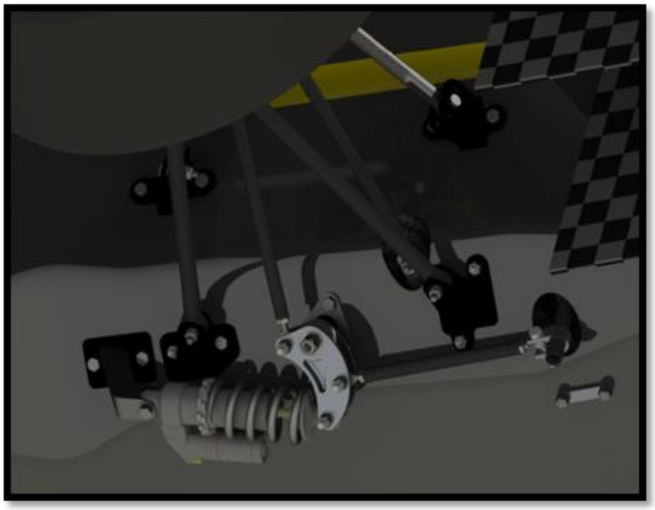


Figure 14 - BR20 front suspension components mounting

To counteract this, the front suspension was the first design criteria for BR21. Once the front suspension geometry was imported into SolidWorks, the FBHS was designed to normalize all of the suspension loads, including the upper and lower control arms, shock and damper, and anti-roll bar. The BR21 suspension mounting normal to the face of the monocoque can be seen in Figure 15.

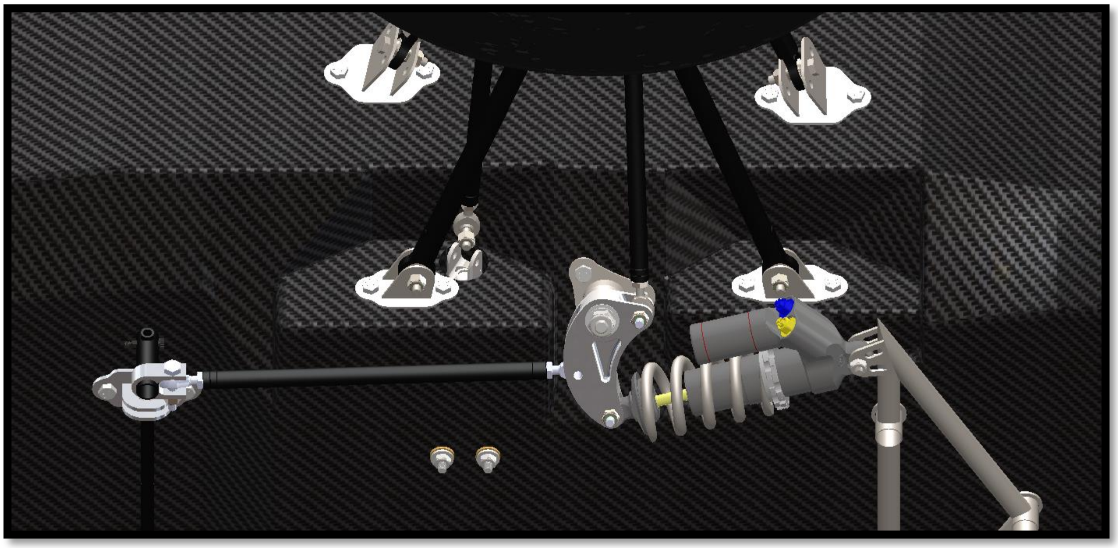


Figure 15 - BR21 front suspension components mounting

Due to the length of the control arms as well as the position of the shock and damper, a complicated and unique stepped design was considered. This stepped design allowed for all four front control arms to be mounted normal to the monocoque and provided the best solution to mount the compact front suspension geometry. One major concern was the space required to mount the bell crank. Due to the position of the bell crank, it had to be mounted in between the control arms. This required a careful calculation of how much deflection the bell crank would experience under extreme load cases so that the lower control arm mounting surface area could be maximized. This was done by treating the system as an inverted crank slider and using mechanism analysis to analyze the system under maximum shock displacement conditions. Additionally, due to the position of the shocks, it was necessary to have half-inch core on the surface above the shocks, highlighted as the pink and dark green regions in Figure 16 below.

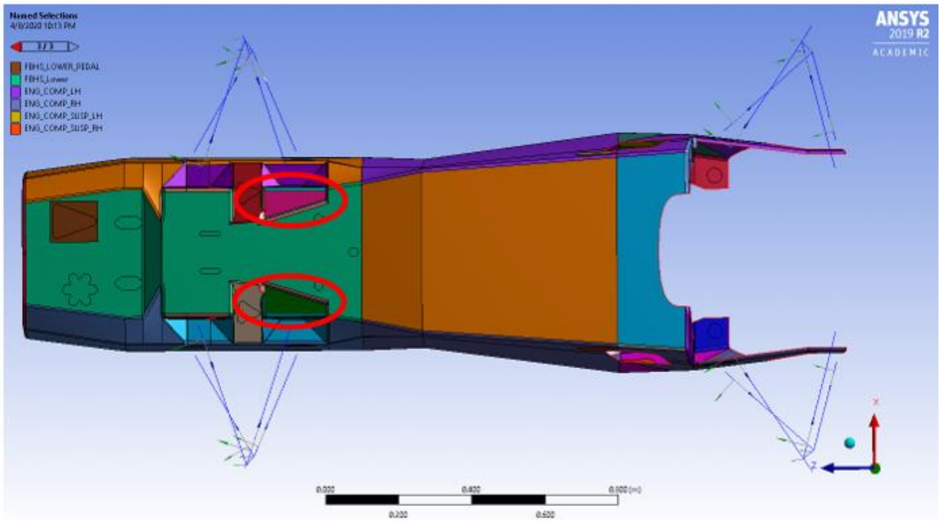


Figure 16 - BR21 monocoque core regions

This allowed for mounting hardware, including a backing plate if necessary, to be mounted behind the rear lower control arm of the front suspension while still leaving room for the shock to actuate below.

In the rear of the monocoque, the suspension had to be mounted normal to the monocoque while still allowing room to access the engine bay and remove the engine. Due to the relationship between the rear suspension and the powertrain, the rear suspension constraints are discussed further in the following section since both constraints had to be considered simultaneously.

3.2.2 Powertrain Constraints

3.2.2.1 Powertrain and Drivetrain Removal

The primary powertrain design constraint was the easy removal of the powertrain and drivetrain from the car. Due to this, it was decided that the rear end of the monocoque had to be removeable. This allowed for the powertrain and drivetrain to be slid out from the back of the car instead of having to be lifted out from a five-sided box. Due to the compact and intricate packaging of the powertrain, it was also decided that the monocoque would only meet the top of the rear end cap while on bottom two steel tubes would connect the monocoque to the cap. This provided solutions to multiple problems. Firstly, the engine can easily be removed by unbolting the two steel bars and end cap and then dropping the engine. Additionally, this reduced the amount of chassis material in rear, which improved weight and packaging. Next, the front lower control arms, shock and damper of the rear suspension were too close to the clutch cover and stator cover of the engine for the monocoque to run in between them with mounting hardware. With the addition of the lower steel tubes, there was now a weldable mounting surface present for the lower control arms as well as powertrain accessories. Lastly, this also allowed there to be no engine bay floor, which is required by rules in case of any leaking fluids. A bottom view of the rear end of the monocoque, highlighting the rear end cap as well as the steel bars is shown below in Figure 17.

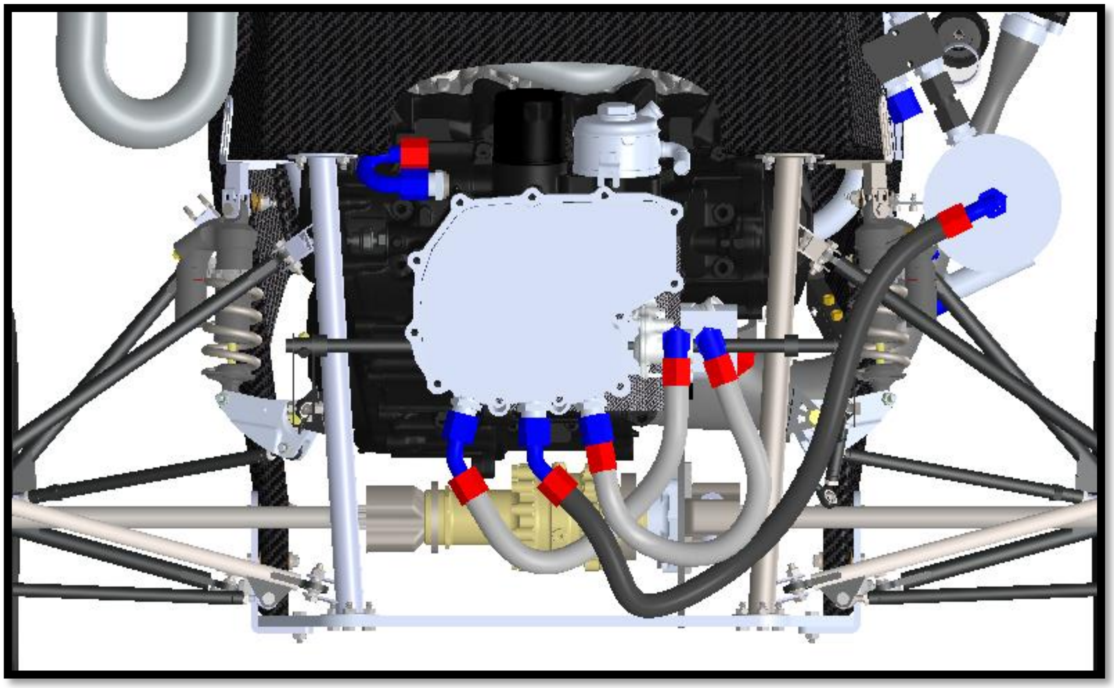


Figure 17 - BR21 rear end cap and steel mounting bars bottom view

3.2.2.2 Cooling

Another important design constraint was ensuring the engine would receive sufficient cooling. In order to do this, two holes must be made on the side of the monocoque behind the main roll hoop. These holes allowed for air to enter through the sidepods, into the engine bay near the hot exhaust headers, and be sucked out by the engine cover. These holes had very careful placement to ensure that they did not weaken the monocoque or require the monocoque to be over built. There also had to be extra care taken to ensure the main roll hoop mounting hardware still had room to pass a perimeter shear test. These cooling holes can be seen in Figure 18.

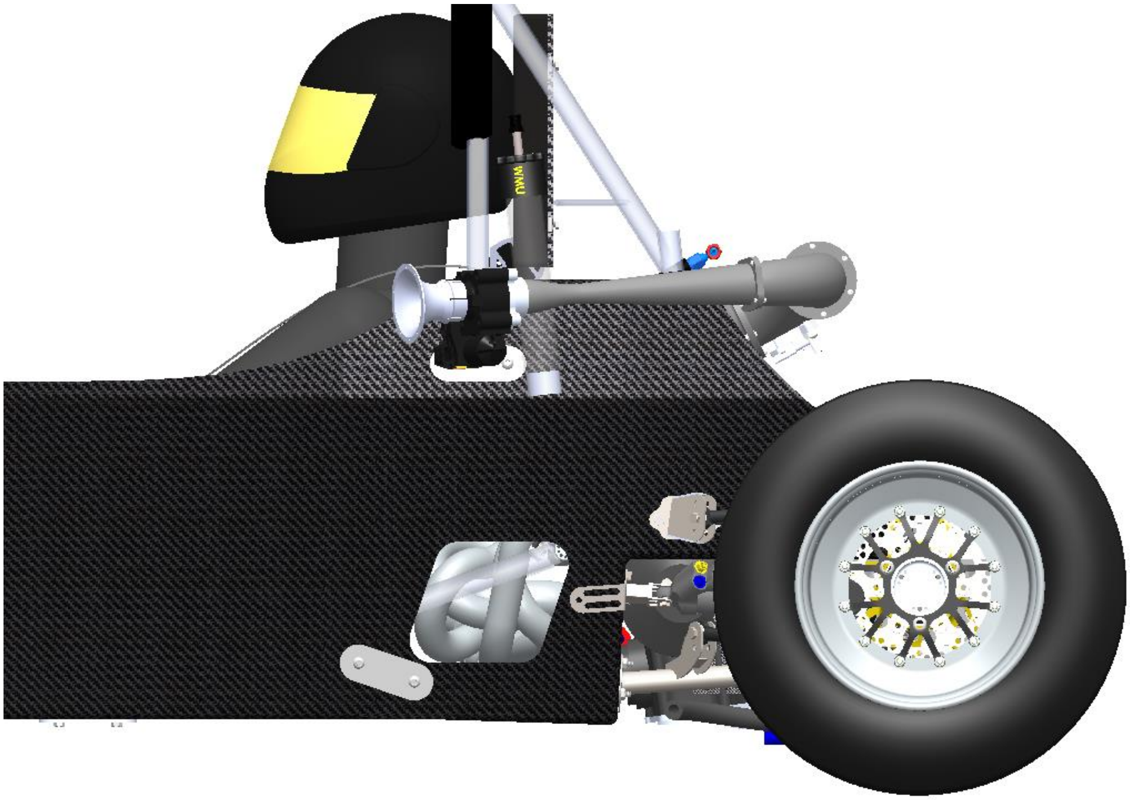


Figure 18 - BR21 holes for cooling

3.2.2.3 Packaging Changes

Another powertrain and drivetrain packaging constraint was that they both needed to be easily accessible while mounted in the car to allow for maintenance and repair work. Previously, there was excess room between the engine and gearbox to allow space for the chain tensioner as well as other powertrain items. This required the subframe to extend further than necessary, increasing weight. To correct this, the entire drivetrain system was moved forward 6 inches until it was nearly touching the powertrain. Now, instead of having separate mounts for the powertrain and drivetrain that each attached to the subframe, the drivetrain is mounted to the rear end cap and the powertrain, and the powertrain is mounted to the monocoque via the main roll hoop. This reduces the unused space in the rear and drastically increases the packaging density, which reduces weight. In order to account for the change in the rear suspension's position and keep the cars wheelbase the same, the front suspension was moved forward on the monocoque. This required a different section of the monocoque to support suspension mounting hardware, which in turn required the FBHS to be longer but also allowed for a more reclined driver position, which lowered the center of gravity (CG) of the vehicle. Another benefit of this mounting system is the increase in stiffness. A half monocoque acts as a compound spring since it has multiple bodies connected between the front and rear suspension, each with a unique stiffness. By mounting the drivetrain and powertrain between the main roll hoop and rear end cap, which are both mounted to the monocoque, a one spring system is created. This reduces the chassis compliance and increases the overall torsional stiffness of the chassis.

3.2.3 Driver Controls Constraints

3.2.3.1 Steering Wheel Position

A major design flaw of the previous car was the position of the steering wheel in relation to the driver. Due to the placement of the wheel, the drivers would have to remove their hands from the wheel while making a turn. This not only decreases performance but can also be a safety hazard. To correct this, ergonomic studies were conducted in collaboration with the driver control team to find the correct steering wheel placement. This was done by creating a mock cockpit and having the drivers practice taking turns while recording the steering wheel position. Once the optimal steering wheel position was determined in relation to the driver, it could be put into the SolidWorks model in relation to Percy, the SAE's standardized human template. These dimensions were found to be 14 inches from the driver's chest and 8.5 inches from the driver's lap. Shown below in Figure 19, these dimensions then determined the height of the front roll hoop since the roll hoop must be taller than the steering wheels tallest position, as discussed previously.

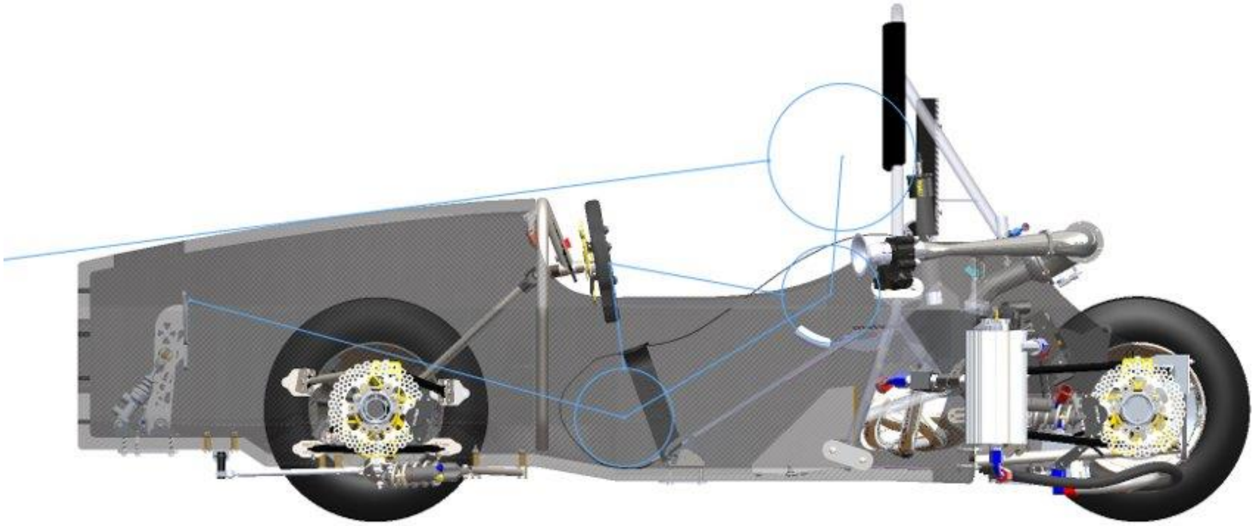


Figure 19 - Percy in BR21 car

3.2.3.2 Cockpit Template

SAE provides each team with a standardized cockpit template, shown in Figure 8 and discussed in Section 2.2, which is the minimum required cockpit size. This template is then used at competition to ensure each team is rules compliant by holding the template horizontal and passing it vertically down into the cockpit until it is 320 mm above the lowest point in the car. This 320 mm limit also then determines the height of the side impact structure, which will be discussed further in following sections. Since the cockpit template is the minimum size the cockpit can be, one of the design constraints was to make the cockpit fit the template as closely as possible. This not only reduces the weight of the car, but also makes it more ergonomic since it will now be caressing the drivers on the sides instead of leaving extra room, making the drivers bounce from side to side of the car as they drive through a slalom. In order to make the cockpit opening as small as possible, it was necessary to redesign the firewall. Now, instead of being one solid sheet, the firewall has two parts, one against the drivers back and one horizontal to the ground. By creating this geometry, the cockpit template is able to pass all the way down to the

320 mm plane. In order to support the firewall while it is supporting the driver's weight, two mounts extend from the main roll hoop and can be seen in Figure 20 below.

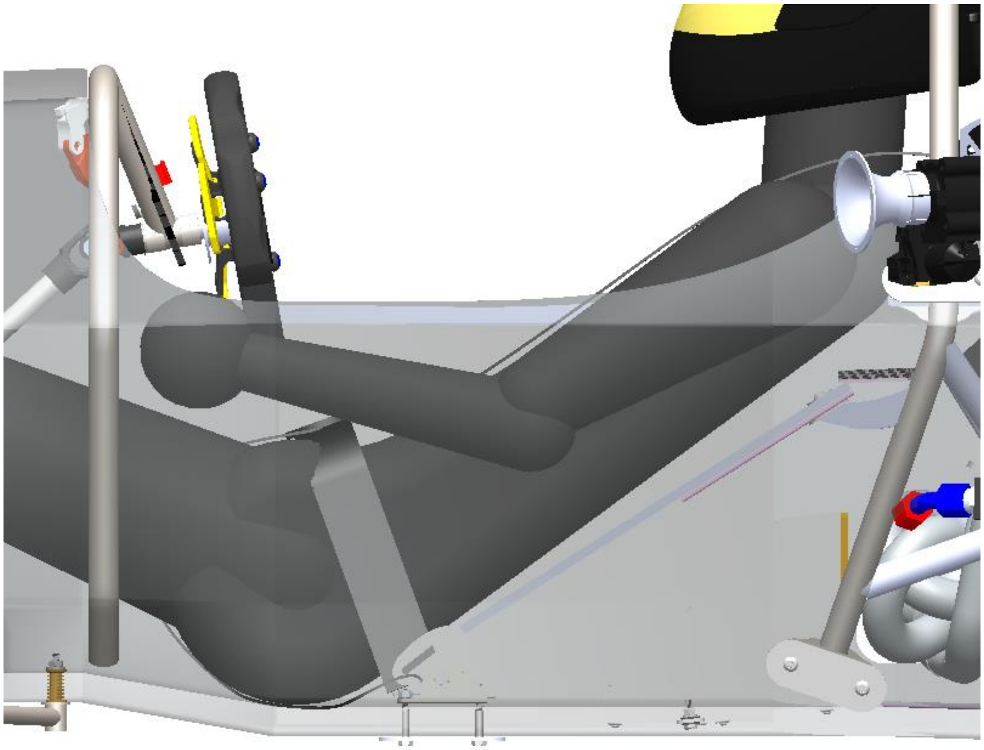
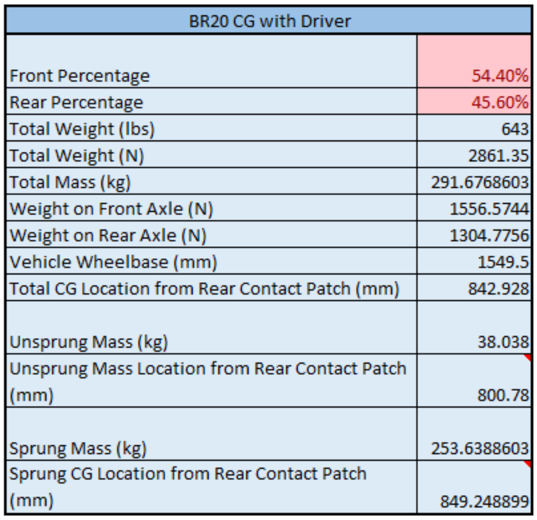


Figure 20 - BR21 driver support mounts on main roll hoop

3.2.4 Center of Gravity Changes

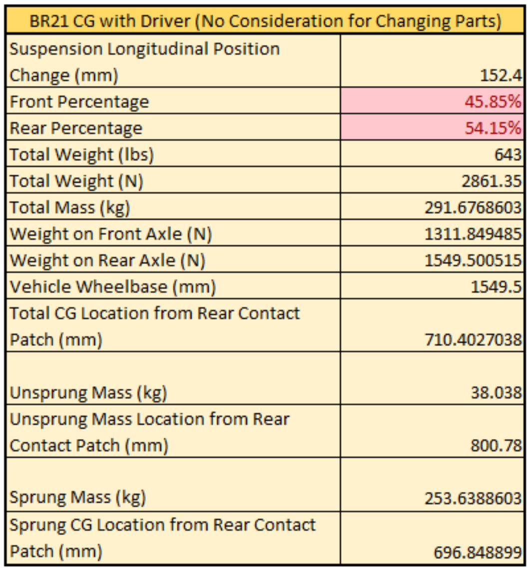
As the suspension was moved to reduce the excess space in the rear of the vehicle, this change has a large effect on the handling characteristics of the vehicle. To combat this, the CG of the entire vehicle was calculated, then parts moved and packaged throughout the vehicle until the CG approached the original or an acceptable position. First, the suspension of the BR20 vehicle was analyzed, and the CG of the calculated for this vehicle. Table 3 below shows the calculations and results of this study, which yielded a 54.4/45.6 front to rear weight distribution. This value was within 0.2% of the measured value at our competition.



BR20 CG with Driver	
Front Percentage	54.40%
Rear Percentage	45.60%
Total Weight (lbs)	643
Total Weight (N)	2861.35
Total Mass (kg)	291.6768603
Weight on Front Axle (N)	1556.5744
Weight on Rear Axle (N)	1304.7756
Vehicle Wheelbase (mm)	1549.5
Total CG Location from Rear Contact Patch (mm)	842.928
Unsprung Mass (kg)	38.038
Unsprung Mass Location from Rear Contact Patch (mm)	800.78
Sprung Mass (kg)	253.6388603
Sprung CG Location from Rear Contact Patch (mm)	849.248899

Table 3 - BR20 CG Calculation

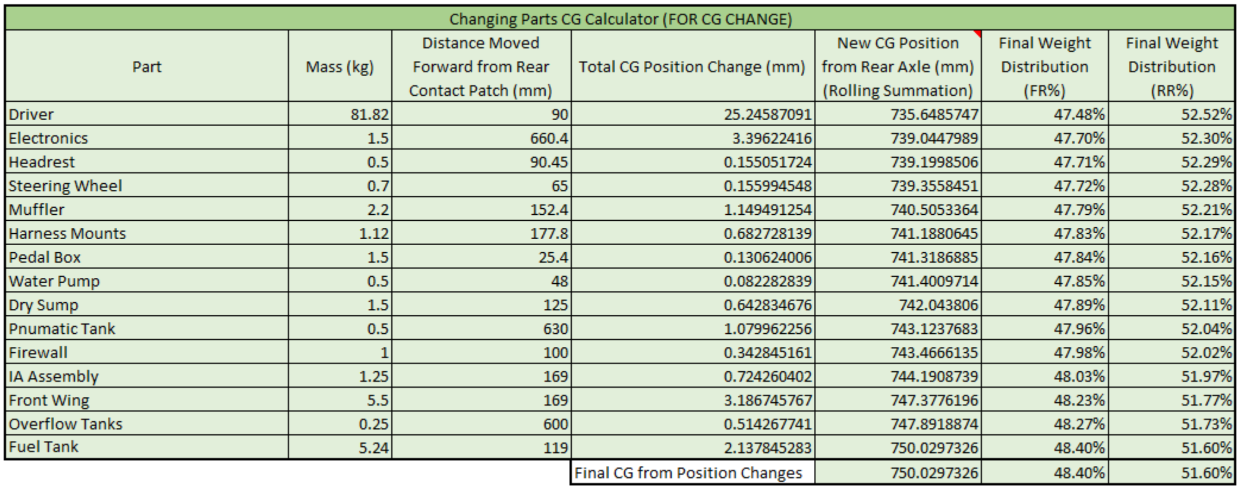
Then, the CG was calculated for the BR21 vehicle after the suspension was moved, without considering any other changing parts. This is shown in Table 4 below, where the new weight distribution was 45.85/54.15 front to rear. This is a large change and will have large effects on the handling characteristics of the vehicle.



BR21 CG with Driver (No Consideration for Changing Parts)	
Suspension Longitudinal Position Change (mm)	152.4
Front Percentage	45.85%
Rear Percentage	54.15%
Total Weight (lbs)	643
Total Weight (N)	2861.35
Total Mass (kg)	291.6768603
Weight on Front Axle (N)	1311.849485
Weight on Rear Axle (N)	1549.500515
Vehicle Wheelbase (mm)	1549.5
Total CG Location from Rear Contact Patch (mm)	710.4027038
Unsprung Mass (kg)	38.038
Unsprung Mass Location from Rear Contact Patch (mm)	800.78
Sprung Mass (kg)	253.6388603
Sprung CG Location from Rear Contact Patch (mm)	696.848899

Table 4 - BR21 CG Calculation without part movement

To find the corrected CG after necessary packaging changes due to the new monocoque design, the analysis was broken into two parts. The first calculates the CG based off of individual parts that do not change, but do move to a new location. This can be seen in Table 5.

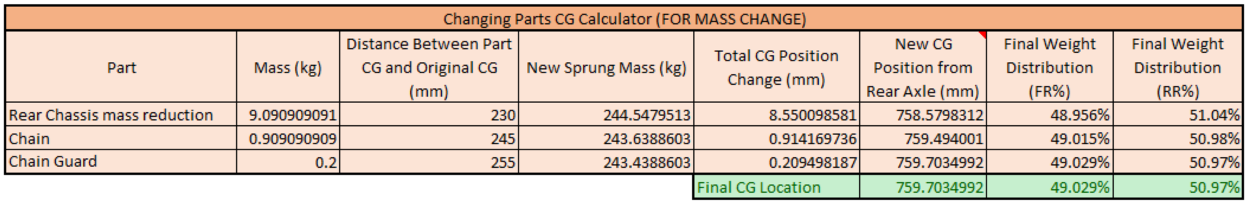


Changing Parts CG Calculator (FOR CG CHANGE)

Part	Mass (kg)	Distance Moved Forward from Rear Contact Patch (mm)	Total CG Position Change (mm)	New CG Position from Rear Axle (mm) (Rolling Summation)	Final Weight Distribution (FR%)	Final Weight Distribution (RR%)
Driver	81.82	90	25.24587091	735.6485747	47.48%	52.52%
Electronics	1.5	660.4	3.39622416	739.0447989	47.70%	52.30%
Headrest	0.5	90.45	0.155051724	739.1998506	47.71%	52.29%
Steering Wheel	0.7	65	0.155994548	739.3558451	47.72%	52.28%
Muffler	2.2	152.4	1.149491254	740.5053364	47.79%	52.21%
Harness Mounts	1.12	177.8	0.682728139	741.1880645	47.83%	52.17%
Pedal Box	1.5	25.4	0.130624006	741.3186885	47.84%	52.16%
Water Pump	0.5	48	0.082282839	741.4009714	47.85%	52.15%
Dry Sump	1.5	125	0.642834676	742.043806	47.89%	52.11%
Pnumatic Tank	0.5	630	1.079962256	743.1237683	47.96%	52.04%
Firewall	1	100	0.342845161	743.4666135	47.98%	52.02%
IA Assembly	1.25	169	0.724260402	744.1908739	48.03%	51.97%
Front Wing	5.5	169	3.186745767	747.3776196	48.23%	51.77%
Overflow Tanks	0.25	600	0.514267741	747.8918874	48.27%	51.73%
Fuel Tank	5.24	119	2.137845283	750.0297326	48.40%	51.60%
			Final CG from Position Changes	750.0297326	48.40%	51.60%

Table 5 - BR21 part movement effects on CG

The final calculation uses the new reduced mass items in the rear end due to the new monocoque geometry. This is seen in Table 6 below. This final calculation set shows that the new weight distribution is 49.02/50.97 front to rear. This range is much closer to the ideal 50/50 of the BR21 platform. The remaining weight distribution changes can be handled by slightly adjusting the vehicle's pullrods.



Changing Parts CG Calculator (FOR MASS CHANGE)

Part	Mass (kg)	Distance Between Part CG and Original CG (mm)	New Sprung Mass (kg)	Total CG Position Change (mm)	New CG Position from Rear Axle (mm)	Final Weight Distribution (FR%)	Final Weight Distribution (RR%)
Rear Chassis mass reduction	9.090909091	230	244.5479513	8.550098581	758.5798312	48.956%	51.04%
Chain	0.909090909	245	243.6388603	0.914169736	759.494001	49.015%	50.98%
Chain Guard	0.2	255	243.4388603	0.209498187	759.7034992	49.029%	50.97%
				Final CG Location	759.7034992	49.029%	50.97%

Table 6 - BR21 mass reduction effects on CG

3.3 Material Selection

3.3.1 Carbon Fiber

Selection of carbon fiber was one design decision that had to made. Woven and unidirectional carbon fiber needed to be selected. Due to budget constraints and other issues, the carbon fiber used in the BR20 car was unavailable, so comparable or better carbon fiber needed to be found. To determine if one type of carbon fiber was better than the other, tensile and compressive strength in each direction was compared. Also, density was compared to the carbon fiber used in BR20 to prevent large increases in weight and possibly decrease the weight of the BR21 monocoque. The exact values for tensile strengths, compressive strengths, and densities were gathered from the manufacturer's technical specifications sheets. The chosen carbon fiber for BR21 and its properties are shown in Table 7 along with the carbon fiber used in BR20, for comparison.

Carbon Fiber Comparision Between BR20 and BR21				
Material Properties	BR20		BR21	
	Hexcel M35-4 3K Twill 2x2	Gurit SE 84LV HEC Unidirectional	Hexcel AS4 3K Twill 2x2	Grafil TR50S Unidirectional
Area Density	346 g/m^2	477 g/m^2	388 g/m^2	251 g/m^2
0° Tensile Strength	950 MPa	2458 MPa	1102 MPa	2950 MPa
0° Compressive Strength	900 MPa	1354 MPa	950 MPa	1600 MPa
90° Tensile Strength	950 MPa	39.2 MPa	1102 MPa	79 MPa
90° Compressive Strength	900 MPa	N/A	950 MPa	N/A

Table 7 - BR21 carbon fiber selection and comparison

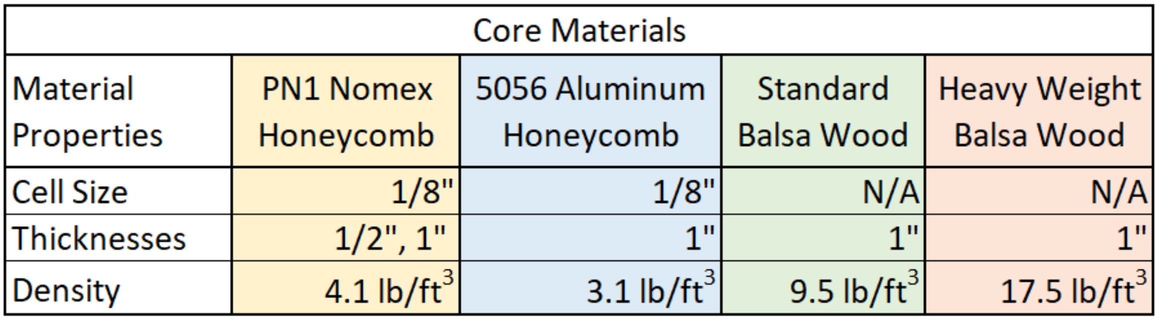
After the unidirectional and woven carbon fibers were selected, the material properties needed to be found to be simulated in ANSYS ACP. Due to carbon fiber having different properties in the x, y, and z directions, it is classified as an orthotropic material. The following material properties needed to be found for each carbon fiber: elastic modulus (E_x, E_y, E_z), shear modulus (G_{xy}, G_{yz}, G_{xz}), Poisson's ratio (ν_{xy}, ν_{yz}, ν_{xz}), tensile strength (σ_x, σ_y, σ_z), compressive strength (σ_x,σ_y, σ_z), shear strength (τ_{xy}, τ_{yz}, τ_{xz}), tensile strain (ε_x, ε_y, ε_z), compressive strain (ε_x, ε_y, ε_z), and shear strain (ε_{xy}, ε_{yz}, ε_{xz}). The equation shown in Figure 21 shows the orthotropic compliance matrix, which was used to find the tensile, compressive, and shear strain based on data obtained from the manufacturer's material data sheet for AS4 or TR50S carbon fiber. The equation was solved once for compressive and again for tensile for each material

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{xz} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_y} & -\frac{\nu_{xz}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{yz}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{xy}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{yz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{xz}} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{bmatrix}$$

Figure 21 - Orthotropic compliance matrix

3.3.2 Core

Core materials for the carbon fiber composite also needed to be selected. The selected core materials, along with their dimensional properties and densities, are shown in Table 8. The selected core materials are the same core materials used in the BR20.



Core Materials				
Material Properties	PN1 Nomex Honeycomb	5056 Aluminum Honeycomb	Standard Balsa Wood	Heavy Weight Balsa Wood
Cell Size	1/8"	1/8"	N/A	N/A
Thicknesses	1/2", 1"	1"	1"	1"
Density	4.1 lb/ft^3	3.1 lb/ft^3	9.5 lb/ft^3	17.5 lb/ft^3

Table 8 - BR21 selected core materials

The usage of each core material will be defined by the stresses imposed on different areas of the monocoque to avoid failure of the core material. The core will primarily be Nomex honeycomb, due to cost savings. The Nomex core will be used in 1/2” and 1” thicknesses, where 1/2” will be used in the low stress areas and 1” in high stress areas. In areas where the Nomex honeycomb core will fail due to higher stresses, the stronger 5056 aluminum honeycomb core will be used. The balsa wood core materials are used in areas where stresses are very high, where the use of honeycomb core could result in core failure. The heavy weight balsa is stronger than the standard balsa and is reserved for areas with the largest stresses.

3.3.3 Composite Panel Potted Inserts

Composite panel potted inserts are used for mounting point in honeycomb sandwich structures. These inserts are placed in drilled out holes in the composite with the honeycomb around the hole removed. Then, epoxy is injected into the hollow space around the insert to secure it to the composite. These inserts are much smaller and weigh much less compared to metal backing plates. The inserts will be used for suspension mounting points and mounting of other systems of the car, like aerodynamics. The suspension, however, will place the largest loads on these inserts.

The monocoque design requires potted inserts that are able to create a mounting hole through a 1” panel and accept a 1/4" bolt. The type of potted insert that corresponds to these requirements is a through-hole insert, specifically NAS-1834-4-1000 style. The chosen inserts to be used are made from a high-performance thermoplastic called Torlon. These inserts are cheaper and lighter compared to metal composite panel inserts. A pullout strength test, discussed later, was performed to confirm the validity of their use. Figure 22 shows a representation of the 1” depth and 1/4” hole insert. A cross sectional view of the mounted insert is shown in Figure 23.

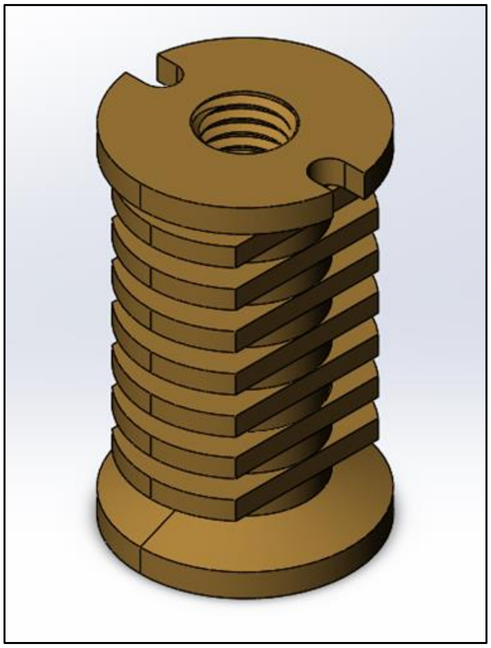


Figure 22 - NAS-1834-4-1000 style potted insert

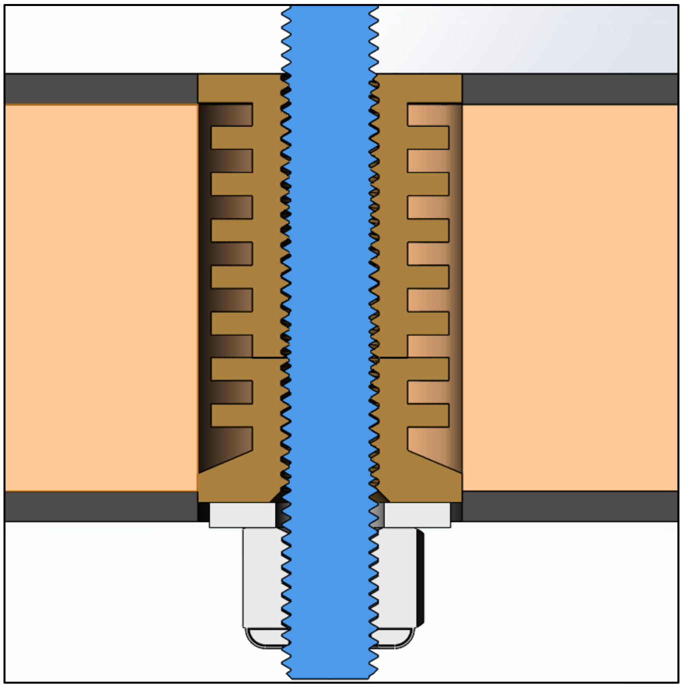


Figure 23 - NAS-1834-4-1000 style insert as a mounting point in a composite panel

The epoxy selected to be used with these potted inserts is 3M Scotch-Weld Epoxy Adhesive EC-3542 B/A FR. This epoxy is specifically designed for use with composite panel inserts and is commonly used for these inserts in industry.

3.4 Laminate Analysis Setup

To determine the necessary laminates throughout the monocoque chassis, ANSYS ACP was used. ANSYS ACP uses a shell approach to demonstrate stress, deformation, and failure of laminates on a ply-by-ply method. This allows for easy visualization of load paths through the laminate. The laminate analysis occurred in a cyclic process, shown below in Figure 24. The initial laminates used were based off of the BR20 platform.

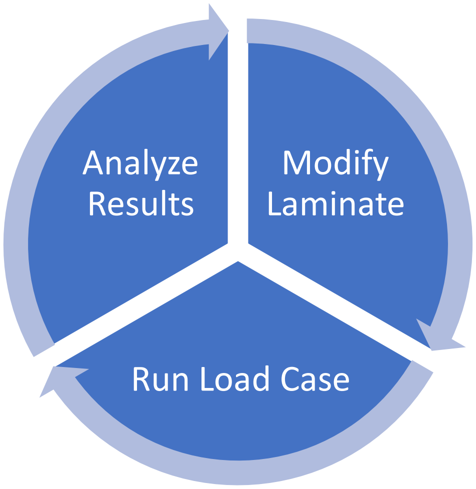


Figure 24 - Laminate analysis process

Additionally, there are multiple simulations that the chassis needed to pass to be viable for use in the BR21 vehicle. Figure 25 shows the process used to simulate the laminates in all scenarios.

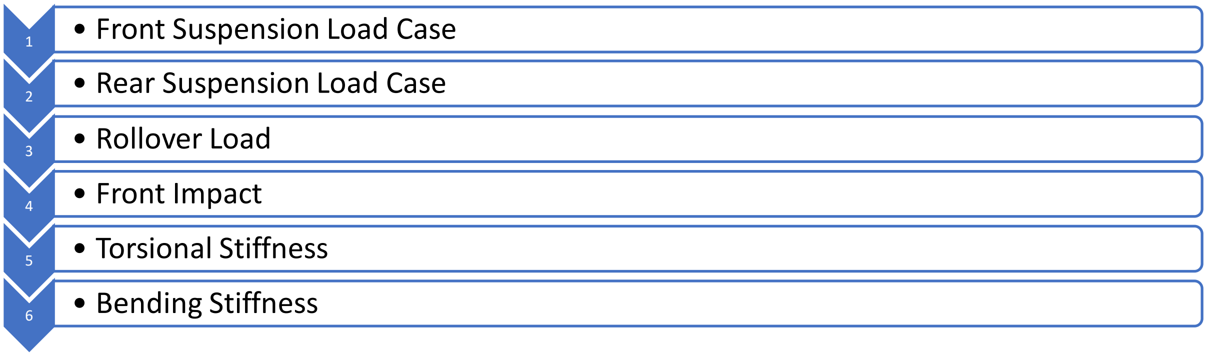


Figure 25 - Laminate simulation scenarios

The suspension load cases were determined to be the first passable test as this load case had the highest concentration of forces spread across the most laminates. Once the front and rear suspension load cases were passed, many of the other tests passed due to the reinforcements needed for the suspension load. Each of these load cases and results are discussed in detail later in this report.

To successfully pass one of the simulations, a factor of safety of 1.65 or higher is necessary. 1.65 was determined as the failure point by breaking down the two largest possible regions of failure. Firstly, material imperfection occurs in the chosen carbon fiber quite frequently. To save on expenses, Bronco Racing routinely purchases expired or defective carbon fiber. Typically, this does not have an effect on the laminate strength, but no quality control measures are put in place. Therefore, a 10% factor of safety was added for this concern.

The other area of concern is in regard to manufacturing quality. The monocoque chassis is created by students in a lab not designed for any particulate control. Due to this, the carbon fiber used is exposed to dirt, debris, and prolonged moisture. To keep this from affecting the chassis, a factor of safety of 55% was added. Total, the factor of safety is 65% over the theoretical strength of the laminate.

The final determination of the monocoque chassis validity is through the use of the Formula SAE structural equivalency spreadsheet (SES). The SES is a required document that must demonstrate that the designed chassis meets all requirements of the Formula SAE rulebook. Each regulated region of the chassis must be physically tested using a regulated representative panel size to find stiffness and laminate failure properties. These properties are then used in calculations based off the designed monocoque’s geometry. Each region must pass all requirements to be usable for a Formula SAE vehicle.

3.4.1 Laminate Region Breakdown

To begin the laminate region analysis, different laminate regions needed to be defined. Based off the BR20 platform and the Formula SAE rulebook, laminate regions were created. To begin, regions outlined in the Formula SAE rulebook were created. Then, regions of particular interest or known load application were created. Doing this created many different laminate regions to remove the BR20 issue of broad laminate application. Additionally, as simulating different load cases yielded unexpected results, additional laminate regions were created to add or reduce layers of carbon fiber in different regions. This method yielded 23 different laminate regions for the BR21 chassis. However, due to the way that ANSYS stacks and orients laminates, it was necessary to create 37 different named regions to allow for right-hand and left-hand laminate sets. Shown below in Figure 26 to Figure 29 are four views demonstrating the different laminate regions throughout the BR21 chassis. The layer breakdown of each laminate region is shown later in this report.

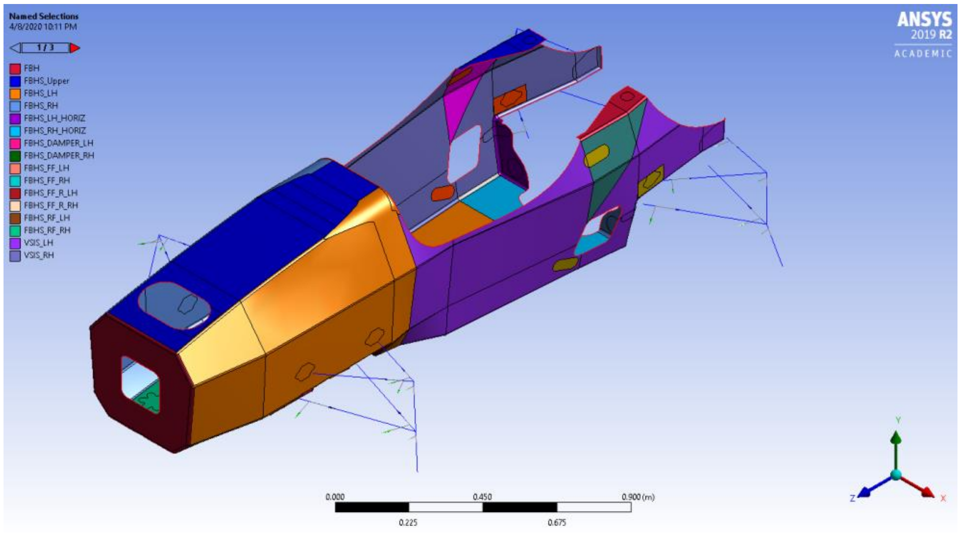


Figure 26 - BR21 laminate regions top view

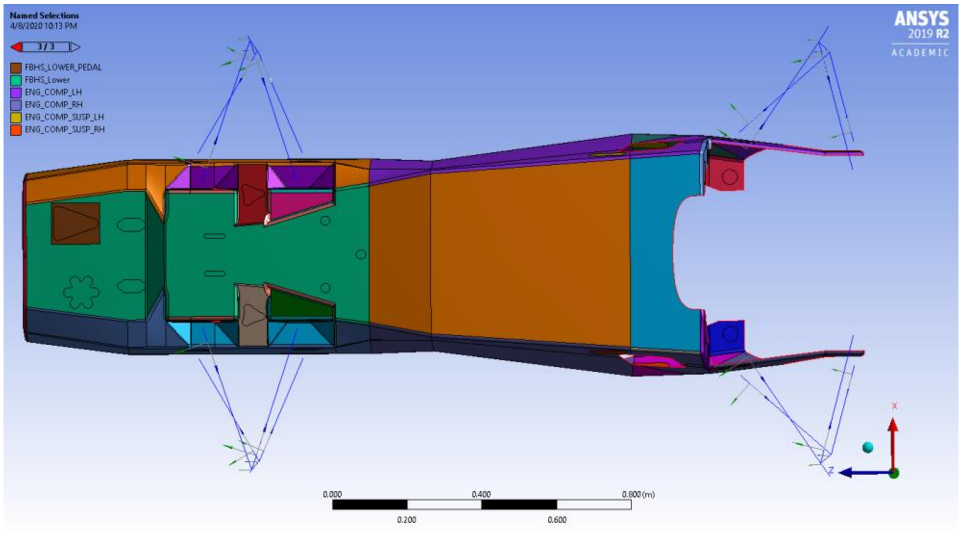


Figure 27 - BR21 laminate regions bottom view

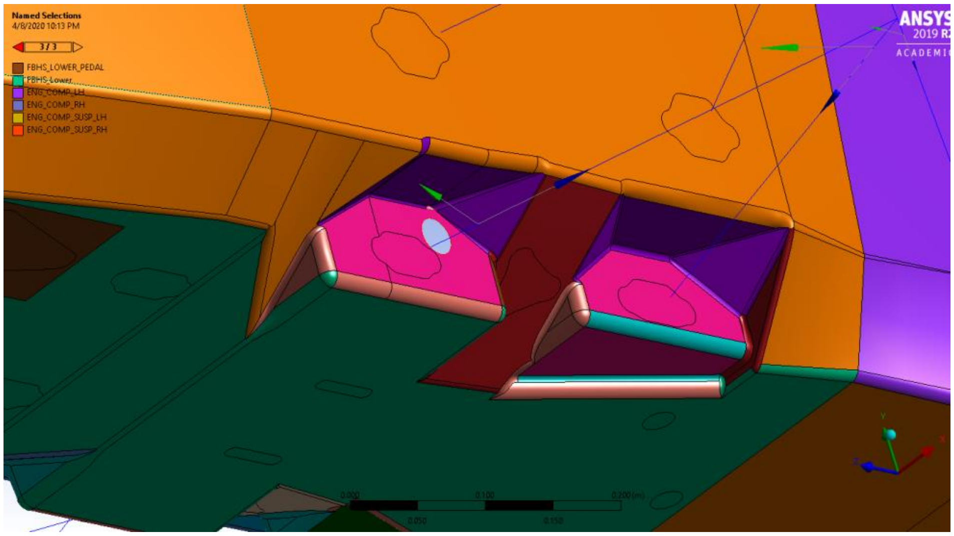


Figure 28 - BR21 laminate regions front suspension view

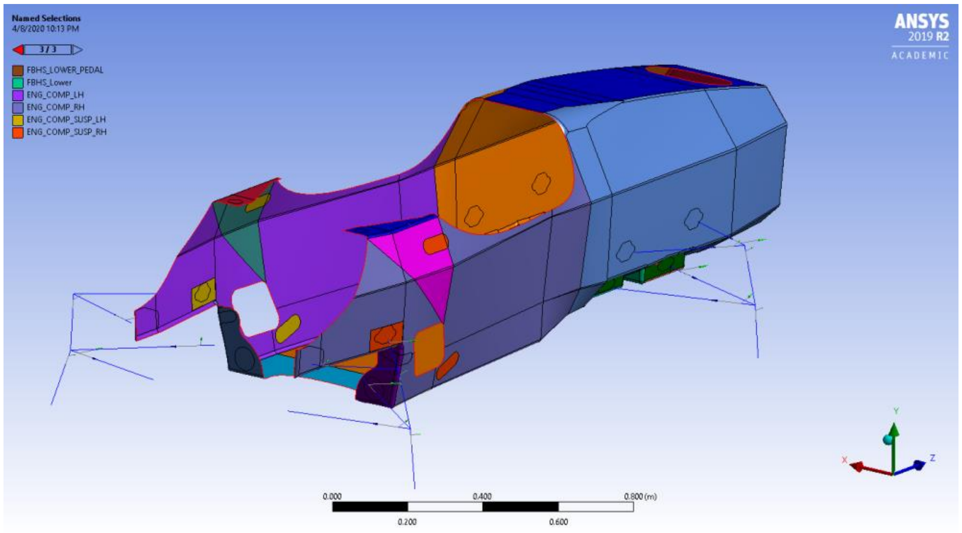


Figure 29 - BR21 laminate regions rear view

Additionally, it should be noted that each fiber orientation is based off a 0° direction. This direction is set as the positive z-axis for all laminates. This results in the primary weave direction occurring longitudinally in the vehicle. Areas such as the front bulkhead and engine compartment flange have the 0° direction defined as the y-axis, as these regions do not have a z-component.

3.4.2 Mesh Creation

To ensure accurate results of the simulation, multiple different meshes were created. Each mesh was used in a different study. The mesh was created to be fine around areas of high interest in the chassis, particularly where loads were applied. Larger less refined mesh was used everywhere else in the structure.

Unfortunately, ANSYS student version licenses limit node and element count to a combined 32,000 items. A structure of this size should take at least 44k nodes and elements to yield precise results. To combat this, mesh size control was used throughout the entire structure. This method allowed areas of load to retain a mesh of at most 9mm, while unloaded areas would have a mesh element size of higher than 35mm. For each load case, the mesh was recreated and resized until the node and elements combined count was higher than 31,500. Ideally, future studies of this chassis will use an ANSYS ACP research license which allows a much more refined mesh. Figure 30 and Figure 31 below show the mesh used in the front suspension load case study.

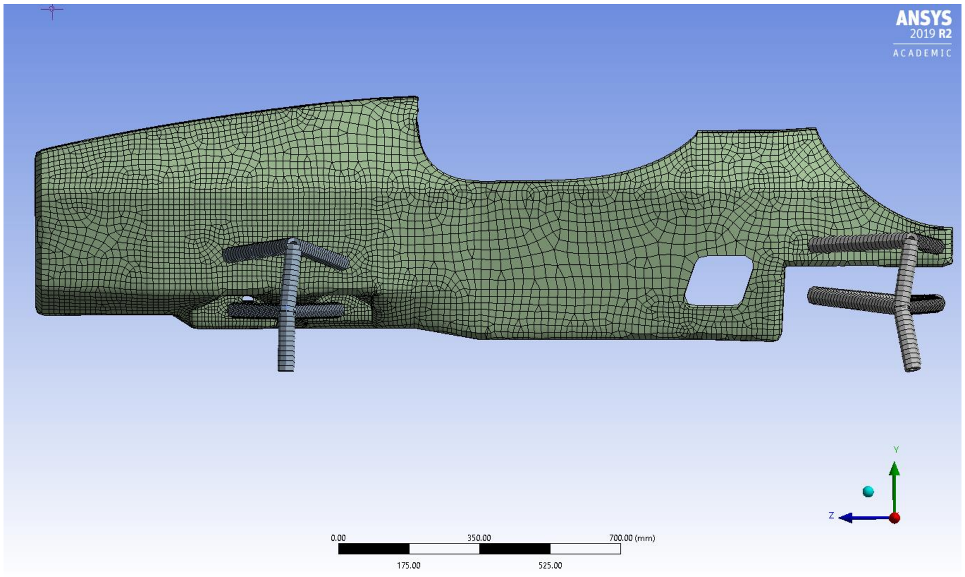


Figure 30 - Front suspension load case mesh side view

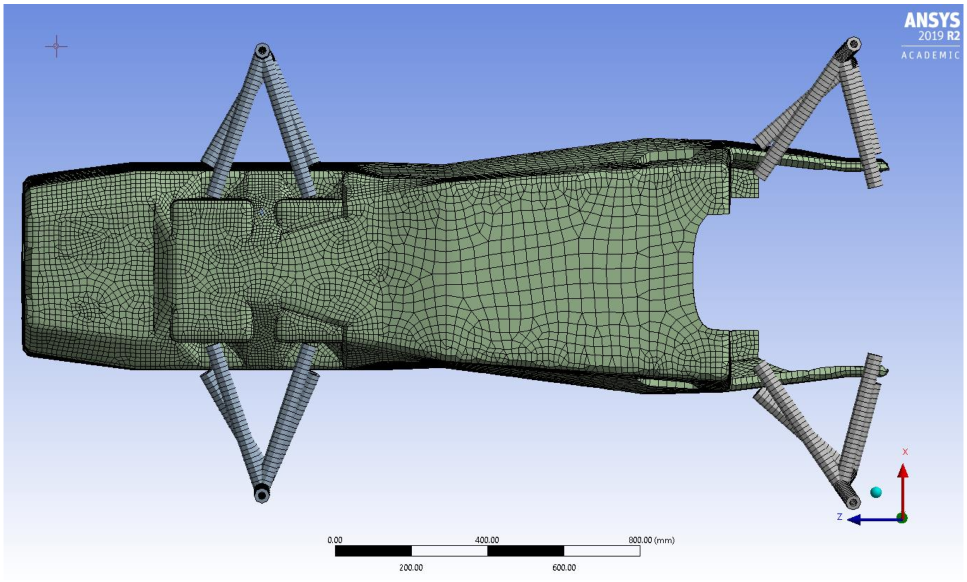
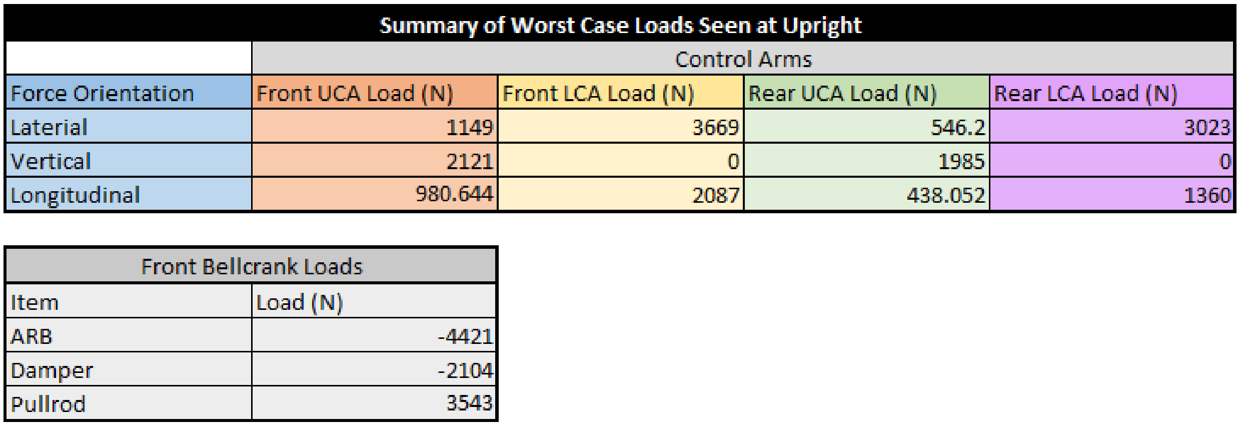


Figure 31 - Front suspension load case mesh bottom view

3.4.3 Load Cases

Each region was designed based off the Formula SAE Rules, as well as load cases experienced by the vehicle. The worst-case load scenario was used for designing each region of the vehicle. This worst-case loading scenario is defined by a 3G bump, 2G turn, during 1.5G braking. This load case was found to enact the largest loads through the control arms by the Formula SAE suspension team in 2017. The load magnitudes were generated through Mathcad. Figure 32 below shows the suspension loads through each region of the vehicle.



Summary of Worst Case Loads Seen at Upright

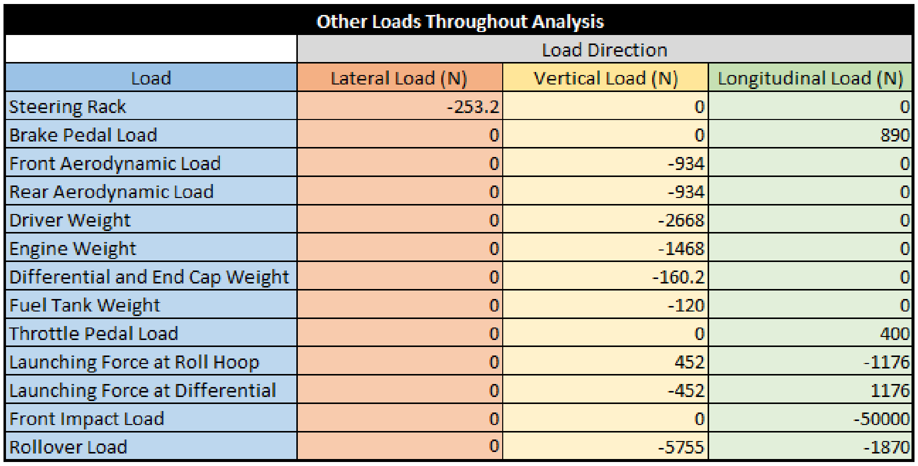
	Control Arms			
Force Orientation	Front UCA Load (N)	Front LCA Load (N)	Rear UCA Load (N)	Rear LCA Load (N)
Laterial	1149	3669	546.2	3023
Vertical	2121	0	1985	0
Longitudinal	980.644	2087	438.052	1360

Front Bellcrank Loads

Item	Load (N)
ARB	-4421
Damper	-2104
Pullrod	3543

Figure 32 - Suspension loads by region

Additionally, loads exist throughout the structure unrelated to the suspension. Figure 33 below shows these loads.



Other Loads Throughout Analysis			
	Load Direction		
Load	Lateral Load (N)	Vertical Load (N)	Longitudinal Load (N)
Steering Rack	-253.2	0	0
Brake Pedal Load	0	0	890
Front Aerodynamic Load	0	-934	0
Rear Aerodynamic Load	0	-934	0
Driver Weight	0	-2668	0
Engine Weight	0	-1468	0
Differential and End Cap Weight	0	-160.2	0
Fuel Tank Weight	0	-120	0
Throttle Pedal Load	0	0	400
Launching Force at Roll Hoop	0	452	-1176
Launching Force at Differential	0	-452	1176
Front Impact Load	0	0	-50000
Rollover Load	0	-5755	-1870

Figure 33 - Loads through other vehicle structures

3.4.3.1 Front Suspension Load Case

The front suspension load case study was the first test conducted, resulting in the most reiterations before finally passing. The front suspension load case uses the previously mentioned 3G bump, 2G turn, 1.5G braking suspension load numbers for the front end of the vehicle in addition to all weight, aerodynamic, and brake loads. The rear end of the vehicle is fixed at the suspension hardpoints. Additionally, the main hoop mounts are fixed because of the mounting method of the engine. The engine acts as a direct stiffener between the main roll hoop and the rear end cap, which houses the rear upper and lower control arm mounts. A setup of this simulation is shown in Figure 34 and Figure 35.

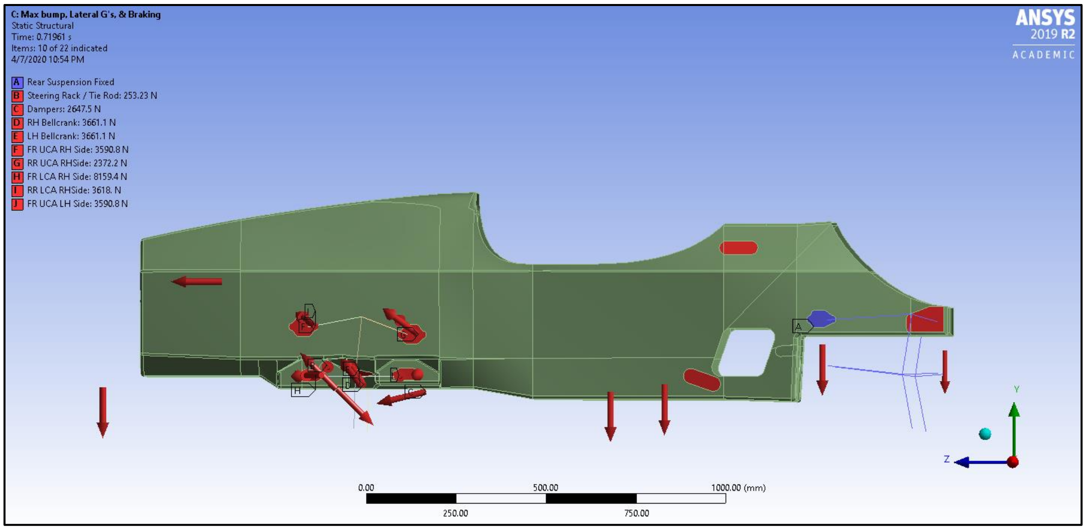


Figure 34 - Front suspension loads setup side view

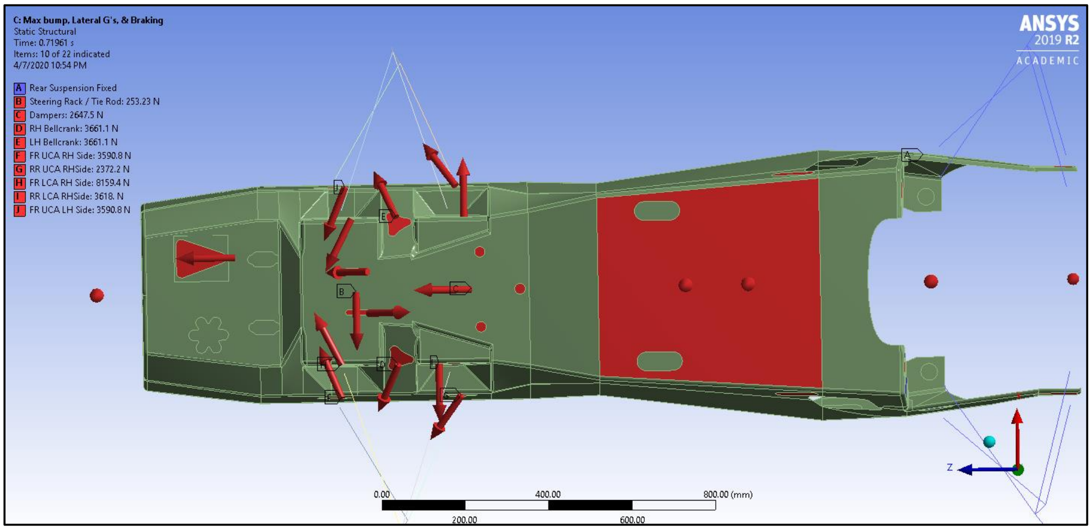
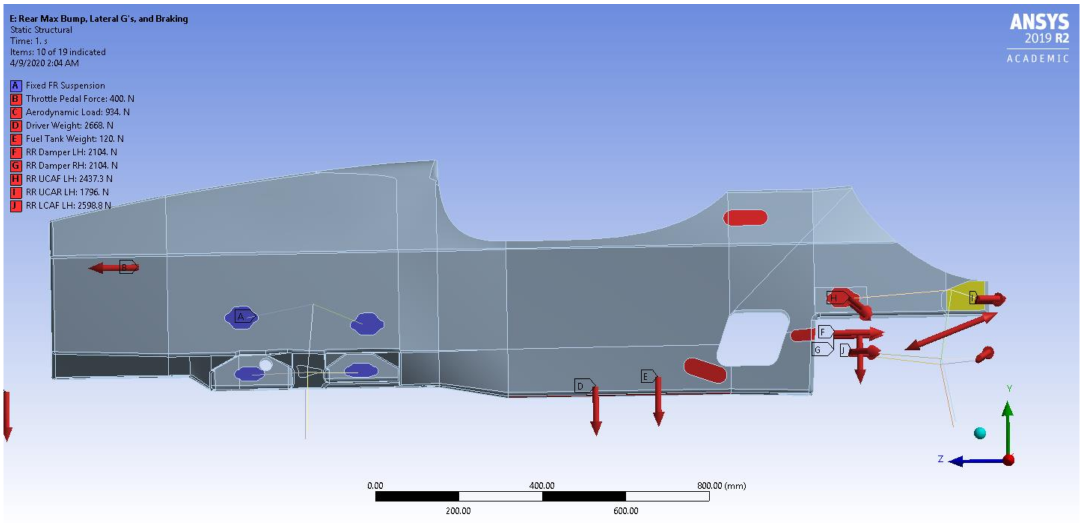


Figure 35 - Front suspension loads setup bottom view

3.4.3.2 Rear Suspension Load Case

The rear suspension load case was identical to that of the front suspension load case, using rear end data. Additionally, the rear suspension load case includes a launching force and throttle pedal force instead of braking. The launching of the vehicle creates a large load onto the rear engine compartment flanges of the vehicle and must be considered to prevent chassis failure at launch.

The simulation does not include the rear end cap or tubes, so a rigid support was included into the model. This support prevented transverse movement of the engine compartment at the regions where the end cap would be bolted to the structure. This accurately represents the end cap as it will still be able to twist inside the chassis but will not be able to compress transversely unless mass buckling occurs. This simulation is conservative however, as it does not represent the stiffness of the engine and the effect that it will play in stiffening the region between the main roll hoop mounts and engine compartment. The setup of this simulation can be seen in Figure 36 and Figure 37.



E: Rear Max Bump, Lateral G's, and Braking
Static Structural
Time: 1. s
Items: 10 of 19 indicated
4/9/2020 2:04 AM

A Fixed FR Suspension
B Throttle Pedal Force: 400. N
C Aerodynamic Load: 934. N
D Driver Weight: 2668. N
E Fuel Tank Weight: 120. N
F RR Damper LH: 2104. N
G RR Damper RH: 2104. N
H RR UCAF LH: 2437.3 N
I RR UCAR LH: 1796. N
J RR LCAF LH: 2598.8 N

Figure 36 - Rear suspension loads setup side view

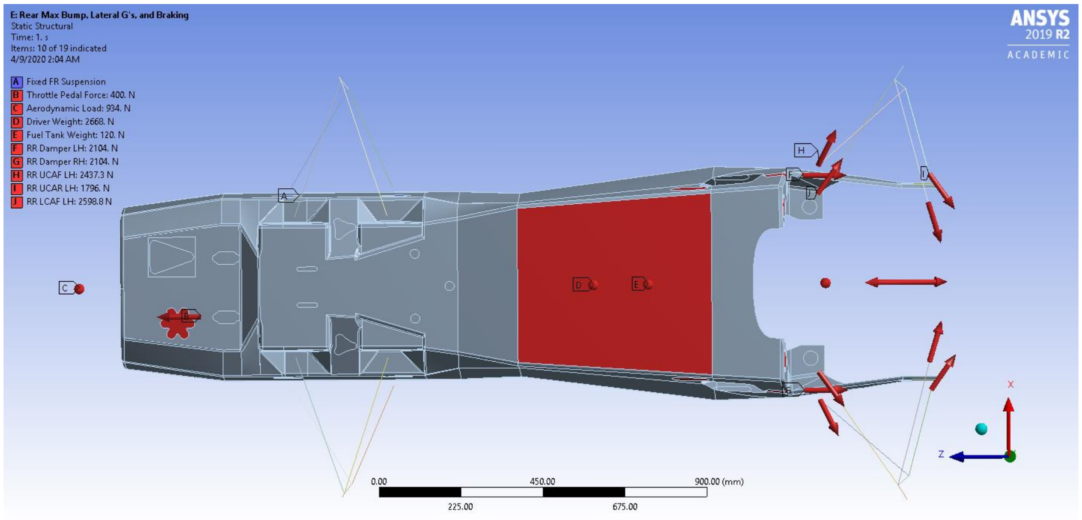


Figure 37 - Rear suspension loads setup bottom view

3.4.3.3 Rollover Load Case

The next simulated load case was a potential rollover scenario. This rollover scenario uses a predicted 2G vehicle load to the top of the chassis perpendicular to the rollover plane of the vehicle. This simulation was conservative in that it does not consider the distribution of force to the front roll hoop. This was done as the front roll hoop will not receive any load until a large portion of the front bulkhead and front bulkhead support is completely destroyed. Realistically, this is extremely unlikely as the front bulkhead laminate is historically extremely thick. To fix the chassis from movement, the suspension was secured as this would provide a distributed fixture. The rollover load case simulation setup can be seen in Figure 38.

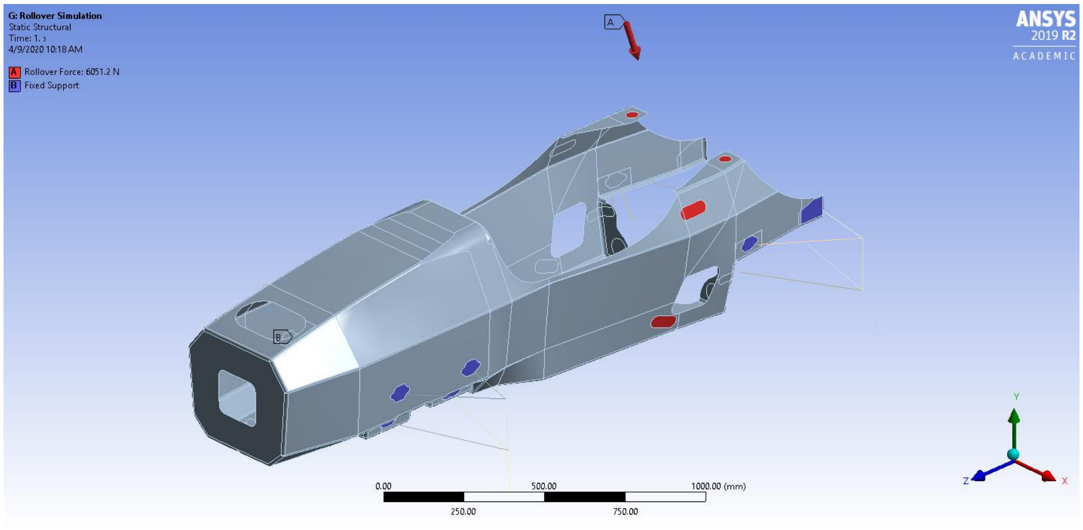


Figure 38 - Rollover load setup

3.4.3.4 Front Impact Load Case

The vehicle must also be able to survive colliding into a solid object at 7m/s per the Formula SAE Rulebook. The verification of this requirement is through quasi-static crush testing of a representative part of the chassis that extends 50mm rearward of the front bulkhead. To simulate this test, a 50mm section of the front end of the vehicle was exported into ANSYS. As the front bulkhead is the highest loaded laminate of the vehicle, it requires special attention in the laminate breakdown. As such, this simulation was created in more detail compared to the full monocoque simulation. Specifically, all areas where carbon fiber overlap occurs during the manufacturing process were given their own laminate designation as they will technically have two different laminates distributed into each region. This resulted in the laminate regions being defined as shown Figure 39 and Figure 40.

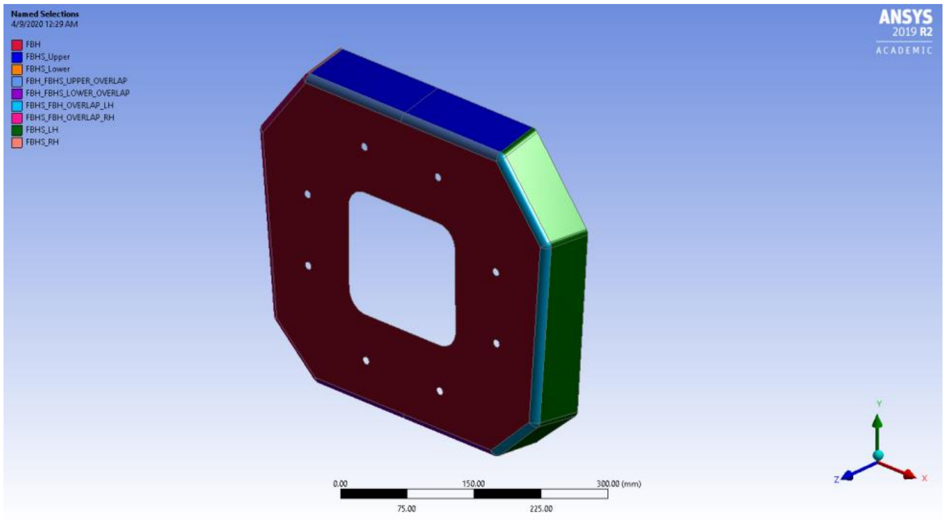


Figure 39 - Front impact load case laminate regions

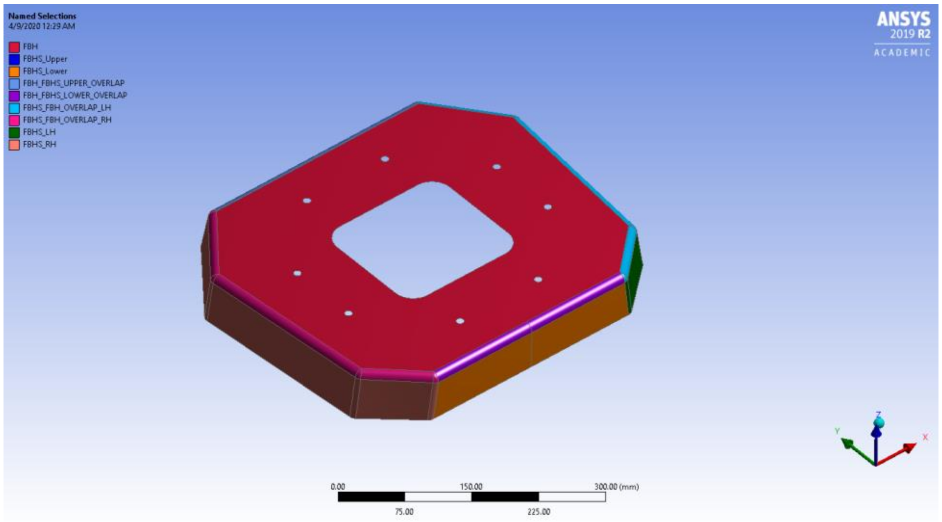


Figure 40 - Front impact load case laminate regions

Additionally, as this region was imported into ANSYS as a separate body, the mesh limit was reset. This allowed for a very fine mesh across the surface of the part. This mesh distribution can be seen in Figure 41 and Figure 42.

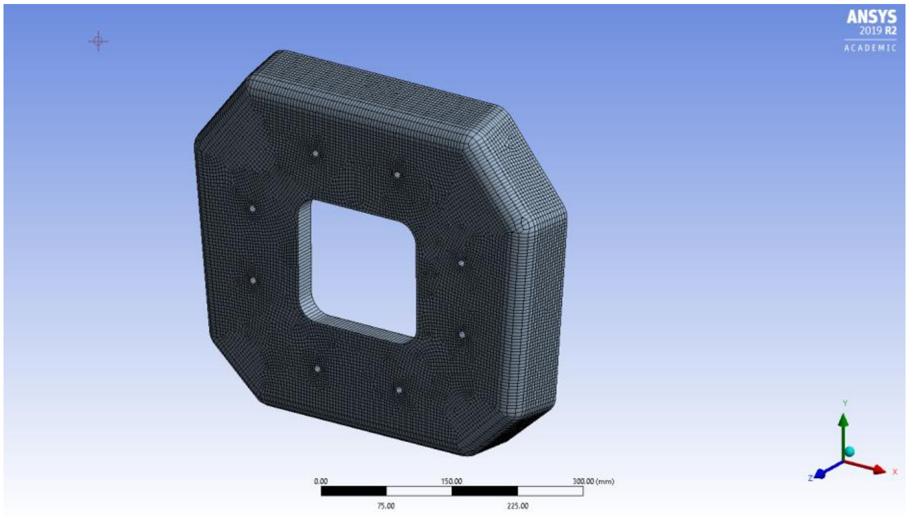


Figure 41 - Front impact load case mesh

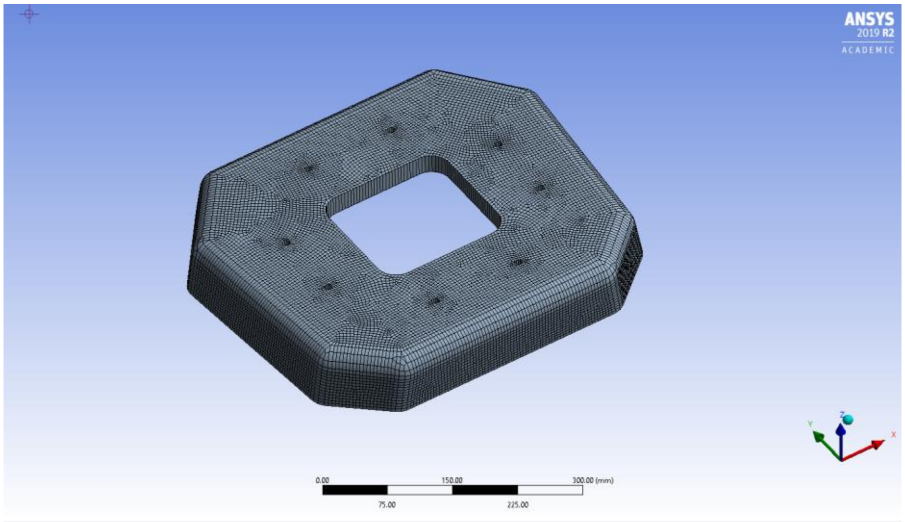


Figure 42 - Front impact load case mesh

Finally, the testing setup was created. During the physical quasi-static testing of the front bulkhead, the impact attenuator is the item being crushed. Bronco Racing uses a Plascore designed aluminum impact attenuator that crushes at a constant force of 50kN. However, this force is not applied directly to the composite front bulkhead. Instead, the force is applied to a 0.19in thick 6061 aluminum plate that is bolted to the front bulkhead. This plate is the rules required anti-intrusion plate.

To accurately demonstrate the front bulkhead, the anti-intrusion plate stiffness had to be considered. A low force deformation simulation was conducted to determine the magnitude of elastic support that the plate would provide to the chassis. Low force was used as plastic deformation of the anti-intrusion plate is not expected during the quasi-static crush test. The simulation is shown in Figure 43.

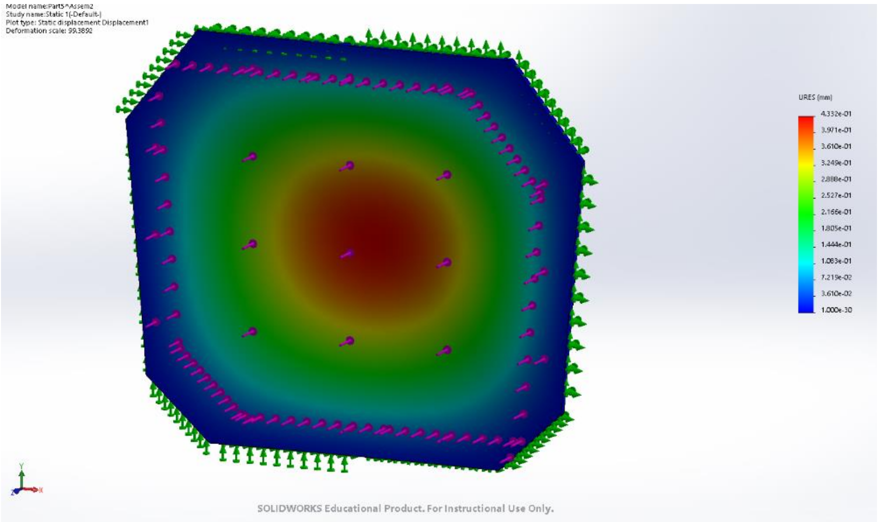


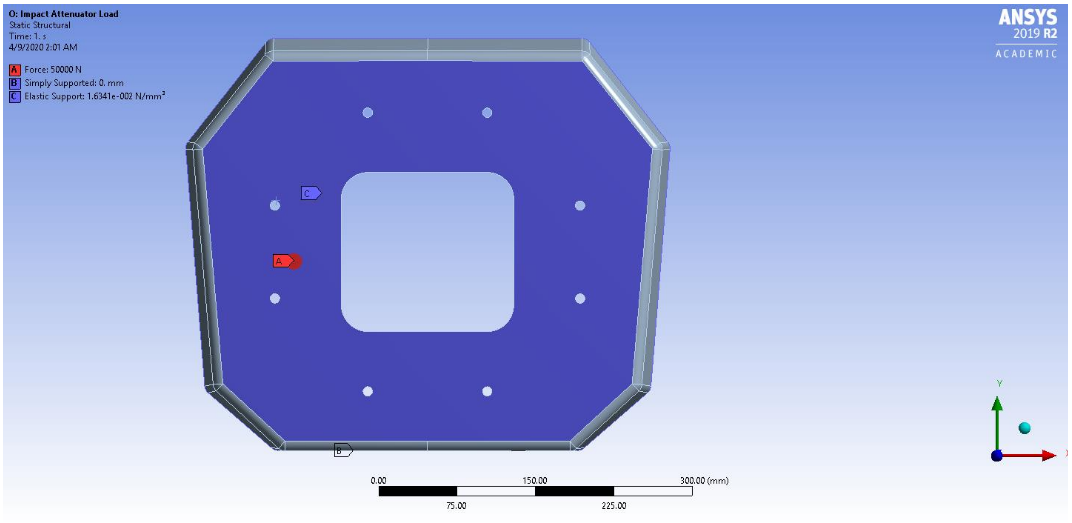
Figure 43 - Anti-intrusion plate stiffness test

The results demonstrate a 0.433mm deformation to the plate with a 1kN load. To determine the elastic foundation stiffness to be applied to the front bulkhead in ANSYS ACP, the equation in Figure 44 was used.

$$Elastic\ Foundation = \frac{Force\ Applied}{(Displacement * Load\ Area)}$$

Figure 44 - Elastic foundation stiffness equation

The resulting elastic foundation was applied to the ANSYS simulation. Additionally, the edges of the front bulkhead support were constrained to represent the fixture that the rest of the chassis would have on the front bulkhead unit. This simulation setup can be seen in Figure 45.



O: Impact Attenuator Load
Static Structural
Time: 1. s
4/9/2020 2:01 AM

A Force: 50000 N
B Simply Supported: 0. mm
C Elastic Support: 1.6341e-002 N/mm³

Figure 45 - Front bulkhead unit simulation setup

3.4.4 Analysis method

3.5 Analysis by Region

To adequately show that the monocoque chassis has been designed to meet all requirements from the load cases experienced and the Formula SAE rules, each region is described in detail below.

3.5.1 Front Bulkhead (FBH)

The front bulkhead region of the chassis is a regulated area in the front portion of the vehicle. This region is primarily responsible for protecting the driver in a front impact collision. Figure 46 below highlights this region on the designed chassis.

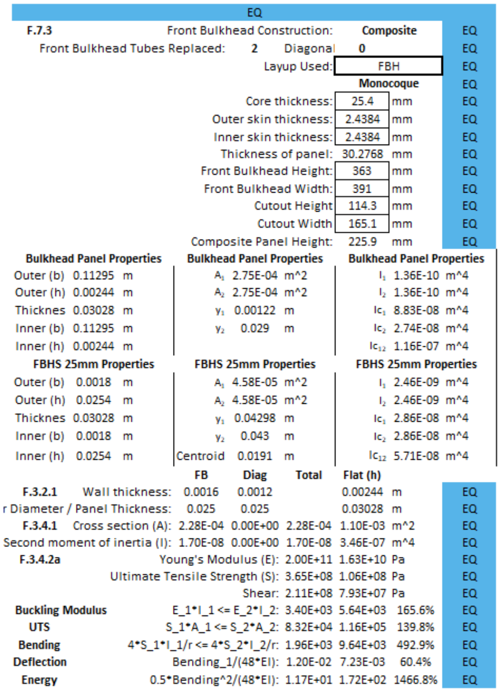
Figure 46 - Front bulkhead region highlighted

3.5.1.1 Rules Equivalence

The front bulkhead is the only regulated region of the vehicle without actual test data to support passing the Formula SAE rulebook. This is due to the shutdown of the WMU Parkview Campus due to the COVID19 pandemic. However, there is still data supporting the passing of all requirements based off previous laminates tested and simulation data.

The rules regarding the front bulkhead stiffness and failure state that the composite section must match yield and ultimate strengths in bending, buckling, and tension to that of a steel tube bulkhead comprised of 1”x0.065” steel tubing. Additionally, the front bulkhead must have a perimeter shear strength equivalent to that of a 1.5mm thick steel plate.

As the laminate was not physically test, a significantly similar laminate was used for stiffness calculations. As seen in Figure 47 below, it is clear that this laminate passes all Formula SAE Rulebook requirements as demonstrated from this portion of the SES.



	EQ			
F.7.3	Front Bulkhead Construction:	**Composite**		EQ
	Front Bulkhead Tubes Replaced: 2 Diagonal	**0**		EQ
	Layup Used:	FBH		EQ
		Monocoque		EQ
	Core thickness:	25.4	mm	EQ
	Outer skin thickness:	2.4384	mm	EQ
	Inner skin thickness:	2.4384	mm	EQ
	Thickness of panel:	30.2768	mm	EQ
	Front Bulkhead Height:	363	mm	EQ
	Front Bulkhead Width:	391	mm	EQ
	Cutout Height	114.3	mm	EQ
	Cutout Width	165.1	mm	EQ
	Composite Panel Height:	225.9	mm	EQ

Bulkhead Panel Properties			**Bulkhead Panel Properties**			**Bulkhead Panel Properties**		
Outer (b)	0.11295	m	A_1	2.75E-04	m^2	I_1	1.36E-10	m^4
Outer (h)	0.00244	m	A_2	2.75E-04	m^2	I_2	1.36E-10	m^4
Thicknes	0.03028	m	y_1	0.00122	m	Ic_1	8.83E-08	m^4
Inner (b)	0.11295	m	y_2	0.029	m	Ic_2	2.74E-08	m^4
Inner (h)	0.00244	m				Ic_{12}	1.16E-07	m^4
FBHS 25mm Properties			**FBHS 25mm Properties**			**FBHS 25mm Properties**		
Outer (b)	0.0018	m	A_1	4.58E-05	m^2	I_1	2.46E-09	m^4
Outer (h)	0.0254	m	A_2	4.58E-05	m^2	I_2	2.46E-09	m^4
Thicknes	0.03028	m	y_1	0.04298	m	Ic_1	2.86E-08	m^4
Inner (b)	0.0018	m	y_2	0.043	m	Ic_2	2.86E-08	m^4
Inner (h)	0.0254	m	Centroid	0.0191	m	Ic_{12}	5.71E-08	m^4

		FB	**Diag**	**Total**	**Flat (h)**		
F.3.2.1	Wall thickness:	0.0016	0.0012		0.00244	m	EQ
	r Diameter / Panel Thickness:	0.025	0.025		0.03028	m	EQ
F.3.4.1	Cross section (A):	2.28E-04	0.00E+00	2.28E-04	1.10E-03	m^2	EQ
	Second moment of inertia (I):	1.70E-08	0.00E+00	1.70E-08	3.46E-07	m^4	EQ
F.3.4.2a	Young's Modulus (E):			2.00E+11	1.63E+10	Pa	EQ
	Ultimate Tensile Strength (S):			3.65E+08	1.06E+08	Pa	EQ
	Shear:			2.11E+08	7.93E+07	Pa	EQ
Buckling Modulus	E_1*I_1 <= E_2*I_2:			3.40E+03	5.64E+03	165.6%	EQ
UTS	S_1*A_1 <= S_2*A_2:			8.32E+04	1.16E+05	139.8%	EQ
Bending	4*S_1*I_1/r <= 4*S_2*I_2/r:			1.96E+03	9.64E+03	492.9%	EQ
Deflection	Bending_1/(48*EI):			1.20E-02	7.23E-03	60.4%	EQ
Energy	0.5*Bending^2/(48*EI):			1.17E+01	1.72E+02	1466.8%	EQ

Figure 47 - Front bulkhead laminate meeting SES requirements

3.5.1.2 Front Impact Simulation

The ANSYS ACP front impact simulation was conducted using the parameters outlined in the previous section. There are two different solvers in this simulation. The result of the failure analysis simulation is shown in Figure 48 below.

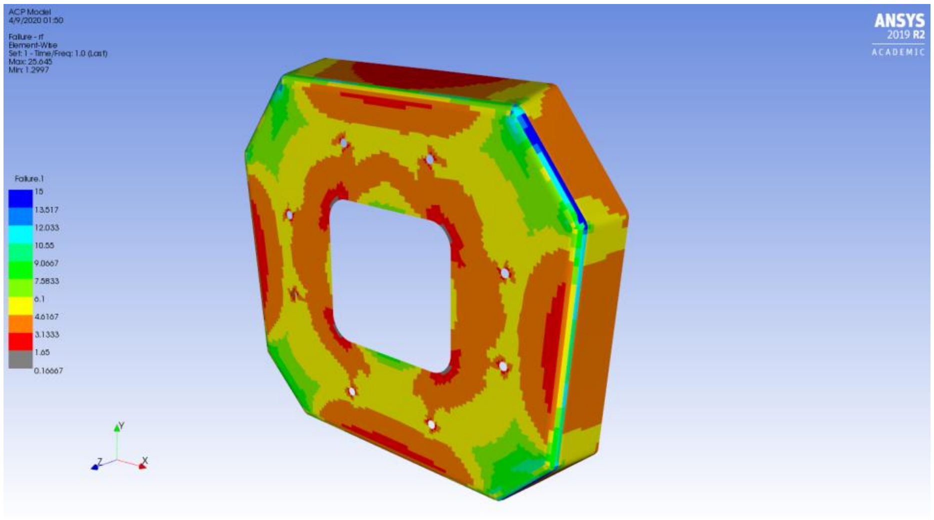


Figure 48 - Front impact failure simulation results

As seen above, the chassis does not meet the 1.65 factor of safety design parameter. However, this design is deemed acceptable for use. This is because the region of failure around the corners of the front bulkhead access hole will be covered in wet layup carbon fiber. This wet layup carbon fiber is required in a separate rule that prohibits exposed chassis core. This wet layup carbon fiber will aid in distributing load from the outer laminate to the inner.

Additionally, the rules require that during front impact the front bulkhead cannot deform more than 25mm during any part of the crash. Figure 49 below shows that the deformation of the front bulkhead is significantly less than the limit during the peak moment of the crash.

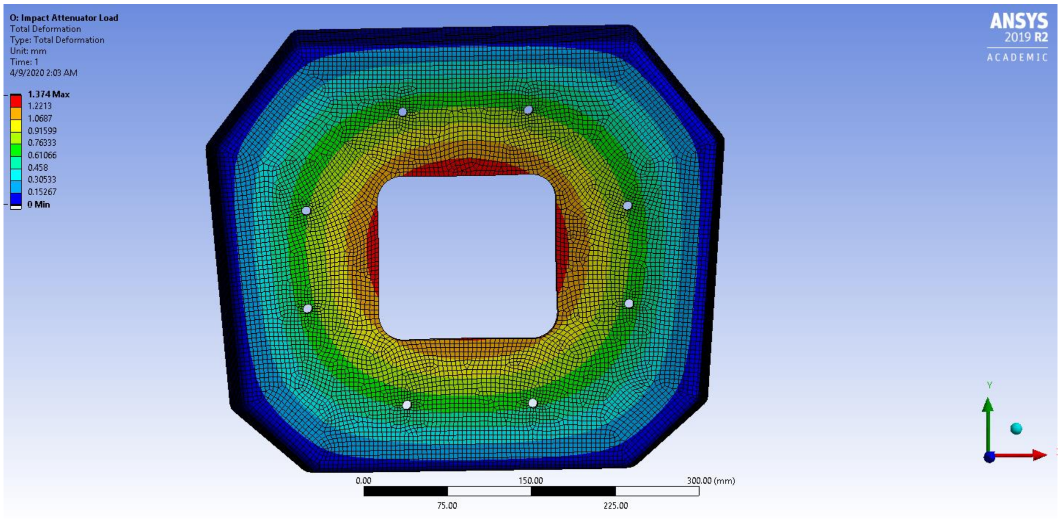


Figure 49 - Front impact deformation simulation results

3.5.2 Front Bulkhead Support (FBHS)

The front bulkhead support region of the vehicle experiences the highest cyclic load on any composite surface. As such, it is broken down into many separate laminate areas. Figure 50 below shows the region defined as the front bulkhead support in the Formula SAE Rulebook. When comparing this region with the regions defined in the ANSYS ACP simulation layout, the rules version of the front bulkhead support is more reduced. This allows for less laminate in regions where it is not necessary to pass the SES.

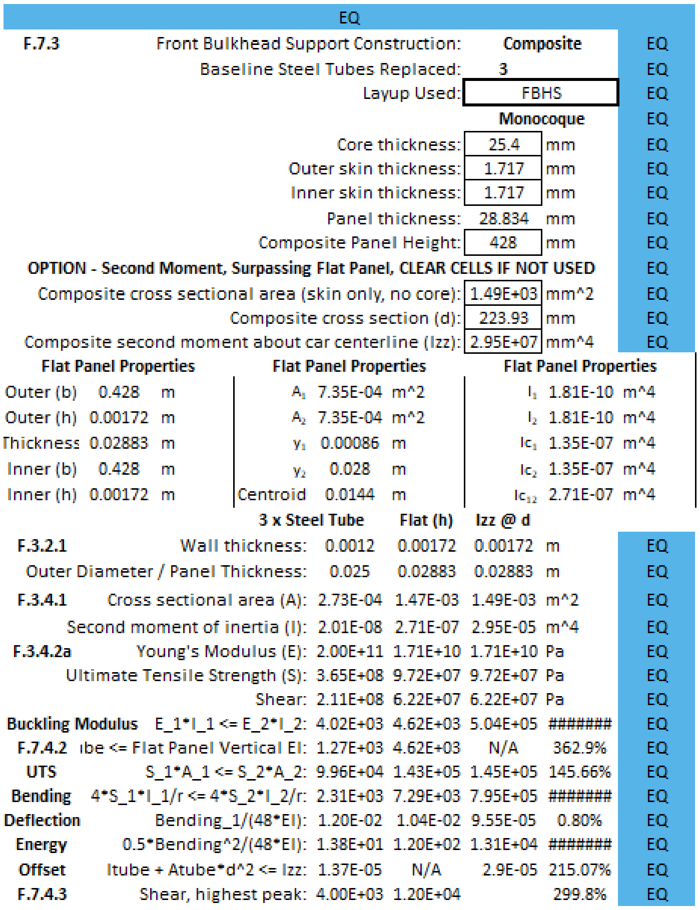
Figure 50 - FBHS Rules Regulated Region

3.5.2.1 Rules Equivalence

To meet the requirements of the SES, the front bulkhead support (FBHS) must meet the equivalent strength and stiffness of three 1”x0.047” steel tubes. However, this laminate region can also use the effective moment of inertia about the car centerline to meet this requirement. The moment of inertia was calculated using SolidWorks built in mass properties feature of the FBHS region, shown in Figure 51. Then, the perimeter of this region was measured to be 435.63 mm for each half. This was multiplied by the composite thickness of 1.717mm to find the composite cross-sectional area.

Figure 51 - FBHS Rules Regulated Region Moment of Inertia Calculation CAD

These values result in the monocoque FBHS region passing the SES. Figure 52 below shows the SES output equivalencies are met.



				EQ
F.7.3	Front Bulkhead Support Construction:	Composite		EQ
	Baseline Steel Tubes Replaced:	3		EQ
	Layup Used:	FBHS		EQ
		Monocoque		EQ
	Core thickness:	25.4	mm	EQ
	Outer skin thickness:	1.717	mm	EQ
	Inner skin thickness:	1.717	mm	EQ
	Panel thickness:	28.834	mm	EQ
	Composite Panel Height:	428	mm	EQ
	OPTION - Second Moment, Surpassing Flat Panel, CLEAR CELLS IF NOT USED			EQ
	Composite cross sectional area (skin only, no core):	1.49E+03	mm^2	EQ
	Composite cross section (d):	223.93	mm	EQ
	Composite second moment about car centerline (Izz):	2.95E+07	mm^4	EQ

Flat Panel Properties			Flat Panel Properties			Flat Panel Properties		
Outer (b)	0.428	m	A_1	7.35E-04	m^2	I_1	1.81E-10	m^4
Outer (h)	0.00172	m	A_2	7.35E-04	m^2	I_2	1.81E-10	m^4
Thickness	0.02883	m	y_1	0.00086	m	Ic_1	1.35E-07	m^4
Inner (b)	0.428	m	y_2	0.028	m	Ic_2	1.35E-07	m^4
Inner (h)	0.00172	m	Centroid	0.0144	m	Ic_{12}	2.71E-07	m^4

		3 x Steel Tube	Flat (h)	Izz @ d		
F.3.2.1	Wall thickness:	0.0012	0.00172	0.00172	m	EQ
	Outer Diameter / Panel Thickness:	0.025	0.02883	0.02883	m	EQ
F.3.4.1	Cross sectional area (A):	2.73E-04	1.47E-03	1.49E-03	m^2	EQ
	Second moment of inertia (I):	2.01E-08	2.71E-07	2.95E-05	m^4	EQ
F.3.4.2a	Young's Modulus (E):	2.00E+11	1.71E+10	1.71E+10	Pa	EQ
	Ultimate Tensile Strength (S):	3.65E+08	9.72E+07	9.72E+07	Pa	EQ
	Shear:	2.11E+08	6.22E+07	6.22E+07	Pa	EQ
Buckling Modulus	E_1*I_1 <= E_2*I_2:	4.02E+03	4.62E+03	5.04E+05	#######	EQ
F.7.4.2	ıbe <= Flat Panel Vertical EI:	1.27E+03	4.62E+03	N/A	362.9%	EQ
UTS	S_1*A_1 <= S_2*A_2:	9.96E+04	1.43E+05	1.45E+05	145.66%	EQ
Bending	4*S_1*I_1/r <= 4*S_2*I_2/r:	2.31E+03	7.29E+03	7.95E+05	#######	EQ
Deflection	Bending_1/(48*EI):	1.20E-02	1.04E-02	9.55E-05	0.80%	EQ
Energy	0.5*Bending^2/(48*EI):	1.38E+01	1.20E+02	1.31E+04	#######	EQ
Offset	Itube + Atube*d^2 <= Izz:	1.37E-05	N/A	2.9E-05	215.07%	EQ
F.7.4.3	Shear, highest peak:	4.00E+03	1.20E+04		299.8%	EQ

Figure 52 - FBHS meeting SES requirements

3.5.2.2 Suspension Hardpoints

The design requirement of the FBHS region is that it must survive the front suspension load case previously defined. The upper control arms mount to the rule-regulated region of the FBHS, while the lower control arms connect to the unregulated region. Due to this, the lower control arm region was able to have reduced core after a series of simulations. Figure 53 below shows the results of the front suspension load case.

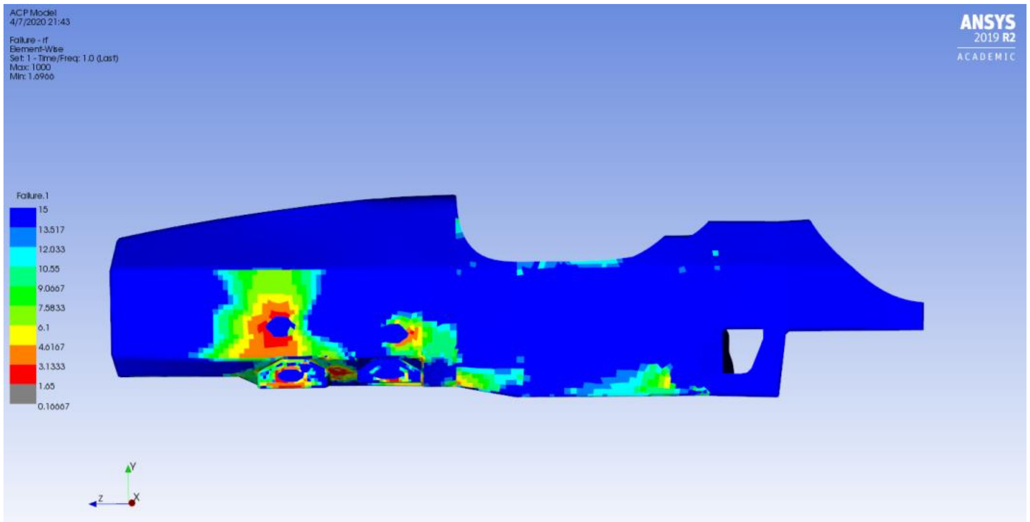


Figure 53 - Regulated FBHS regions front suspension load case results

This failure simulation shows that the FBHS structure passes the factor of safety requirement, achieving a 1.696 factor of safety in the FBHS region. Additionally, the unregulated regions of the vehicle at the FBHS lower laminate pass while also maintaining close to the required factor of safety. The highest area of stress in the FBHS lower laminate is at the brake pedal mount point, where standard grade balsa was placed to prevent core failure. The FBHS lower laminate failure can be seen in Figure 54.

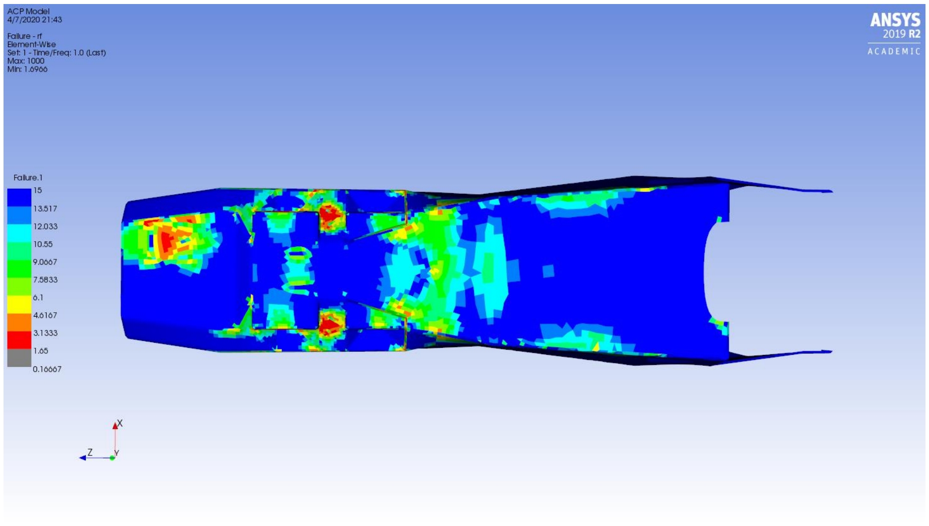


Figure 54 - Unregulated FBHS regions front suspension load case results

The final large subregion of the FBHS is the upper laminate. The upper laminate houses the access panel cutout for accessibility and maintenance to the pedal pox. This cutout is the only stressed region of the laminate; however, the stress is extremely minimal. Realistically, the largest load seen by this region will occur when someone is leaning on it while working on another component. As this is a very low stress region, the core was reduced to 0.5" thick Nomex core with an extremely thin laminate. Even with the extremely reduced laminate, the factor of safety of this region is extremely high. This can be seen in the factor of safety plot in Figure 55.

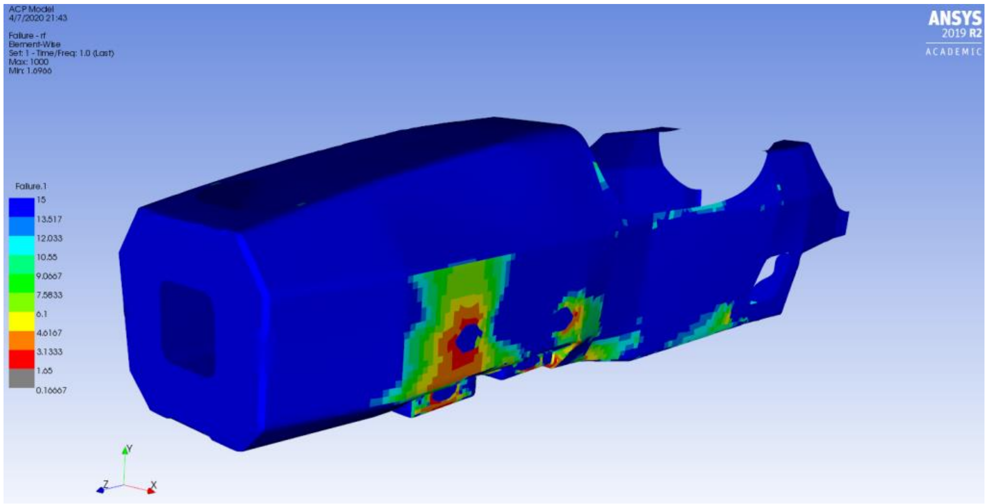


Figure 55 - FBHS factor of safety results

3.5.3 Front Roll Hoop

The front roll hoop is a regulated tube that must be rigidly mounted to the front portion of the chassis. The intention of this roll hoop is to prevent the driver cockpit from being crushed in a rollover scenario. However, due to the geometry of the designed monocoque, there would have to be extreme composite failure throughout the chassis for this roll hoop to be utilized. As a result, a simulation was not used, instead the rollover simulation focuses entirely on the main roll hoop, as described in the load case section previously. Instead, the front roll hoop was mathematically analyzed to ensure failure did not occur until the entire surrounding laminates fail. The front roll hoop is shown in Figure 56 below.

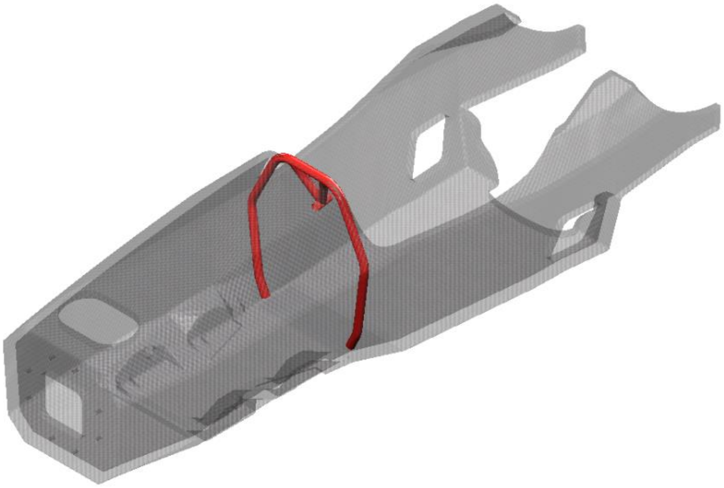


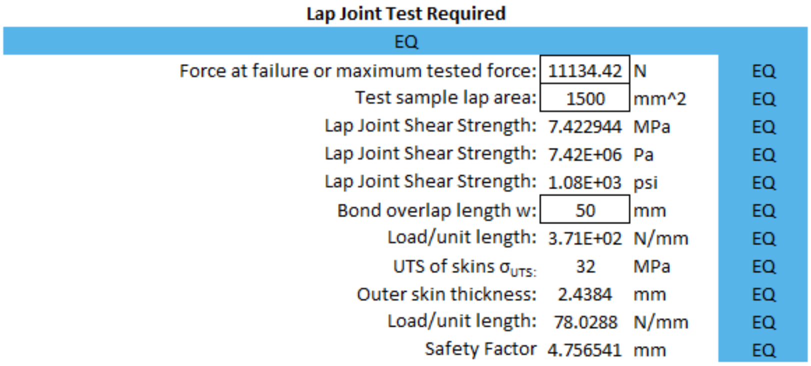
Figure 56 - Front roll hoop highlighted

The front roll hoop is bonded to the surrounding structure by a lap joint of carbon fiber. The carbon fiber wraps around the front roll hoop and lays on top of the prepared FBHS and vertical side impact structure (VSIS) laminates. When this joint is vacuum bagged and cured, it creates an extremely strong bond. More on the creation of this joint can be seen in Appendix A – Manufacturing Report. This lap joint will look similar to the BR19 lap joint of the same region shown in Figure 57 below.

Figure 57 – BR19 front roll hoop lap joint

3.5.3.1 Rules Equivalence

To mathematically calculate the strength of the lap joint, test samples were created. This setup and method of testing is explained in the testing section of this report. For this lap joint, it was found that a laminate that overlapped the bond region by 50mm was sufficiently strong. This laminate was able to support 11,134N before failure. Shown in Figure 58 below is the SES portion of this lap joint demonstrating that it is stronger than the monocoque's strongest laminate, the VSIS.



Lap Joint Test Required

EQ

Force at failure or maximum tested force:	11134.42	N	EQ
Test sample lap area:	1500	mm^2	EQ
Lap Joint Shear Strength:	7.422944	MPa	EQ
Lap Joint Shear Strength:	7.42E+06	Pa	EQ
Lap Joint Shear Strength:	1.08E+03	psi	EQ
Bond overlap length w:	50	mm	EQ
Load/unit length:	3.71E+02	N/mm	EQ
UTS of skins $\sigma_{UTS:}$	32	MPa	EQ
Outer skin thickness:	2.4384	mm	EQ
Load/unit length:	78.0288	N/mm	EQ
Safety Factor	4.756541	mm	EQ

Figure 58 - Front roll hoop lap joint meeting SES requirements

3.5.3.2 Simulation with Steering Loads

In addition to the Formula SAE Rulebook, the front roll hoop must also have supporting structure for the steering wheel assembly. The steering wheel assembly undergoes high amounts of torque from steering input. Additionally, the assembly must withstand large longitudinal and transverse forces from the driver while they brace themselves around tight turns. A simulation was created in SolidWorks to demonstrate that the front roll hoop meets the required loads. To begin the simulation, the front roll hoop was the rulebook required minimum of 1”x0.095”, while the steering column mount was started at the thinnest 1” tube available to maximize the effective moment of inertia without compromising welding ability. Figure 59 shows the resulting stress from a 100lb longitudinal load as well as a 100lb transverse load is significantly less than yield strength. The factor of safety of this design is 4.5.

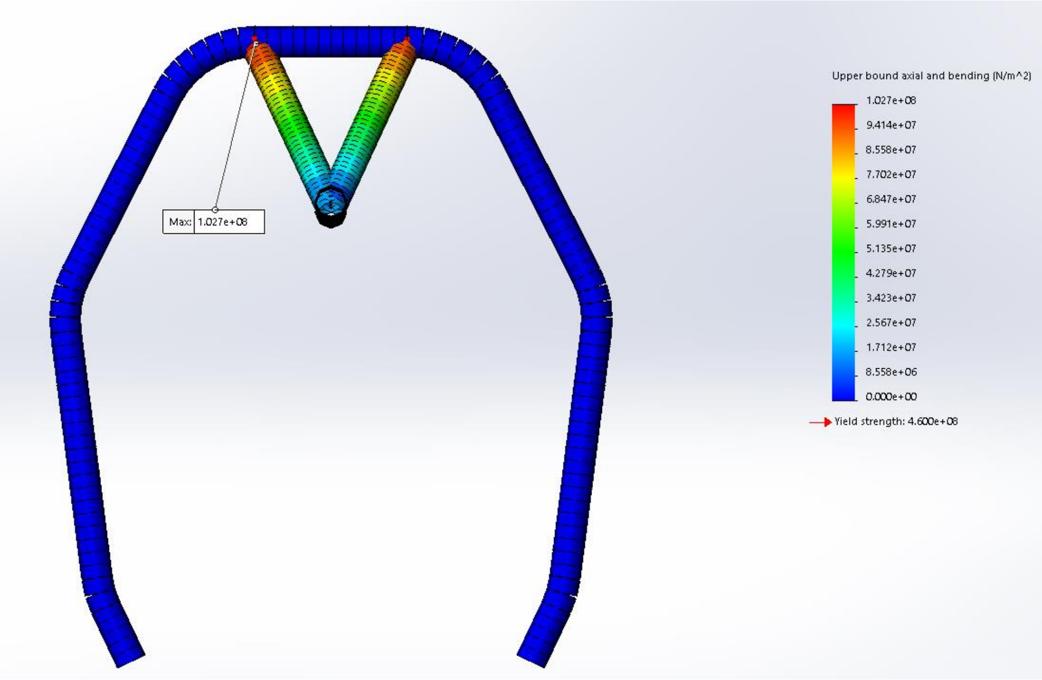


Figure 59 - Front roll hoop stresses with steering loads

It should be noted that this type of analysis utilizes beam theory. This is not an accurate representation of the structure at the weld surfaces of the tube. This analysis used joint bonding to represent the interaction of tube surfaces. However, the large factor of safety eliminates the need to pursue a more precise analysis.

To prevent unwanted movement of the wheel, the deflection of the steering assembly mount was measured. The total deflection was 0.316mm, demonstrating an acceptable amount of movement as it will not impact steering ability. The deflection gradient can be seen in Figure 60.

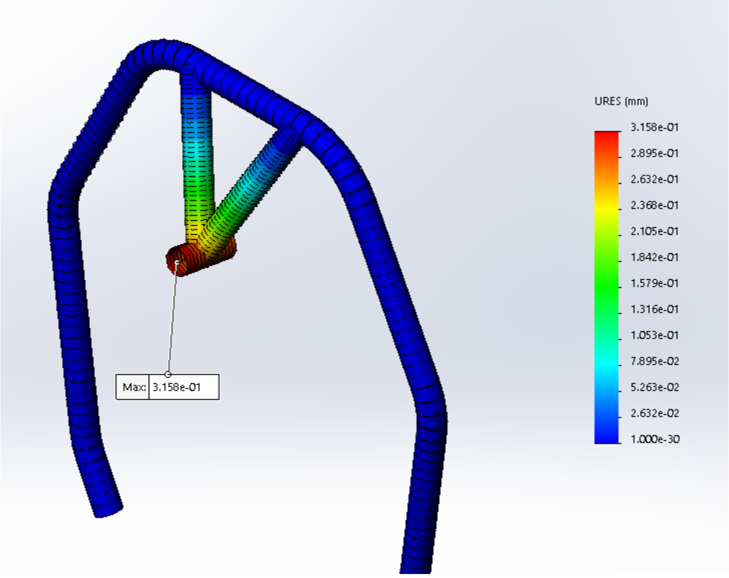


Figure 60 - Front roll hoop deflections with steering loads

Therefore, the final design of the front roll hoop followed the dimensions shown in Figure 61 below.

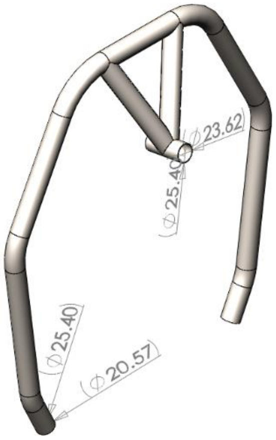


Figure 61 - Front roll hoop final dimensions

3.5.4 Horizontal Side Impact Structure (HSIS)

The horizontal side impact region is the regulated horizontal zone between the front roll hoop and main roll hoop. This region serves as a base for the vertical side impact structure. The Formula SAE Rulebook requires that this region be equivalent to at least one 1”x0.065” tube for strength and stiffness. This region is highlighted below in Figure 62.

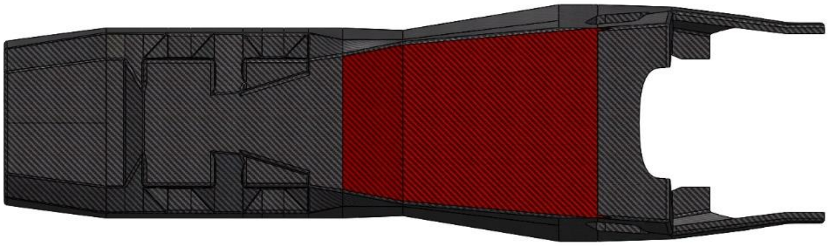


Figure 62 - HSIS region highlighted

The worst-case loading of front and rear suspension is the largest test of this laminate region. Figure 63 and Figure 64 show the impact of this loading on the region.

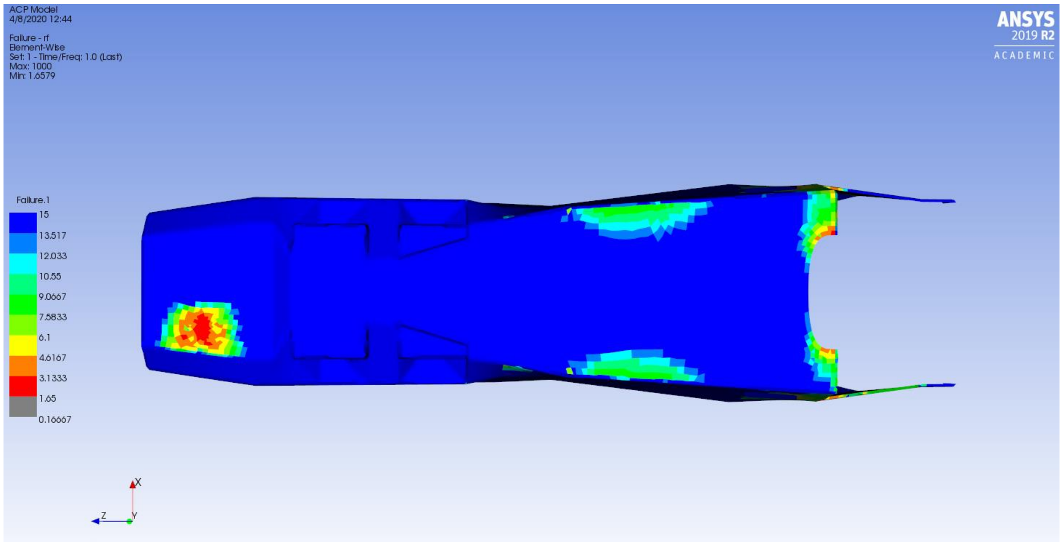


Figure 63 - Front and rear suspension load case on HSIS

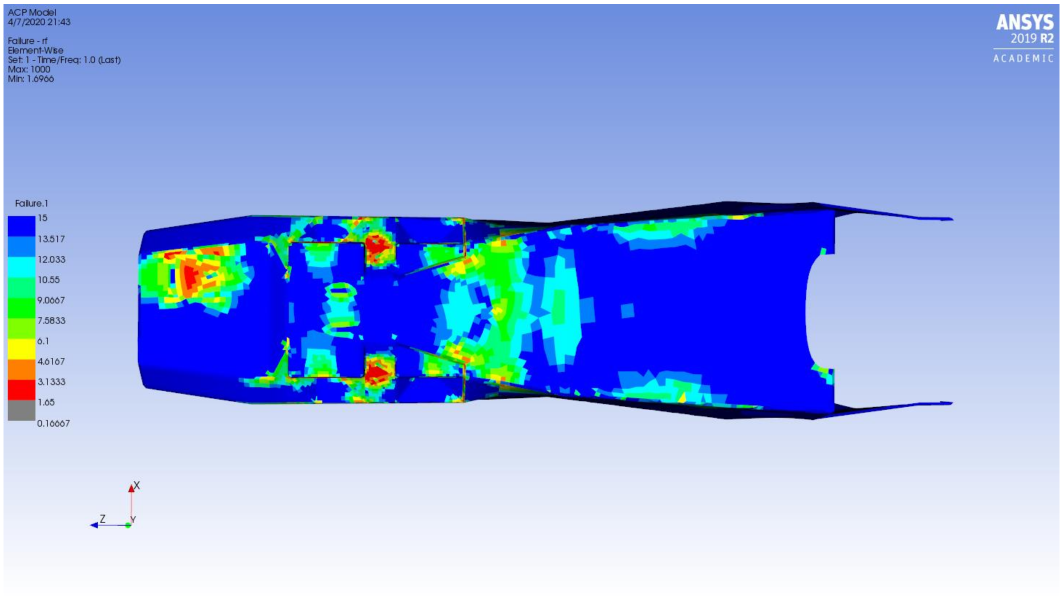
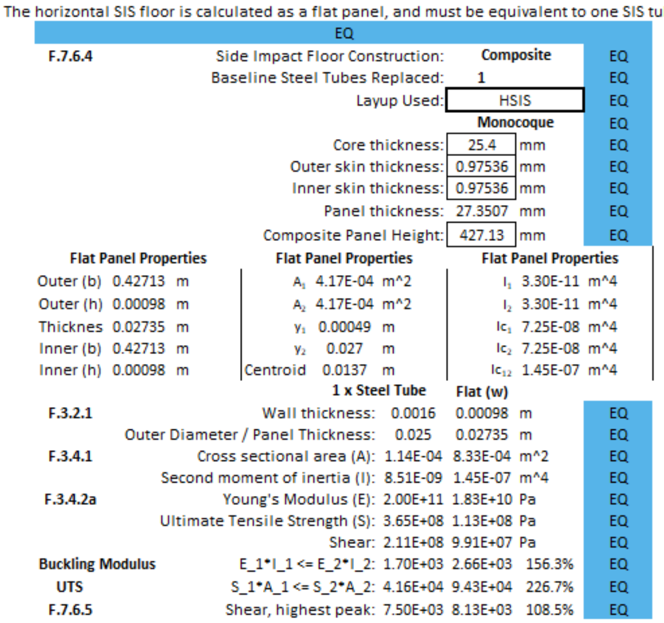


Figure 64 - Front and rear suspension load case on HSIS

3.5.4.1 Rules Equivalence

To confirm that this laminate was sufficiently stiff, the region was physically tested using the three-point bend method approach. The panel properties were then used to confirm that this region passes all requirements in the SES. This equivalence is shown in Figure 65 below.



The horizontal SIS floor is calculated as a flat panel, and must be equivalent to one SIS tube.

EQ

F.7.6.4	Side Impact Floor Construction:	**Composite**		EQ
	Baseline Steel Tubes Replaced:	1		EQ
	Layup Used:	HSIS		EQ
		Monocoque		EQ
	Core thickness:	25.4	mm	EQ
	Outer skin thickness:	0.97536	mm	EQ
	Inner skin thickness:	0.97536	mm	EQ
	Panel thickness:	27.3507	mm	EQ
	Composite Panel Height:	427.13	mm	EQ

Flat Panel Properties			**Flat Panel Properties**			**Flat Panel Properties**		
Outer (b)	0.42713	m	A_1	4.17E-04	m^2	I_1	3.30E-11	m^4
Outer (h)	0.00098	m	A_2	4.17E-04	m^2	I_2	3.30E-11	m^4
Thicknes	0.02735	m	y_1	0.00049	m	Ic_1	7.25E-08	m^4
Inner (b)	0.42713	m	y_2	0.027	m	Ic_2	7.25E-08	m^4
Inner (h)	0.00098	m	Centroid	0.0137	m	Ic_{12}	1.45E-07	m^4

		1 x Steel Tube	**Flat (w)**		
F.3.2.1	Wall thickness:	0.0016	0.00098	m	EQ
	Outer Diameter / Panel Thickness:	0.025	0.02735	m	EQ
F.3.4.1	Cross sectional area (A):	1.14E-04	8.33E-04	m^2	EQ
	Second moment of inertia (I):	8.51E-09	1.45E-07	m^4	EQ
F.3.4.2a	Young's Modulus (E):	2.00E+11	1.83E+10	Pa	EQ
	Ultimate Tensile Strength (S):	3.65E+08	1.13E+08	Pa	EQ
	Shear:	2.11E+08	9.91E+07	Pa	EQ
Buckling Modulus	E_1*I_1 <= E_2*I_2:	1.70E+03	2.66E+03	156.3%	EQ
UTS	S_1*A_1 <= S_2*A_2:	4.16E+04	9.43E+04	226.7%	EQ
F.7.6.5	Shear, highest peak:	7.50E+03	8.13E+03	108.5%	EQ

Figure 65 - HSIS meeting SES requirements

3.5.4.2 Harness Mounting

In addition to this section being regulated for steel tube equivalence, it must also support the lap belt and anti-submarine belt mounting points. A minimum perimeter shear strength of the laminate is regulated to be 7.5kN for a 25mm diameter punch. After testing the laminate, a perimeter shear of 105.08N/mm was determined, which provides a factor of safety of 1.12. Using this value, the harness mount was designed.

Due to the perimeter shear strength requirement, the backing plate of the harness mount must have a perimeter of at least 306.19mm. The mount itself must also withstand 19.5kN per the Formula SAE Rulebook. Using this, the mount was designed to the dimensions shown in Figure 66 below. This mount will be constructed of individual waterjet pieces of 4130 chromoly steel welded together along multiple seams.

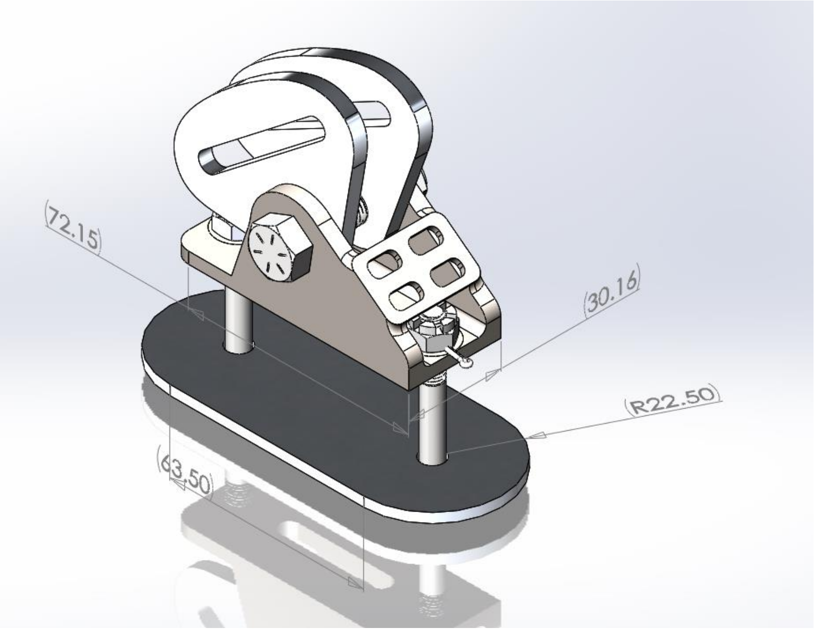


Figure 66 - Harness mount design dimensions

This mount was then simulated to ensure that the mount itself did not fail when fully loaded. The 19.5kN load was applied in the direction of the belts, and the fixtures occur at the bolt head locations.

As seen in Figure 67, this mount passes the Formula SAE Rulebook requirements from the mount itself through to the structural integrity of the supporting laminate. Physical testing of this mount occurred and is demonstrated in the testing section of this report.

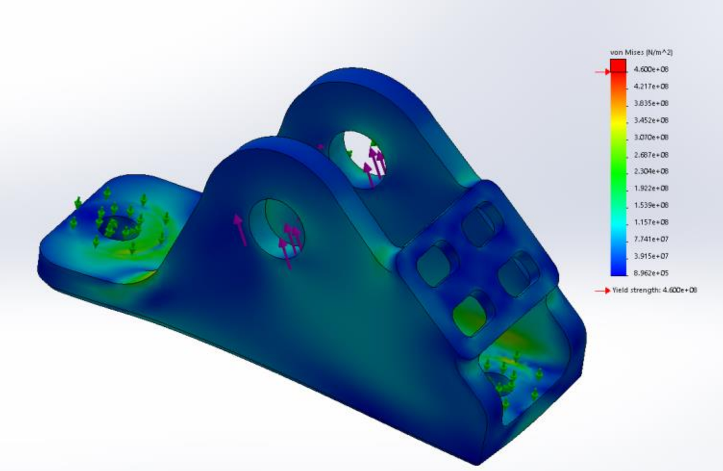


Figure 67 - Harness mount simulation results

3.5.5 Main Roll Structure

3.5.5.1 Main Roll Hoop

The main roll hoop is the primary method of protection for the driver of the vehicle in a rollover scenario. The roll hoop is heavily regulated in size and geometry. Shown in Figure 68 is the tubing defined as the main roll hoop.

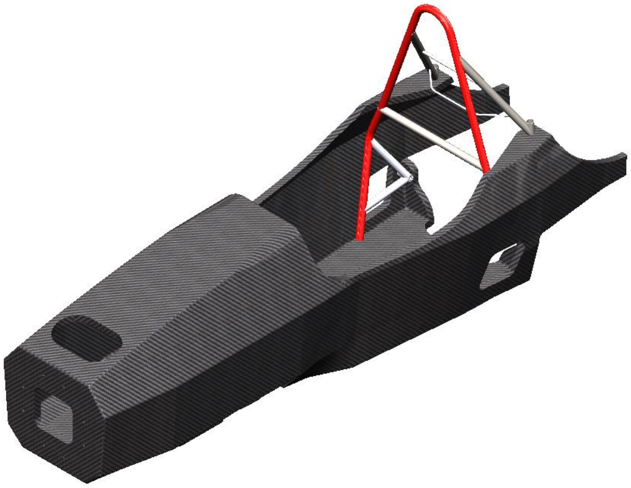
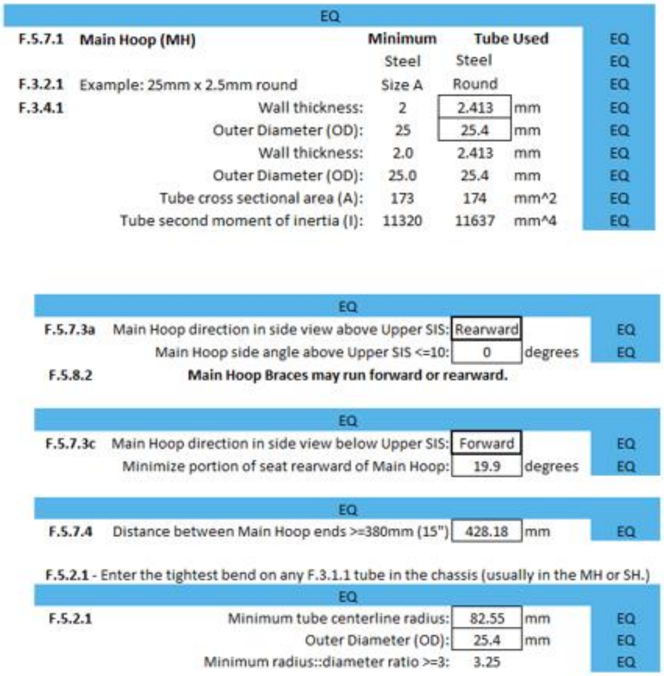


Figure 68 - Main roll hoop highlighted

The main roll hoop is required to be at least 1”x0.095” tubing or stiffer. Additionally, the rules require that the roll hoop is braced within a certain distance of the upper hoop surface, as well as braced at all bends. The structure designed uses a completely vertical hoop with only one bend. This bend is braced to the main hoop mount laminate shown in the ANSYS ACP region definition section. This laminate then distributes load into the VSIS and main hoop bracing supports region. These mounts can be seen in the mount design region of this report. The tubing size was chosen to be the minimum regulated size to reduce weight. As the minimum regulatory tube sizes were used, a simulation was not deemed necessary to confirm compliance. Figure 69 shown below demonstrates the adherence of the main roll hoop geometry to the SES.



		EQ			
F.5.7.1	**Main Hoop (MH)**	**Minimum**	**Tube Used**		EQ
		Steel	Steel		EQ
F.3.2.1	Example: 25mm x 2.5mm round	Size A	Round		EQ
F.3.4.1	Wall thickness:	2	2.413	mm	EQ
	Outer Diameter (OD):	25	25.4	mm	EQ
	Wall thickness:	2.0	2.413	mm	EQ
	Outer Diameter (OD):	25.0	25.4	mm	EQ
	Tube cross sectional area (A):	173	174	mm^2	EQ
	Tube second moment of inertia (I):	11320	11637	mm^4	EQ

		EQ		
F.5.7.3a	Main Hoop direction in side view above Upper SIS:	Rearward		EQ
	Main Hoop side angle above Upper SIS <=10:	0	degrees	EQ
F.5.8.2	**Main Hoop Braces may run forward or rearward.**			

		EQ		
F.5.7.3c	Main Hoop direction in side view below Upper SIS:	Forward		EQ
	Minimize portion of seat rearward of Main Hoop:	19.9	degrees	EQ

		EQ		
F.5.7.4	Distance between Main Hoop ends >=380mm (15")	428.18	mm	EQ

F.5.2.1 - Enter the tightest bend on any F.3.1.1 tube in the chassis (usually in the MH or SH.)

		EQ		
F.5.2.1	Minimum tube centerline radius:	82.55	mm	EQ
	Outer Diameter (OD):	25.4	mm	EQ
	Minimum radius::diameter ratio >=3:	3.25		EQ

Figure 69 - Main roll hoop meeting SES requirements

Another purpose of the main roll hoop is to create a weldable surface that various items of the powertrain can mount to. The designed main roll hoop structure includes engine mounts and firewall mounts that weld directly to this tubing. These items can be seen highlighted in red in Figure 70 below.

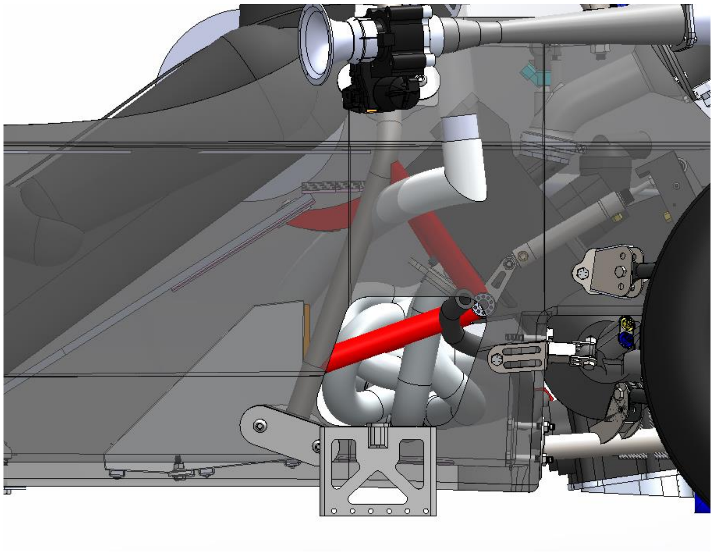


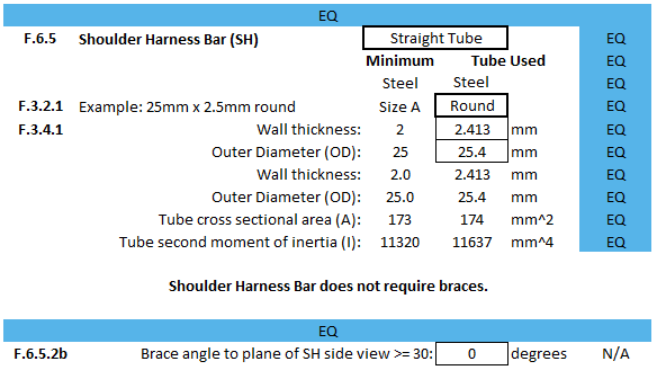
Figure 70 - Mounts on main roll hoop highlighted

3.5.5.2 Shoulder Harness Bar

The shoulder harness bar is a regulated tube attached to the main roll hoop. The Formula SAE Rulebook allows for two different methods of securing the shoulder harness. The first is 1”x0.095” steel tube or stiffer. The other option is the equivalent strength made of carbon fiber laminate. Due to the spacing required to bridge the laminates from each side of the vehicle to behind the driver, it was found to be easier and lighter to use the minimum sized tube. This tube spans the distance between two vertical components of the main roll hoop, behind the driver’s neck. This design is also efficient in that it does not require any extra bracing that a bent harness tube would need. Figure 71 shows the designed shoulder harness bar.

Figure 71 - Shoulder harness bar highlighted

Due to the minimum regulatory size used, a simulation was not deemed necessary. Figure 72 below shows that the shoulder harness bar meets the requirements of the SES.



			EQ		
F.6.5	**Shoulder Harness Bar (SH)**	Straight Tube			EQ
		Minimum	**Tube Used**		EQ
		Steel	Steel		EQ
F.3.2.1	Example: 25mm x 2.5mm round	Size A	Round		EQ
F.3.4.1	Wall thickness:	2	2.413	mm	EQ
	Outer Diameter (OD):	25	25.4	mm	EQ
	Wall thickness:	2.0	2.413	mm	EQ
	Outer Diameter (OD):	25.0	25.4	mm	EQ
	Tube cross sectional area (A):	173	174	mm^2	EQ
	Tube second moment of inertia (I):	11320	11637	mm^4	EQ

Shoulder Harness Bar does not require braces.

		EQ		
F.6.5.2b	Brace angle to plane of SH side view >= 30:	0	degrees	N/A

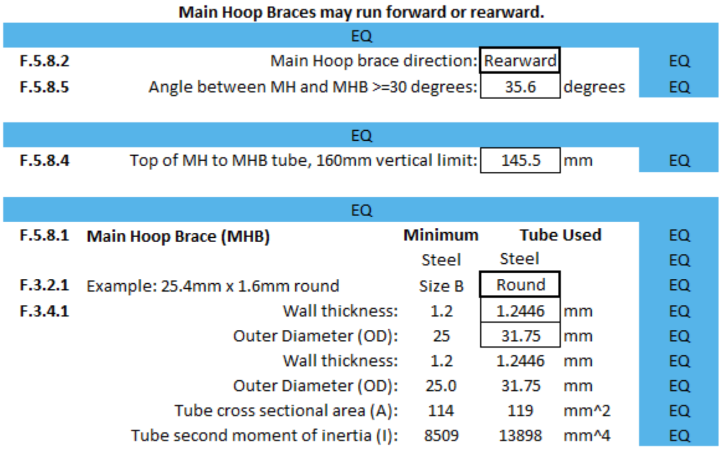
Figure 72 - Shoulder harness bar meeting SES requirements

3.5.5.3 Main Hoop Bracing

The final portion of the main hoop structure is the bracing that supports the hoop in a rollover event. This tubing is regulatory and must be as strong and stiff as a 1”x0.065” tube. Two supports must weld to the main roll hoop less than 160mm below the upper surface of the hoop. Additionally, these mounts must have an angle of at least 30° to the main roll hoop to ensure enough longitudinal support. Due to these constraints, the braces were designed as shown in Figure 73.

Figure 73 - Main roll hoop bracing highlighted

Equivalence to the rules for the main hoop bracing is shown in the excerpt of the SES shown in Figure 74.



Main Hoop Braces may run forward or rearward.

		EQ			
F.5.8.2	Main Hoop brace direction:		Rearward		EQ
F.5.8.5	Angle between MH and MHB >=30 degrees:		35.6	degrees	EQ
		EQ			
F.5.8.4	Top of MH to MHB tube, 160mm vertical limit:		145.5	mm	EQ
		EQ			
F.5.8.1	**Main Hoop Brace (MHB)**	**Minimum**	**Tube Used**		EQ
		Steel	Steel		EQ
F.3.2.1	Example: 25.4mm x 1.6mm round	Size B	Round		EQ
F.3.4.1	Wall thickness:	1.2	1.2446	mm	EQ
	Outer Diameter (OD):	25	31.75	mm	EQ
	Wall thickness:	1.2	1.2446	mm	EQ
	Outer Diameter (OD):	25.0	31.75	mm	EQ
	Tube cross sectional area (A):	114	119	mm^2	EQ
	Tube second moment of inertia (I):	8509	13898	mm^4	EQ

Figure 74 - Main roll hoop bracing meeting SES requirements

3.5.6 Main Hoop Bracing Support (MHBS)

The next two sections are completely new composite regions compared to the BR20 vehicle. Previously, the main hoop bracing support was constructed of two 1”x0.049” tubes that connected from the MHB to the VSIS. This region of composite continues the same load path as the steel tubes but through a much shorter span, saving weight. Shown in Figure 75 below is the MHBS region.

Figure 75 - MHBS region highlighted

3.5.6.1 Rules Equivalence

The MHBS region is unique in that the load path of the region is very specific. To properly transfer load from the main roll hoop back to the VSIS, the fibers of the laminate are adjusted to follow the expected load path. Figure 76 below shows that the 0° direction is now rotated to follow the desired load path.

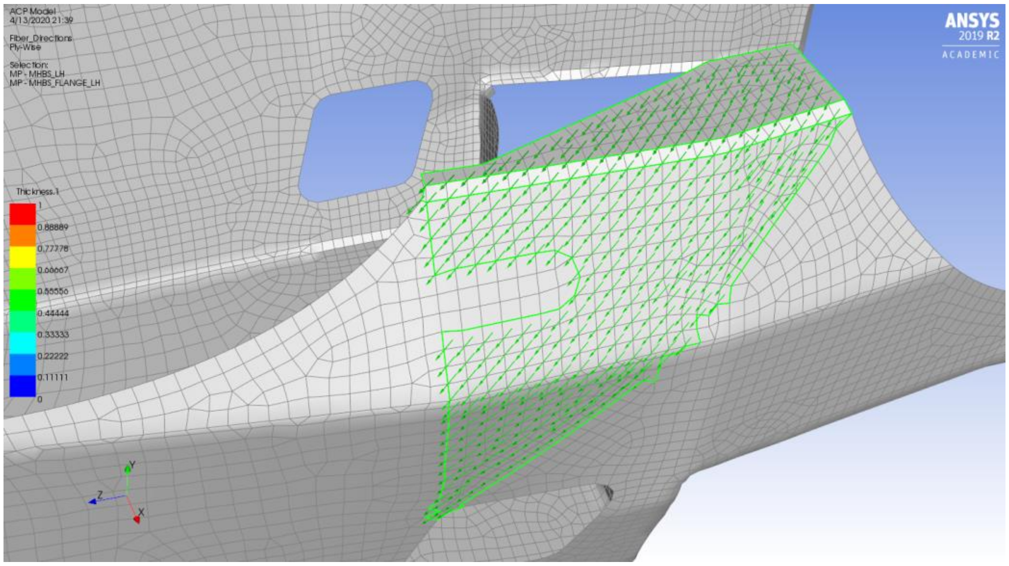
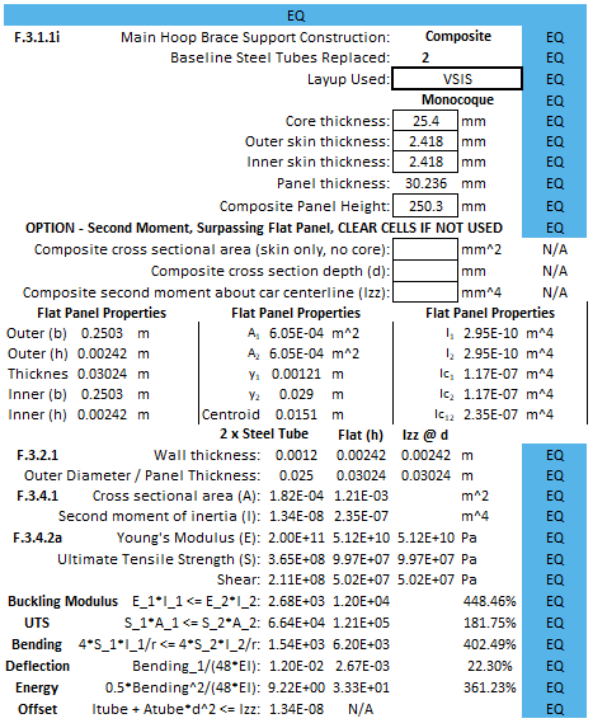


Figure 76 - Laminate fiber direction for MHBS

Additionally, this region must be able to meet geometric requirements from the SES, shown in Figure 77. There are two options, one of which must be met. The first option is that the flat panel equivalence exceeds that of the previous two steel tubes used. If the flat panel version equivalence is not used, then monocoque geometry can be used to show equivalent stiffness in the structure, similar to the method used on the FBHS. However, the designed monocoque is able to use the flat panel equivalence demonstrated below in an excerpt from the SES. Note that VSIS is used as the composite. This is because the MHBS and VSIS are identical laminates to reduce unnecessary complexity.



EQ

F.3.1.1i	Main Hoop Brace Support Construction:	**Composite**		EQ
	Baseline Steel Tubes Replaced:	**2**		EQ
	Layup Used:	VSIS		EQ
		Monocoque		EQ
	Core thickness:	25.4	mm	EQ
	Outer skin thickness:	2.418	mm	EQ
	Inner skin thickness:	2.418	mm	EQ
	Panel thickness:	30.236	mm	EQ
	Composite Panel Height:	250.3	mm	EQ
	OPTION - Second Moment, Surpassing Flat Panel, CLEAR CELLS IF NOT USED			EQ
	Composite cross sectional area (skin only, no core):		mm^2	N/A
	Composite cross section depth (d):		mm	N/A
	Composite second moment about car centerline (Izz):		mm^4	N/A

Flat Panel Properties			**Flat Panel Properties**			**Flat Panel Properties**		
Outer (b)	0.2503	m	A_1	6.05E-04	m^2	I_1	2.95E-10	m^4
Outer (h)	0.00242	m	A_2	6.05E-04	m^2	I_2	2.95E-10	m^4
Thicknes	0.03024	m	y_1	0.00121	m	Ic_1	1.17E-07	m^4
Inner (b)	0.2503	m	y_2	0.029	m	Ic_2	1.17E-07	m^4
Inner (h)	0.00242	m	Centroid	0.0151	m	Ic_{12}	2.35E-07	m^4

		2 x Steel Tube	**Flat (h)**	**Izz @ d**		
F.3.2.1	Wall thickness:	0.0012	0.00242	0.00242	m	EQ
	Outer Diameter / Panel Thickness:	0.025	0.03024	0.03024	m	EQ
F.3.4.1	Cross sectional area (A):	1.82E-04	1.21E-03		m^2	EQ
	Second moment of inertia (I):	1.34E-08	2.35E-07		m^4	EQ
F.3.4.2a	Young's Modulus (E):	2.00E+11	5.12E+10	5.12E+10	Pa	EQ
	Ultimate Tensile Strength (S):	3.65E+08	9.97E+07	9.97E+07	Pa	EQ
	Shear:	2.11E+08	5.02E+07	5.02E+07	Pa	EQ
Buckling Modulus	E_1*I_1 <= E_2*I_2:	2.68E+03	1.20E+04		448.46%	EQ
UTS	S_1*A_1 <= S_2*A_2:	6.64E+04	1.21E+05		181.75%	EQ
Bending	4*S_1*I_1/r <= 4*S_2*I_2/r:	1.54E+03	6.20E+03		402.49%	EQ
Deflection	Bending_1/(48*EI):	1.20E-02	2.67E-03		22.30%	EQ
Energy	0.5*Bending^2/(48*EI):	9.22E+00	3.33E+01		361.23%	EQ
Offset	Itube + Atube*d^2 <= Izz:	1.34E-08	N/A			EQ

Figure 77 - MHBS meeting SES requirements

3.5.6.2 Simulated Rollover

To ensure that the vehicle is safe in a rollover situation, the MHBS was analyzed using the rollover scenario described previously. The results of this study show that the design has a factor of safety of 3.44 for the worst-case rollover scenario. The factor of safety plot can be seen in Figure 78.

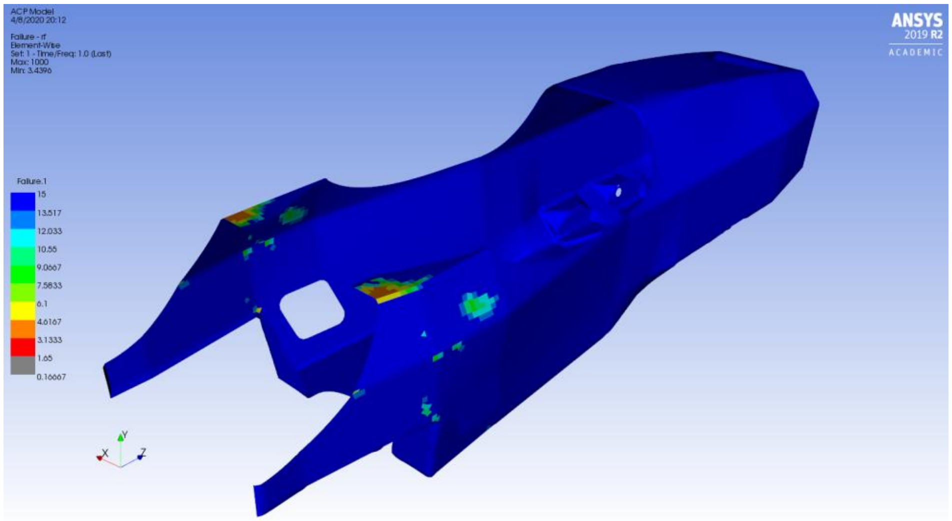


Figure 78 - MHBS rollover simulation results

3.5.7 Engine Compartment Region

The engine compartment is an unregulated region that connects the rear upper control arms to the rest of the chassis. This area also connects to the rear end cap, as well as surrounding the entire engine. Shown in red in Figure 79 below is the engine compartment region.

Figure 79 - Engine compartment region highlighted

3.5.7.1 Simulated Worst Case Loading

The worst-case loading scenario for this part of the chassis is the rear suspension load case. In this analysis, the rear composite “legs” are shown to connect to the rear end cap using a x-component displacement limiter. This is done to ensure that the simulation is as accurate as possible. However, the currently proposed endcap and rear tube setup will likely change due to Bronco Racing requirements. This will lead to another analysis to be needed to check these component’s total compliance. Figure 80 and Figure 81 below shows the results of the rear suspension load case.

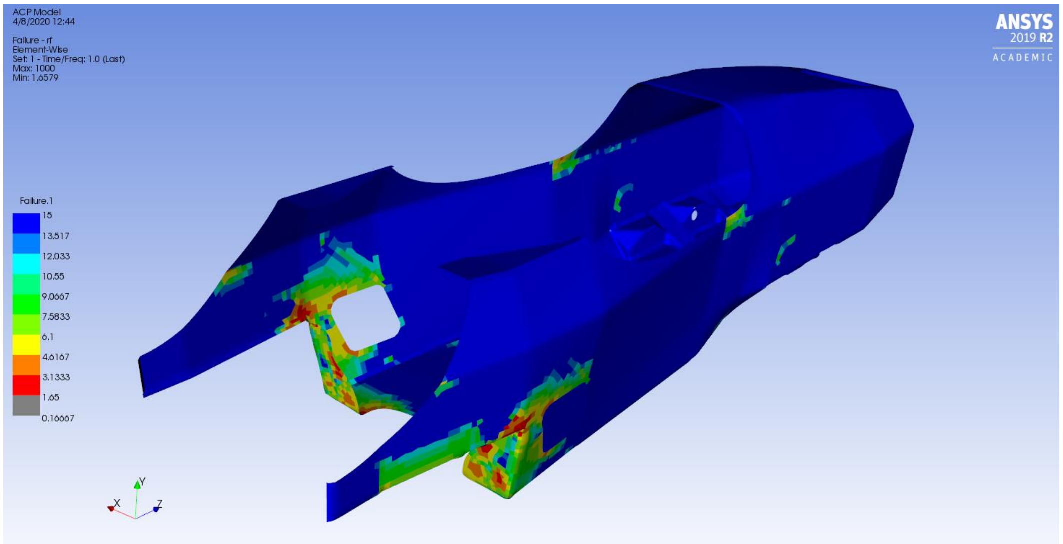


Figure 80 - Engine compartment rear suspension load case results

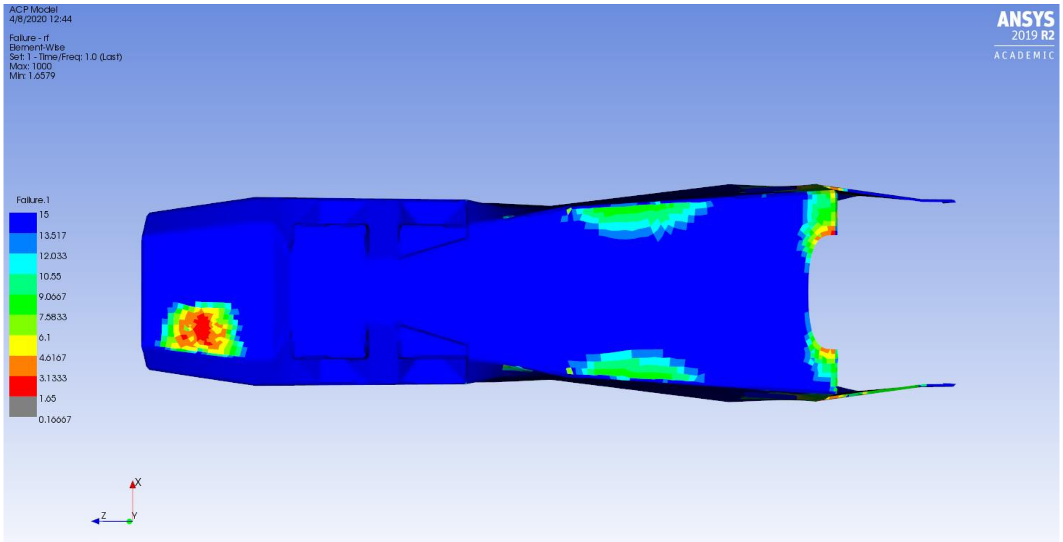


Figure 81 - Engine compartment rear suspension load case results

As seen above, the factor of safety for these regions meets the design parameter of 1.65. This analysis yields a factor of safety of 1.658, demonstrating a design that meets all requirements without being overbuilt.

3.5.8 Vertical Side Impact Structure (VSIS)

The vertical side impact structure is the vertical region between the front roll hoop and main roll hoop. This region is particularly different as it is required to absorb a certain amount of energy if an impact were to occur. Figure 82 below shows the vertical side impact region.

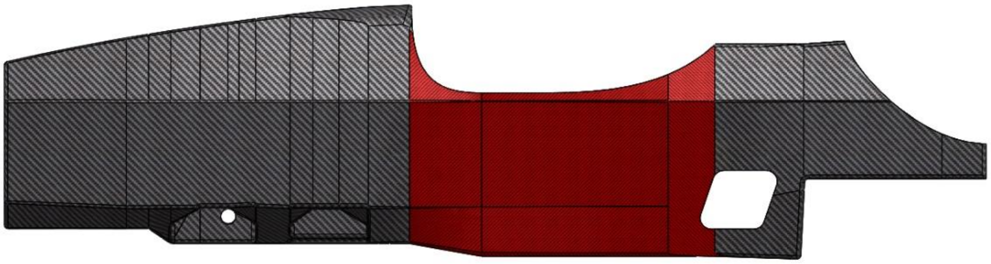


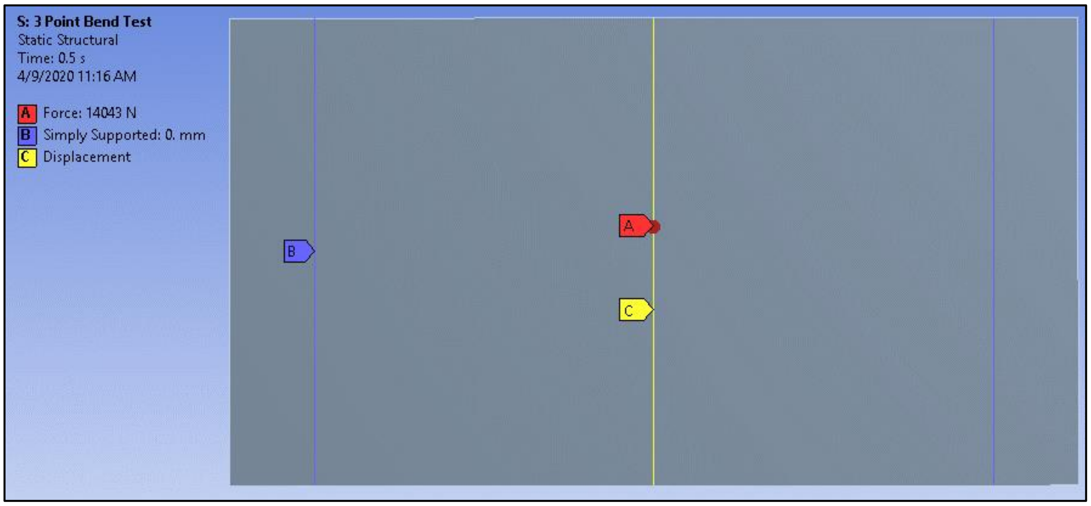
Figure 82 - VSIS region highlighted

3.5.8.1 Rules Equivalence

The vertical side impact region must meet the same type of requirements as the FBHS, with the addition of an energy absorption requirement. This energy absorption requirement must be equivalent to two 1”x0.065” tubes crushed to a total displacement of 19mm. This is described in the testing section of this report in more detail. After running multiple trials, a total energy absorption of 198.92J was deemed necessary. After a series of three-point bend tests, a laminate that utilized aluminum core was found to meet all strength and energy absorption requirements. This laminate was input into the ANSYS ACP load case simulations to verify it would be the remaining design parameters. The previously shown simulation figures show this region under all load cases and the large factor of safety present in the analysis of this region.

3.5.8.2 Energy Absorption

To help predict the laminate that would be ideal for use in the VSIS region, an ANSYS ACP simulation was created to predict panel absorption. The three-point bend setup is shown in Figure 83, where the laminate panel is simply supported, and transverse load is applied. The actual test setup can be seen in the testing section of this report.



S: 3 Point Bend Test
Static Structural
Time: 0.5 s
4/9/2020 11:16 AM

A Force: 14043 N
B Simply Supported: 0. mm
C Displacement

Figure 83 - Three-point bend test setup

This simulation setup allowed for repetitive iterations of designs. Shown below in Figure 84 is the final VSIS laminate shown in the ANSYS ACP simulation. This gradient shows the strain energy in the panel from the applied loading. The applied load caused a factor of safety of 1.0, this is intentional as any higher force will lead to non-linear effects that are not able to be captured accurately.

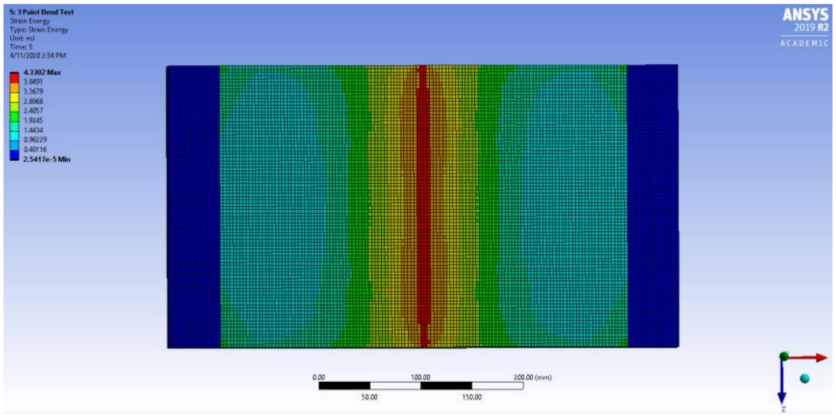
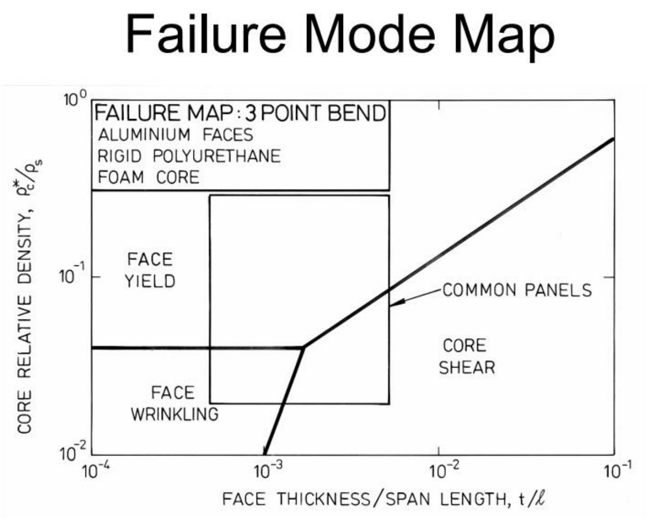


Figure 84 - VSIS three-point bend test results

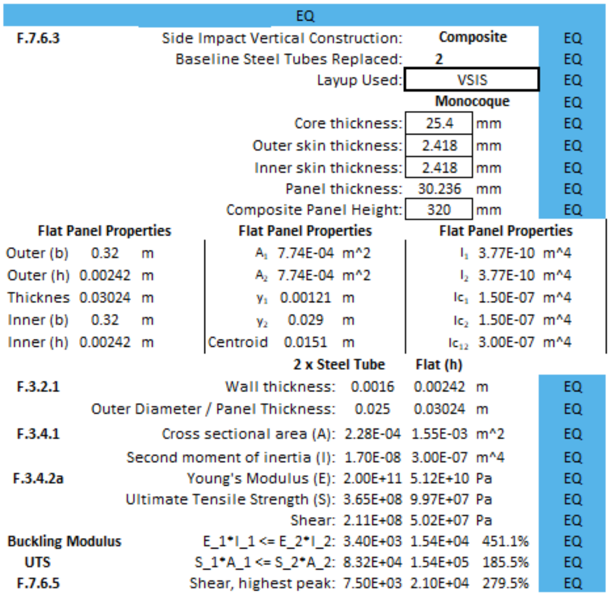
However, a flaw was found in this analysis type. The panel’s primary energy absorption range was after the compressed laminate skin failure until the skin in tension fails. This can be seen in the VSIS region of the testing results section of this report. The above ANSYS ACP analysis does not account for any failure in this range, therefore it predicts an extremely low energy absorption value. To combat this, the failure modes of the panel were analyzed through physical testing. Each failure type was logged and categorized with the laminate thickness and core density. Then, using Figure 85 below as an example, the failure mode regions were approximated to predict the ideal laminate. The ideal laminate would experience compressed face yield at the same time as local core failure at the load region.



Gibson, L. J., and M. F. Ashby. *Cellular Solids: Structure and Properties*. 2nd ed. Cambridge University Press, © 1997. Figure courtesy of Lorna Gibson and Cambridge University Press.

Figure 85 - Failure mode regions map

This method yielded the final laminate type used in the ANSYS ACP load case studies. Additionally, the laminate used was input into the SES to demonstrate that the overall geometry paired with the result laminate stiffness is adequate to the Formula SAE rules. This can be seen in Figure 86 below.



	EQ			
F.7.6.3	Side Impact Vertical Construction:	**Composite**		EQ
	Baseline Steel Tubes Replaced:	**2**		EQ
	Layup Used:	VSIS		EQ
		Monocoque		EQ
	Core thickness:	25.4	mm	EQ
	Outer skin thickness:	2.418	mm	EQ
	Inner skin thickness:	2.418	mm	EQ
	Panel thickness:	30.236	mm	EQ
	Composite Panel Height:	320	mm	EQ

Flat Panel Properties			**Flat Panel Properties**			**Flat Panel Properties**		
Outer (b)	0.32	m	A_1	7.74E-04	m^2	I_1	3.77E-10	m^4
Outer (h)	0.00242	m	A_2	7.74E-04	m^2	I_2	3.77E-10	m^4
Thicknes	0.03024	m	y_1	0.00121	m	Ic_1	1.50E-07	m^4
Inner (b)	0.32	m	y_2	0.029	m	Ic_2	1.50E-07	m^4
Inner (h)	0.00242	m	Centroid	0.0151	m	Ic_{12}	3.00E-07	m^4

		2 x Steel Tube	**Flat (h)**		
F.3.2.1	Wall thickness:	0.0016	0.00242	m	EQ
	Outer Diameter / Panel Thickness:	0.025	0.03024	m	EQ
F.3.4.1	Cross sectional area (A):	2.28E-04	1.55E-03	m^2	EQ
	Second moment of inertia (I):	1.70E-08	3.00E-07	m^4	EQ
F.3.4.2a	Young's Modulus (E):	2.00E+11	5.12E+10	Pa	EQ
	Ultimate Tensile Strength (S):	3.65E+08	9.97E+07	Pa	EQ
	Shear:	2.11E+08	5.02E+07	Pa	EQ
Buckling Modulus	E_1*I_1 <= E_2*I_2:	3.40E+03	1.54E+04	451.1%	EQ
UTS	S_1*A_1 <= S_2*A_2:	8.32E+04	1.54E+05	185.5%	EQ
F.7.6.5	Shear, highest peak:	7.50E+03	2.10E+04	279.5%	EQ

Figure 86 - VSIS meeting SES requirements

3.6 Torsional Stiffness

To ensure that the designed chassis does not negatively affect the suspension, a torsional stiffness simulation was conducted. This simulation was conducted by applying a known vertical load to the tire contact patch of the suspension. The suspension was modeled as rigid to demonstrate only the stiffness of the chassis while maintaining the correct load paths. The simulation is shown in Figure 87, where the rear suspension is fixed.

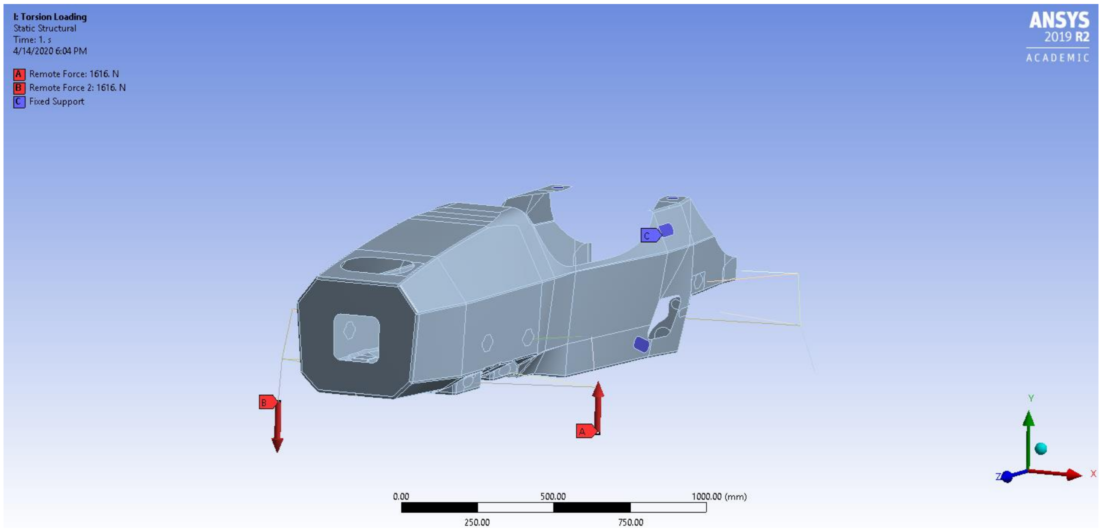


Figure 87 - Torsional stiffness simulation setup

3.6.1 Results of Torsional Stiffness Analysis

This simulation results in a deformation gradient around the chassis. The area of interest is the location in which the load was applied. Shown in Figure 88 below is the deformation gradient around the z-axis.

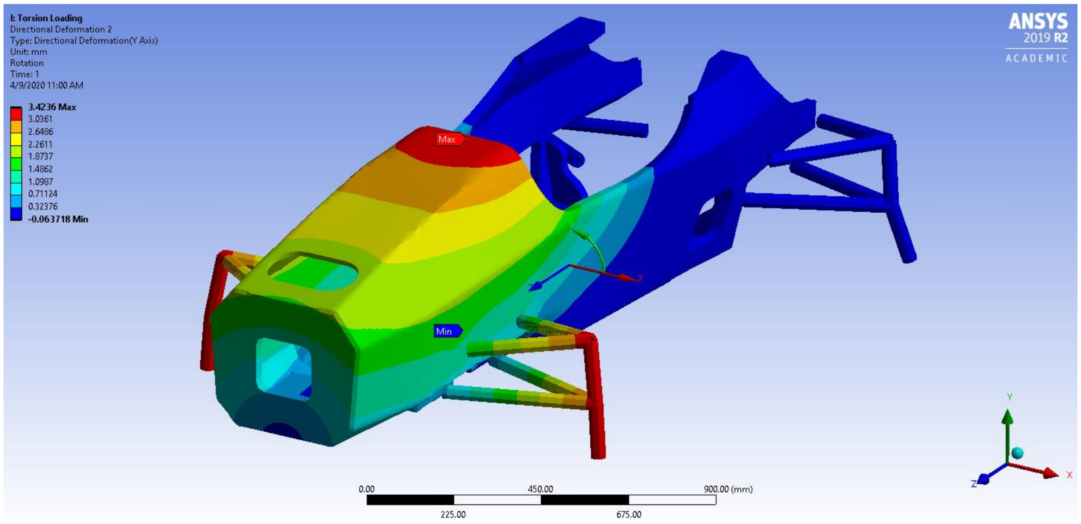


Figure 88 - Torsional stiffness analysis deformation results

This simulation shows that the max deformation at the tire contact patch is 3.42mm, using a 1,616N load. Using the equation in Figure 89, the total angular deformation was found.

$$Angular\ Deformation\ = \frac{360 * Max\ Deformation}{2 * \pi * Moment\ Arm}$$

Figure 89 - Angular deformation equation

Where the moment arm is half of the front suspension track width, 0.6145m. Using this angular deformation, the total torsional stiffness was then found using the equation in Figure 90.

$$Torsional\ Stiffness = \frac{2 * Force\ Applied * Moment\ Arm}{Angular\ Deformation}$$

Figure 90 - Torsional stiffness equation

This results in a torsional stiffness of 6,074.16Nm/deg. This meets our functional requirement of at least 3,599Nm/deg. The 3,599Nm/deg target comes from a design parameter of 4.4 times the suspension roll stiffness. The value of this desired roll stiffness multiplier was sourced internally from Bronco Racing design requirements. Typically, an acceptable range is 2-6 times roll stiffness. To meet this requirement without adding large amounts of weight, 4 times the suspension roll stiffness was accepted. An additionally 0.4 times was added as margin for mounting structures and manufacturing quality.

Due to the suspension system also mounting to the rear end cap assembly, the total torsional stiffness of the chassis is not just the monocoque stiffness. The stiffness of the rear end cap needs to be considered as a spring in series with the monocoque. To calculate the required stiffness of the rear end cap, the equation in Figure 91 was used.

$$\frac{1}{K_{Total\ Chassis}} = \frac{1}{K_{Monocoque}} + \frac{1}{K_{End\ Cap}}$$

Figure 91 - Rear end cap stiffness equation

Where K represents the torsional stiffness of each component of the vehicle. The total chassis stiffness needs to meet the 3,599Nm/deg requirement. Therefore, the rear endcap assembly must have a torsional stiffness of at least 8,837Nm/deg. While this stiffness seems quite large, the rear end cap is a very small and rigid piece of the rear end assembly. The rear lower control arm mounts are at the connection between the rear tube and rear end cap plate. This joint directs all the force directly into the end cap plate. Therefore, this load path passes directly through an extremely rigid and low compliance plate.

However, the other rear lower control arm mount connects at a larger tab that extends away from the rear tube. This tab then has an additional tapped hole to allow a large bolt to pass through and contact the engine case. This contact will give the tab additional bracing to prevent deflection. However, this feature will not help in tension loads. While the current proposed design will work, it has been advised to the Bronco Racing team to consider developing a custom engine case on the stator and clutch. Doing this will allow the suspension mount to connect directly to the engine, which is the most rigid structure in the vehicle. The engine is also hard mounted to the secured main roll hoop and rear end cap. This type of suspension mount would drastically reduce mount compliance.

3.7 Bending Stiffness

Bending stiffness of the monocoque has no direct design parameter. However, this value must be exceptionally high to avoid unwanted suspension characteristics. Additionally, any bending of the monocoque structure would reduce energy from the vehicle's launching capability. While this effect is very small, it is not an issue that should be ignored. Any repetitive bending effects from launching and braking the vehicle can also lead to additional stress on vehicle components, such as the headers, engine block, and aerodynamics. Therefore, the criteria for the bending stiffness of the chassis was evaluated. Figure 92 below shows the results of a bending load applied at both front tire contact patches.

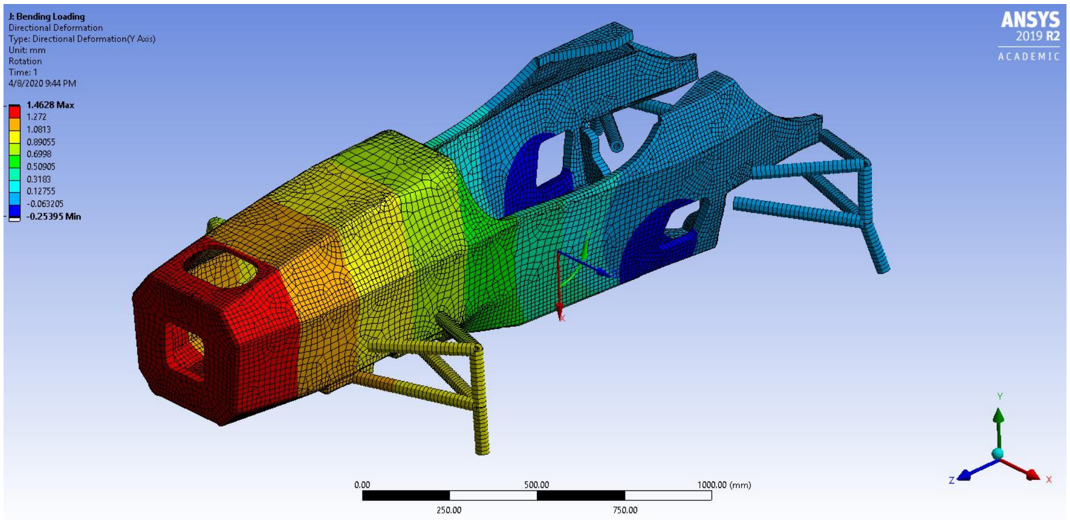


Figure 92 - Bending stiffness simulation results

From the deflection found around the x-axis in this study, the bending stiffness was found using the same method as torsional stiffness. This resulted in a bending stiffness of 113,649Nm/deg for the monocoque chassis. This value was deemed acceptable as a significant front track event would need to occur to create any large deflections in the engine compartment region of the vehicle. The front end of the chassis is capable of taking much larger deflections as all mounting structures have relatively small spans and all mount to the same composite structure.

4 Suspension Mount Design

The suspension mounts are a critical part to the design of the chassis. If designed incorrectly, the mount can pierce the composite and injure the driver or make the vehicle uncontrollable. To accurately design the mounts, the designed laminates that were confirmed in the ANSYS ACP study were tested in a perimeter shear test, which is described in more detail in the testing section. Using the results of the testing, the mounts were designed based off of the minimum required perimeter against the chassis surface to prevent perimeter shear. The other requirement was to keep the previous control arm mounting holes in the same spot as the previous vehicle to avoid suspension geometry changes.

Each mount was simulated to confirm that it met factor of safety requirements and had minimal deflection to avoid suspension compliance. Each mount was simulated with the worst-case scenario load defined previously, where the minimum acceptable factor of safety is 1.25. A 1.25 factor of safety was deemed acceptable since each mount is simple 4130 chromoly steel plates TIG welded together. The stress plots were checked to ensure that the mount was not near yield. Fatigue was not considered due to the low cycle count expected on the suspension. On-track time of a vehicle over a competition season is typically under 100 hours.

4.1 Front Upper Control Arms

The front upper control arms use a mounting system very similar to that of the BR20 vehicle. This method of mounting to the chassis was found to be very effective in providing a lightweight and strong design for these regions. Figure 93 below shows the front upper control arm mounts in red. Figure 94 shows the mount in detail, demonstrating the Torlon insert mounting method.

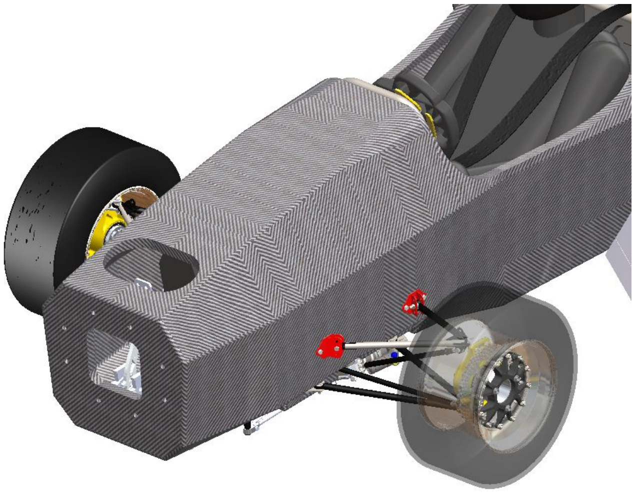


Figure 93 - Front upper control arms mounts highlighted

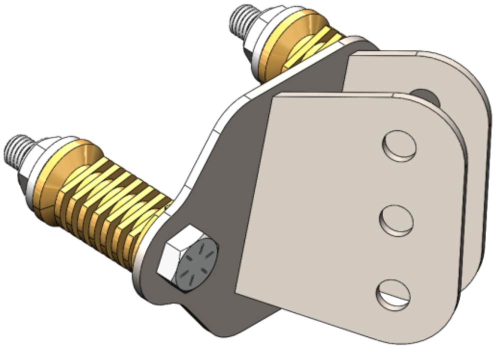


Figure 94 - Front upper control arm mount

4.1.1 Stress

For the front upper control arm mounts, these connect directly to the FBHS structure, which has a perimeter shear of 110.38N/mm. Therefore, the required minimum perimeter of the tab with the known worst case loading scenario is 54.84mm. The smallest reasonable tab perimeter to allow full welding of all pieces was 262.8mm which is well over the minimum requirement. Additionally, this mount was simulated in the worst-case load scenario with the control arms set to the “neutral” control arm position. Figure 95 below shows the resulting stress plot.

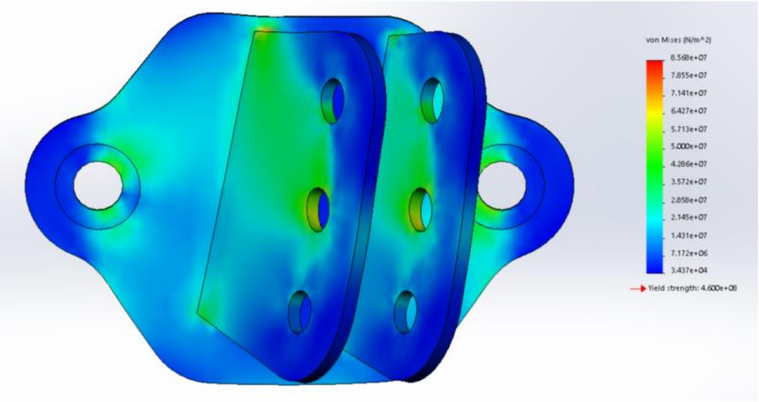


Figure 95 - Front upper control arm mount stress results

As seen above, the mount has a factor of safety of 5.37, showing it is significantly strong for the application.

4.1.2 Deformation

The deformation plot is shown below in Figure 96, where peak deformation occurred at the control arm mount point at 0.0133mm. The mount matches expectations that the surface of the mount will attempt to pull away from the mounting surface of the monocoque, while the control arm mounts will pull away from the vehicle.

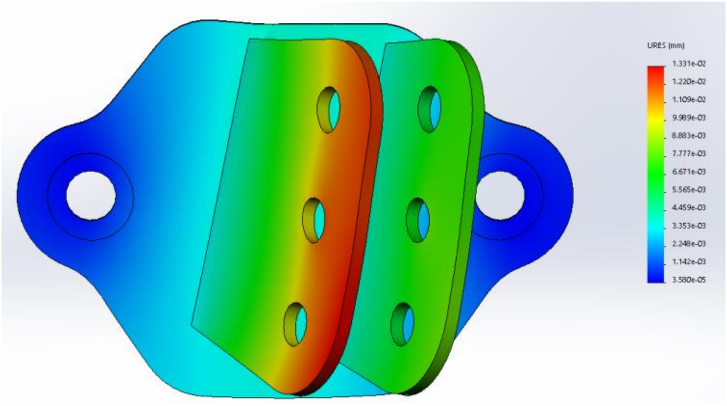


Figure 96 - Front upper control arm mount deformation results

4.2 Front Lower Control Arm Mounts

The front lower control arms mount to the vertical portion of the FBHS structure. This region is different as it does not use core and is not regulated. This is done to save weight on the inserts, hardware, composite structure. As there is no core used, the perimeter shear of the laminate effectively doubles as the carbon fiber inner and outer skins are joined. The lower control arms are shown in red in Figure 97, and in detail in Figure 98.

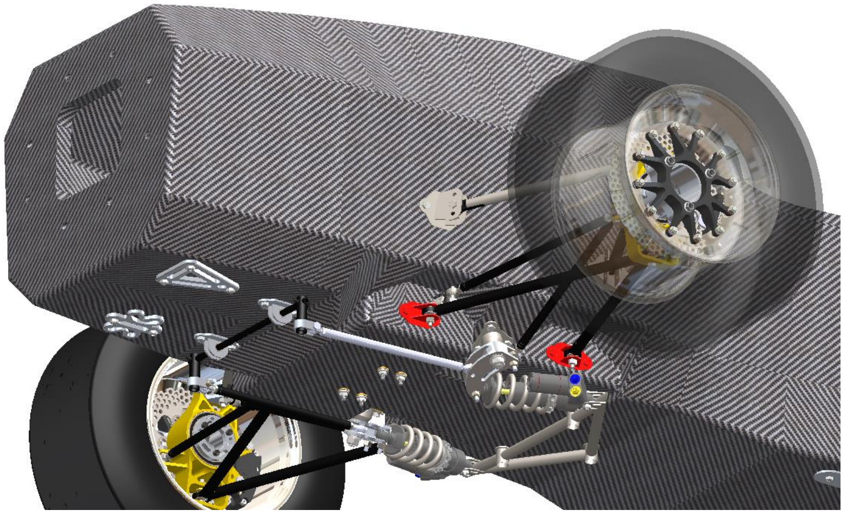


Figure 97 – Front lower control arm mounts highlighted

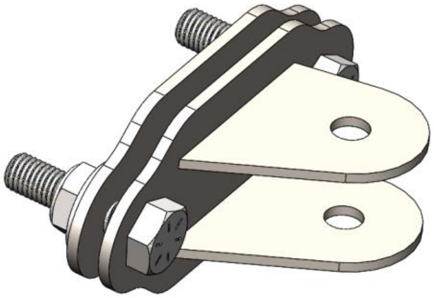


Figure 98 - Front lower control arm mounts

4.2.1 Stress

While the laminates that these mounts bolt to was not tested for perimeter shear, it is known that the minimum allowable perimeter is at least equivalent to that of the FBHS mounts, at 54.84mm. This is because this FHBS vertical region is twice as thick as the FBHS region, while also having additional layers of carbon fiber. Using the FBHS laminate provides a large factor of safety without having to test another laminate on the MTS.

These mounts have a perimeter of 223.78mm as this is this is the minimum size possible for a stiff tab that can still be fully welded. Additionally, the backing plate matches the perimeter of the tab, with a large weight reduction hole cut through the center. The backing plate prevents any tensile forces from ripping out the hardware of the mount. The mounts were again simulated with the worst-case loading scenario, and the results shown in Figure 99 below. It can be seen that the mount has a 4.02 factor of safety.

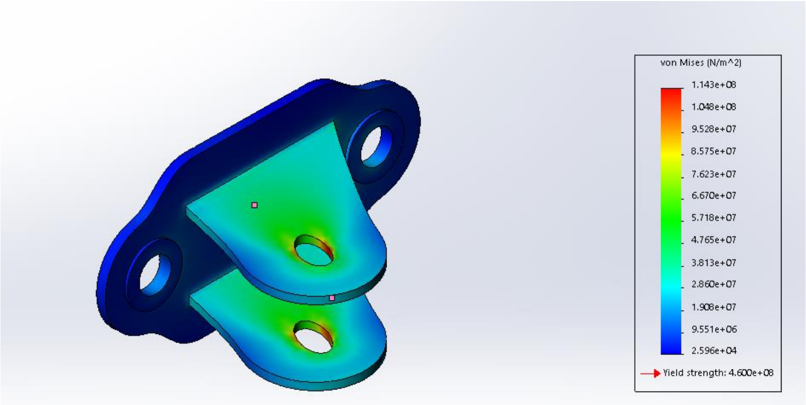


Figure 99 - Front lower control arm mounts stress results

4.2.2 Deformation

The mount deformation from worst-case loading can be seen in Figure 100 below. The resulting deformation is extremely small at a peak of 0.006715mm.

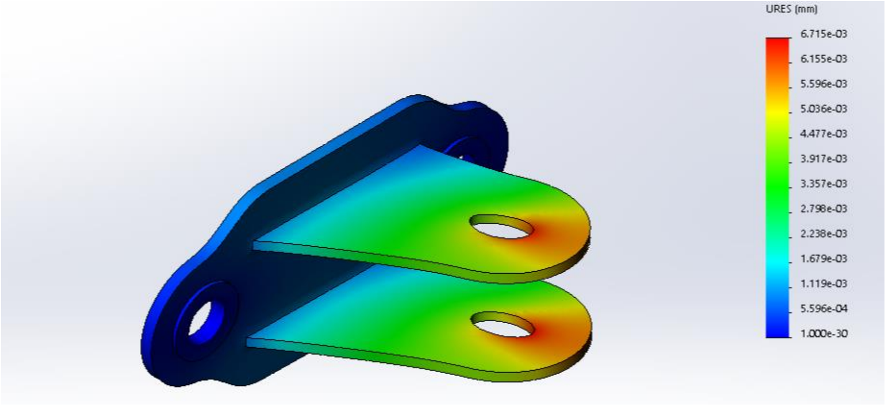


Figure 100 - Front lower control arm mounts deformation results

4.3 Rear Upper Control Arm Mounts

The rear upper control arm mounts are very similar to that of the front upper control arm mounts. However, the angle that the rear upper control arm approaches the chassis is much more narrow. Due to this, the mount must be wider. However, with the mounting points span increased, the tab was more prone to deflection and was reinforced. Figure 101 shows the location of the rear upper control arm mounts in red, while Figure 102 shows a detailed look at the mount.

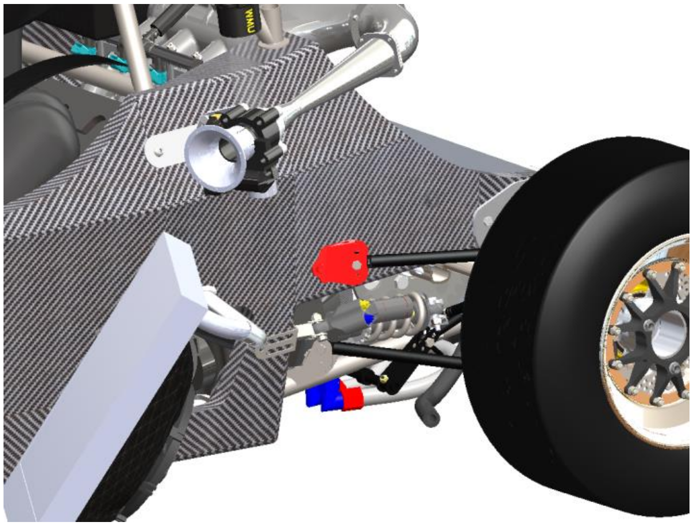


Figure 101 - Rear upper control arm mounts highlighted

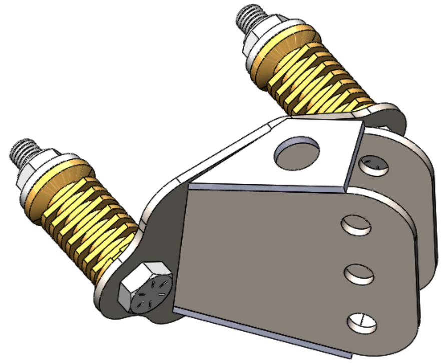


Figure 102 - Rear upper control arm mounts

4.3.1 Stress

The engine compartment laminate matches that of the FBHS structure, therefore the same minimum perimeter value of 54.84mm could be used to prevent shear. Again, due to required mount geometry, the mount has a much greater perimeter than this at 254.45mm. With the worst case load scenario applied, the mount passed the minimum factor of safety requirement with a factor of safety of 2.6 as seen in Figure 103 below.

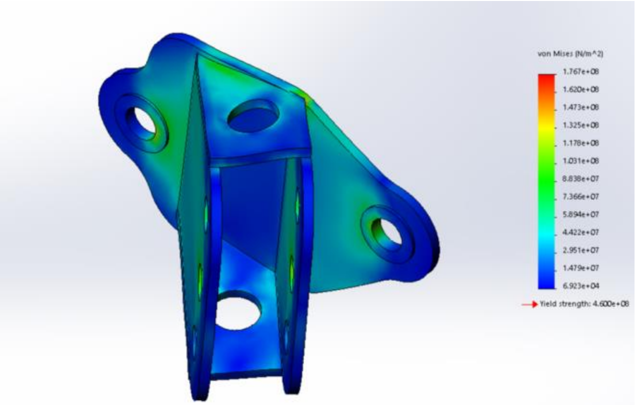


Figure 103 - Rear upper control arm mounts stress results

4.3.2 Deformation

As previously mentioned, the angle of the mount prevents the mounting holes to be accessible under a normal mount span. Therefore, the mount span was increased. Doing this increased the horizontal region of the tab, enabling more deflection. To combat this compliance, the mount was braced between the control arm mounts and base tab, creating a stiffer structure. This can be seen in the deformation plot shown in Figure 104, where the peak deflection is 0.02664mm.

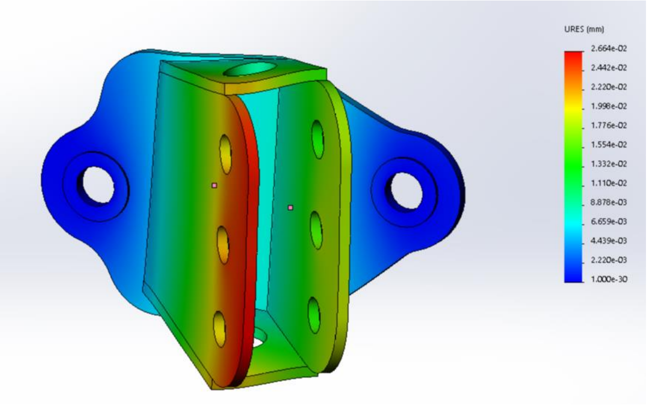


Figure 104 - Rear upper control arm mounts deformation results

4.4 Front Bellcrank Mount

The front bellcrank mount is an adaptation of the BR20 design. However, the BR19 vehicle used a mounting angle between the bellcrank and chassis that made construction difficult. The new design utilizes the monocoque geometry redesign to make the bellcrank and monocoque planes parallel. This allows the new mount to simply sit perpendicular to the surface of the monocoque. The location of this new bellcrank mount can be seen in Figure 105 shown in red.

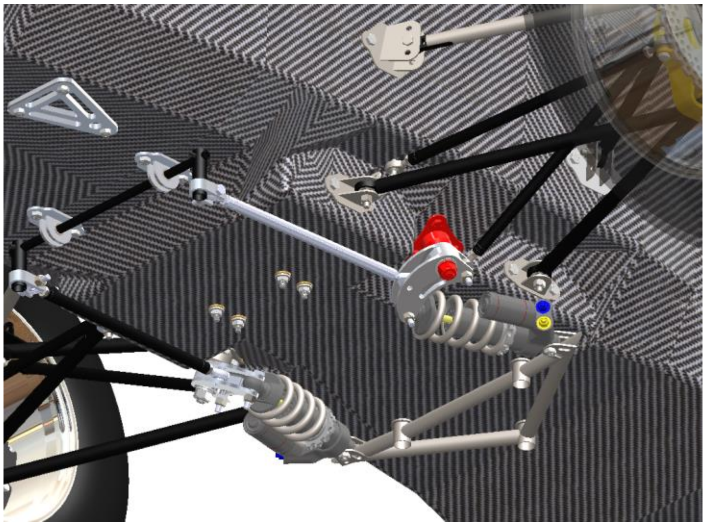


Figure 105 - Front bellcrank mount highlighted

The details of the new bellcrank mount design can be seen in Figure 106.

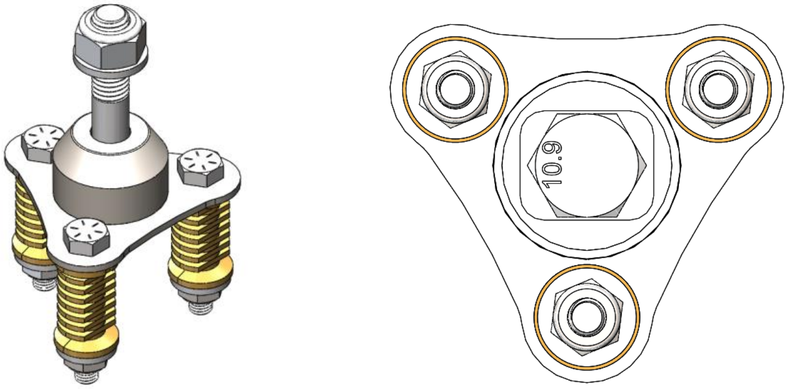


Figure 106 - Front bellcrank mount

As seen above, the base tab houses a chromoly steel mount that houses the bolthead of the bellcrank mount. This allows the rules to be upheld in using a 10.9 grade metric bolt, while also being able to easily service the bellcrank without having to remove the entire bellcrank mount.

4.4.1 Stress

The bellcrank mount should not have a large amount of force through it if the suspension is properly aligned. However, due to different testing setups and ride height requirements, the front bellcrank loads to become out of plane. This creates a bending load on the bellcrank mount. Using this load, the bellcrank mount was simulated to support this load. Additionally, the perimeter shear was verified for the mount attached to this region of the FBHS laminate. Laminate simulation has shown that heavyweight balsa core is required for this region, therefore the core supporting the FBHS laminate is stronger than the FBHS region, and perimeter shear requirements of the FBHS region can be used for a conservative analysis. The bellcrank mount perimeter meets the 54.84mm required perimeter with a total outer perimeter of 365.86mm. this mount has a large surface area due to the need for three different mounting holes. Under worst case scenario loading from the bellcrank fulcrum center, the stress distribution is shown in Figure 107. This mount shows a 1.61 factor of safety under these conditions.

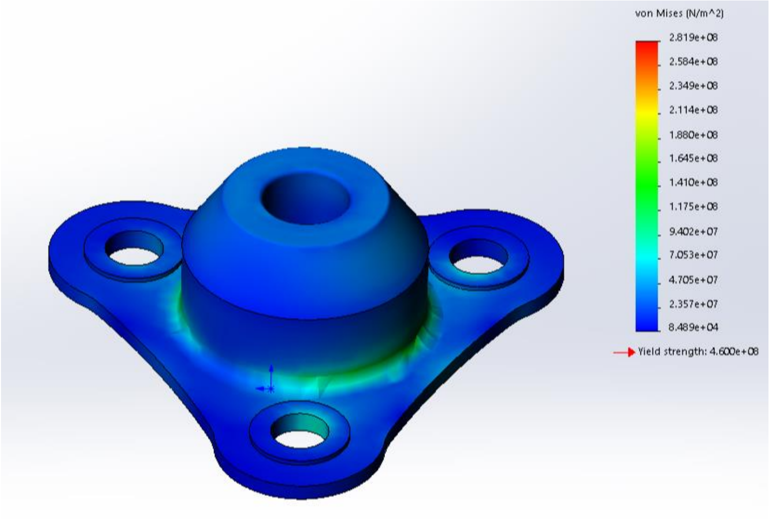


Figure 107 - Front bellcrank mount stress results

4.4.2 Deformation

Even under worst-case loading it is crucial to keep the bellcrank in-plane and prevent any deflection from bending loads. The deflection of this unit was checked to ensure that excessive deflection did not occur. Figure 108 shows that the bellcrank deflects a maximum of 0.0102mm at the bellcrank mounting face.

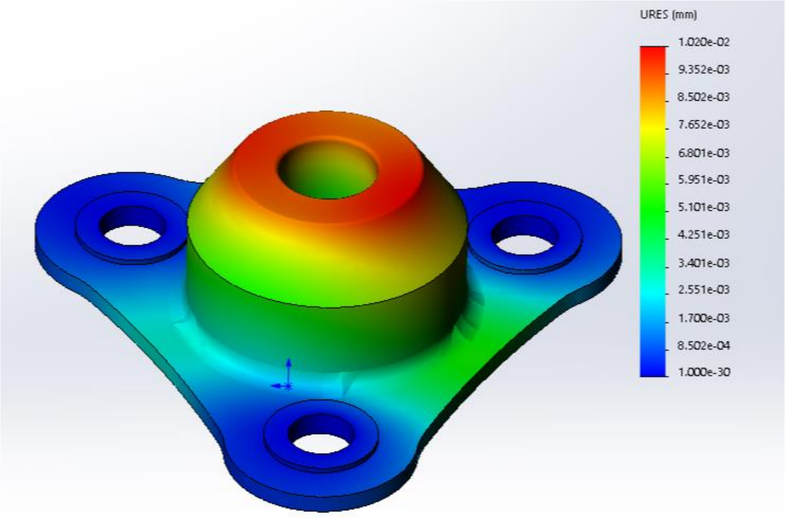


Figure 108 - Front bellcrank mount deformation results

4.5 Rear Damper Mount

The rear damper mount mounts to the unregulated engine compartment region. As previously explained, the FBHS laminate can be used as a conservative perimeter shear requirement. The rear damper mount connects to two different faces of the monocoque. This is done to help prevent load concentration on the engine compartment flange. As the bolt holes are nearly perpendicular to each other, the mounts utilize the face strength of the carbon fiber, and the shear strength of the adhesive in the potted inserts. Figure 109 below shows the location of the rear damper mount, while Figure 110 shows this mount in detail.

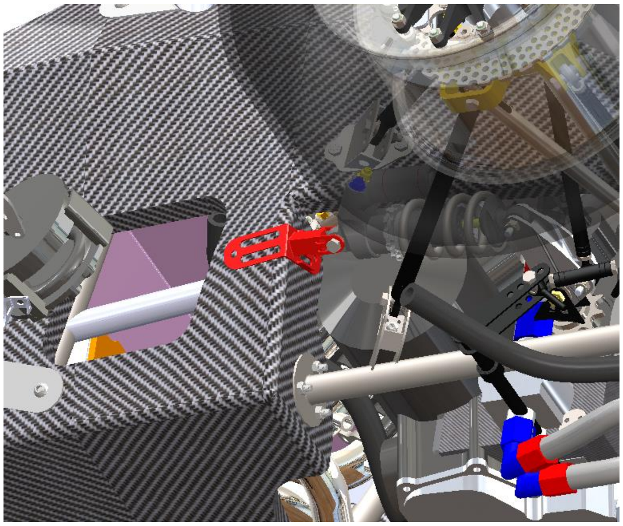


Figure 109 - Rear damper mount highlighted

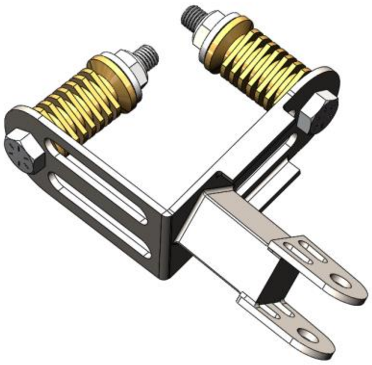


Figure 110 - Rear damper mount

4.5.1 Stress

As this mount is in both shear and normal stress, the two surfaces of the mount must be treated differently. For the shear mounting face, this section of the mount is in normal stress. Due to this, large cutouts can be made in the tab as the load path is simply parallel to the edges of the mount. However, the normal mounting face is placed in bending when loaded. Typical loading will press the mount into the composite surface, so bending loads will be quite minimal as it is supported along the length of the tab. For tensile forces, additional braces were added to prevent the tab from deflecting off of the monocoque surface due to the large mounting span. The worst-case-scenario stress results can be seen in Figure 111, where the factor of safety is 2.91.

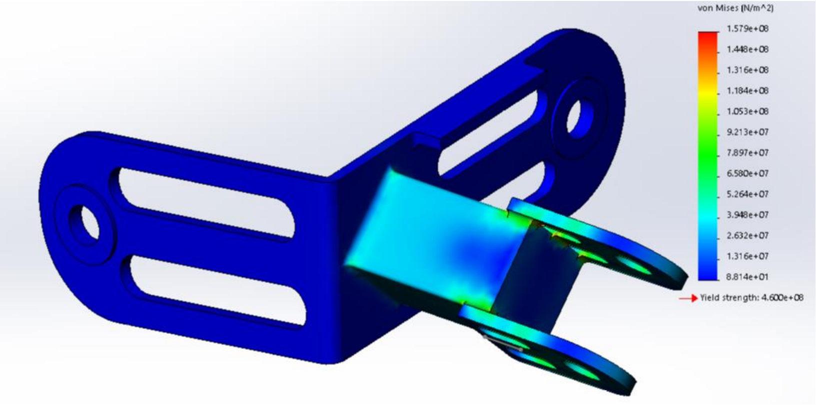


Figure 111 - Rear damper mount stress results

4.5.2 Deformation

To prevent undesired additional deflection of the damper, the damper mount should be as rigid as possible. Figure 112 shows that the damper only deflects 0.01076mm at peak loading.

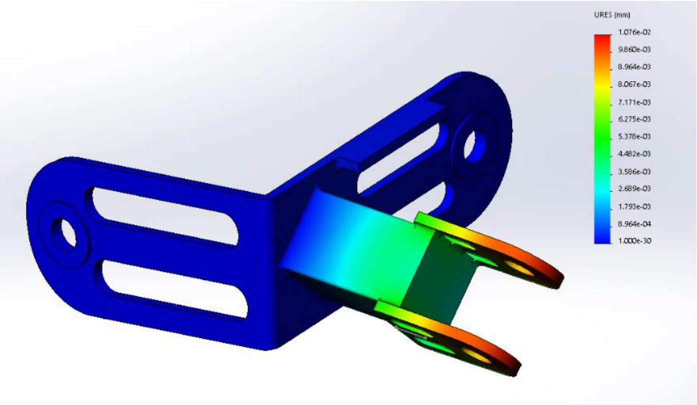


Figure 112 - Rear damper mounts deformation results

4.6 Front Damper Mount

The front damper mount was designed to minimize weight while increasing the stiffness over the previous monocoque design. To do this effectively, the front dampers were both connected through a small subframe system in the front of the chassis. This effectively distributes load across the composite face, while still providing a stiff mounting structure. This mount can be seen in Figure 113 and Figure 114 below.

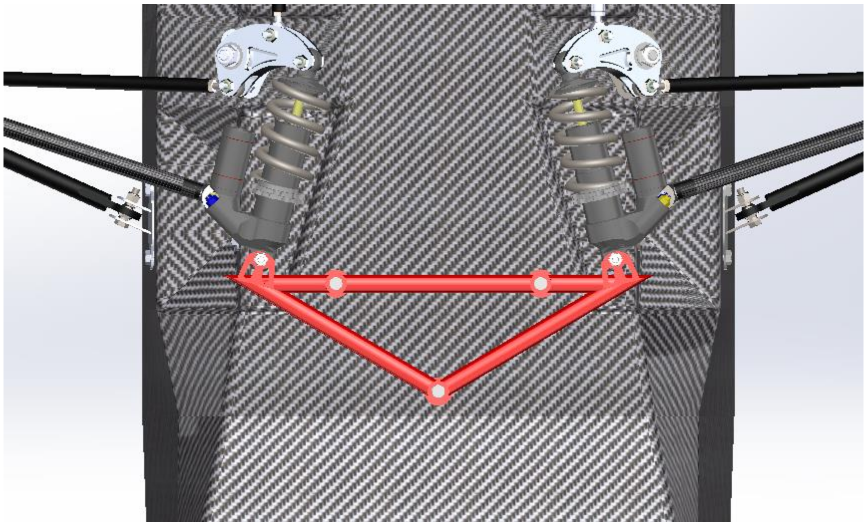


Figure 113 - Front damper mount highlighted

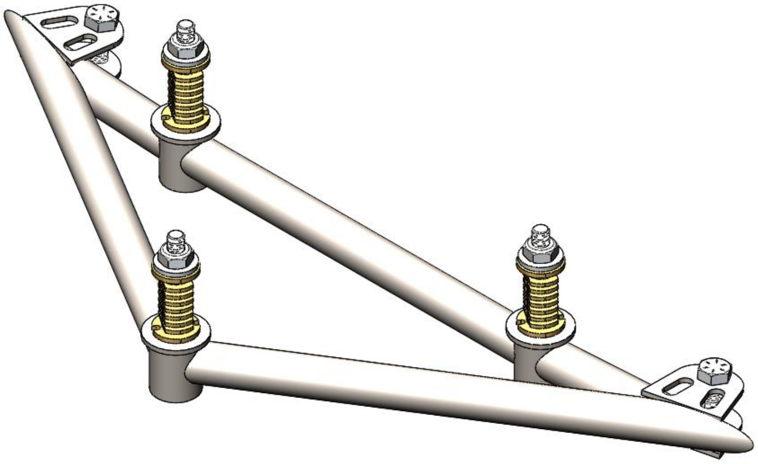


Figure 114 - Front damper mount

5 Testing

Testing the composite laminates is a requirement of the Formula SAE rulebook. This testing is used to determine the overall panel properties that will then be directly compared to the required equivalent steel structure. Other testing is conducted to ensure design parameters are met, such as the composite potted inserts. All physical testing was conducted at Eaton or the WMU Fatigue and Fracture lab. Due to testing limitations as the WMU Parkview campus closed from COVID-19 related government orders, the front bulkhead laminate was not tested. All other laminates have completed three-point bend test data and perimeter shear data.

5.1 Composite Panel Potted Inserts

A pullout strength test was conducted on composite panel inserts to validate their viability as mounting points for the suspension hardpoints to the monocoque. The inserts tested were thermoplastic composite 1/4" diameter through-hole for 1" thick composite panels, or NAS-1834-4-1000 style, inserts made from Torlon. The test panel consisted of a carbon fiber laminate skin, Nomex core composite mockup with one through hole insert placed in a drilled-out hole in the center of the panel. 3M Scotch-Weld epoxy adhesive (EC-3542 B/A FR) was then injected into the cavity around the insert to bond it in place.

5.1.1 Testing Jig

A testing jig was created for the pullout test to be conducted on an MTS tensile testing machine. The pullout test jig with the test panel is shown in Figure 115 and a cross section view is shown in Figure 116. The test jig is made from steel and holds a square carbon fiber test panel with a Torlon through hole insert in the middle. The test jig allows for a bolt to be inserted through the middle of the panel and fastened with a nut on the underside. There is a round steel bar on the bottom side of the plate and steel piece of bar with the center drilled out around the bolt, which allowed the MTS machine to grip onto the test jig and perform the test. There are four rectangular sections of steel plate that each have two bolts that are used to fasten the carbon fiber test panel to the test jig on each side of the square panel.

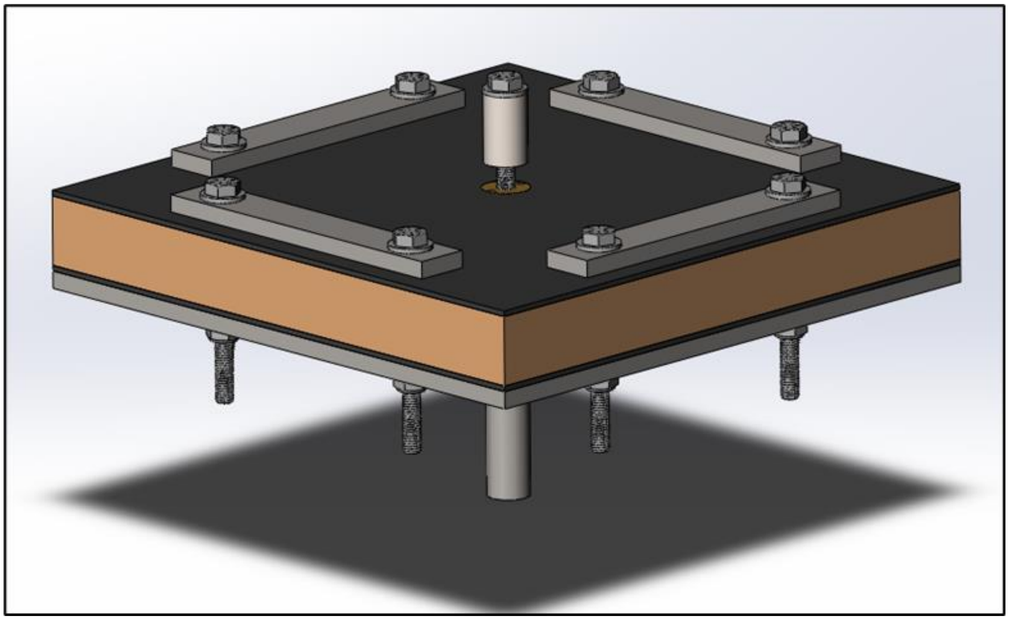


Figure 115 - Torlon insert pullout test jig

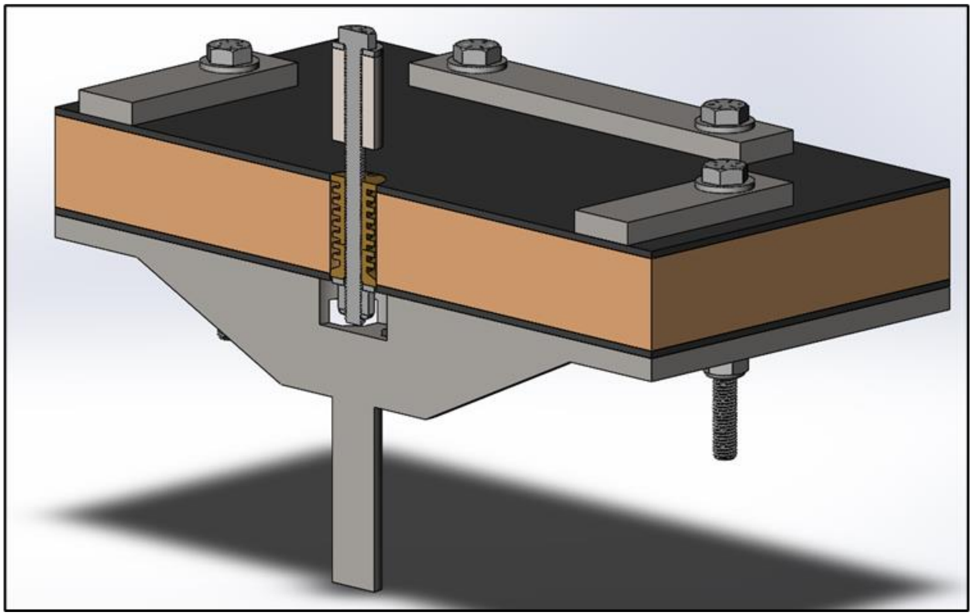


Figure 116 - Cross section of Torlon insert pullout test jig

5.1.2 Test Panel

A drilled hole of 1” diameter and was drilled completely through the panel using a stepped drill bit to avoid delamination. An Allen wrench was connected to a drill and was spun around in the drilled out hole to clear out the core material for the epoxy. The core was cleared out of the hole as much as possible to allow the epoxy more surface contact on the carbon fiber skin. The Torlon insert was then inserted into the hole in the panel and the bottom was taped off to prevent epoxy from leaking. The installion tab was then placed on the top of the insert and epoxy was injected into the hole then allowed to cure.

5.1.3 Test and Results

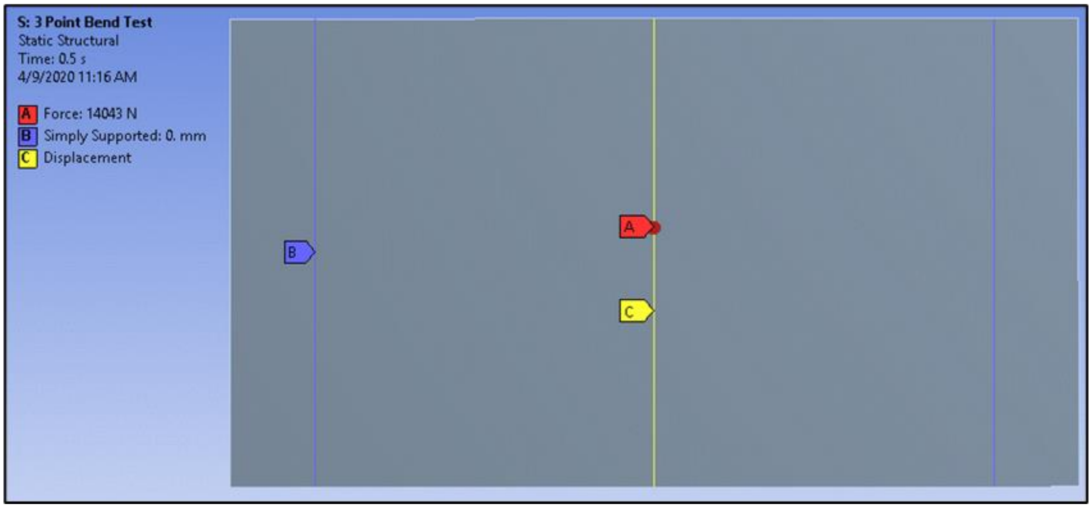
Due to COVID-19 causing campus-wide closure, physical testing of the inserts was not possible. Although, research done on these inserts show promising results. According to a test done by students at California Polytechnic State University, pull-out strength testing done on 3/8” depth blind potted Torlon inserts, which only are partially inserted into the panel, show the pull-out strength to be at a mean of 723 lbf with a 99% percentile minimum of 604.4 lbf. (Allen, et al.) It is believed that a 1” depth through hole insert can sustain more load due to a greater surface being available for the epoxy to adhere to. A physical pull-out test to verify the use of these insert in the design will be conducted later by the Bronco Racing team.

5.2 Three-Point Bend Test

A three-point bend test was needed to verify the results received during simulation in ANSYS. The three-point bend test allows the flexural stiffness of a carbon fiber test panel to be determined. The three-point bend test consists of supporting a rectangular test panel on the two short ends and placing a load along the width directly in the middle of the two supports.

5.2.1 Setup

The test is first conducted in ANSYS to determine the flexural stiffness that must be matched in the physical testing to verify the simulation. The simulated test can be seen in Figure 117.


S: 3 Point Bend Test
Static Structural
Time: 0.5 s
4/9/2020 11:16 AM

A Force: 14043 N
B Simply Supported: 0. mm
C Displacement

Figure 117 - Three-point bend test in ANSYS

The physical test is conducted on an MTS and requires a testing jig to be manufactured. This test is required to be conducted according to the FSAE rule book, so a testing jig was readily available from the previous monocoque design. A physical three-point bend test conducted on an MTS can be seen in Figure 118.

Figure 118 - Three-point bend test conducted on MTS

5.2.2 Results

5.2.2.1 Front Bulkhead Support

The front bulkhead support laminate was tested and met all SES requirements. The force and displacement chart can be seen in Figure 119, and the derived panel properties can be seen in Figure 120.

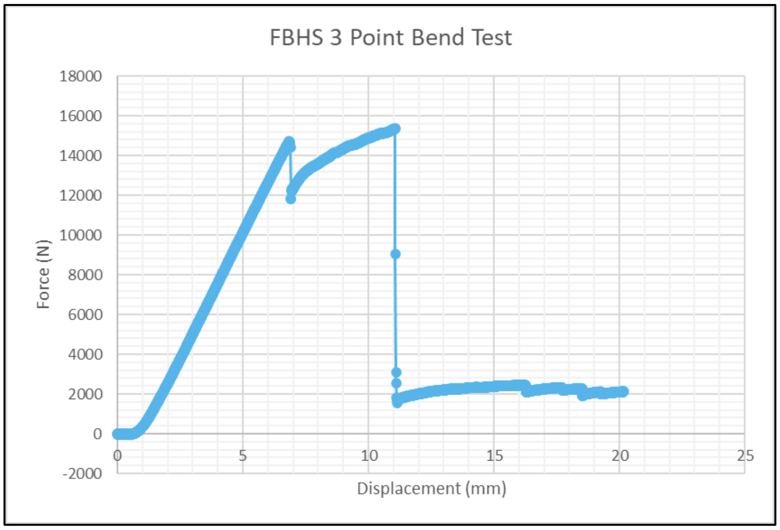
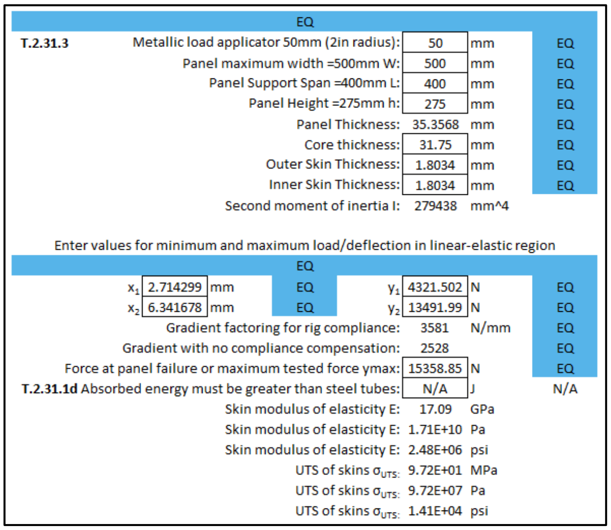


Figure 119 - FBHS three-point bend test force vs displacement



EQ

T.2.31.3	Metallic load applicator 50mm (2in radius):	50	mm	EQ
	Panel maximum width =500mm W:	500	mm	EQ
	Panel Support Span =400mm L:	400	mm	EQ
	Panel Height =275mm h:	275	mm	EQ
	Panel Thickness:	35.3568	mm	EQ
	Core thickness:	31.75	mm	EQ
	Outer Skin Thickness:	1.8034	mm	EQ
	Inner Skin Thickness:	1.8034	mm	EQ
	Second moment of inertia I:	279438	mm^4	

Enter values for minimum and maximum load/deflection in linear-elastic region

EQ

x_1	2.714299	mm	EQ	y_1	4321.502	N	EQ
x_2	6.341678	mm	EQ	y_2	13491.99	N	EQ

	Gradient factoring for rig compliance:	3581	N/mm	EQ
	Gradient with no compliance compensation:	2528		EQ
	Force at panel failure or maximum tested force ymax:	15358.85	N	EQ
T.2.31.1d	Absorbed energy must be greater than steel tubes:	N/A	J	N/A
	Skin modulus of elasticity E:	17.09	GPa	
	Skin modulus of elasticity E:	1.71E+10	Pa	
	Skin modulus of elasticity E:	2.48E+06	psi	
	UTS of skins $\sigma_{UTS:}$	9.72E+01	MPa	
	UTS of skins $\sigma_{UTS:}$	9.72E+07	Pa	
	UTS of skins $\sigma_{UTS:}$	1.41E+04	psi	

Figure 120 - FBHS derived panel properties

5.2.2.2 Steel Tube Energy Equivalency

To find the required energy absorption of the VSIS, two steel tubes were required to be tested. These steel tubes are 1”x0.065” and use the same setup as the composite panel three-point bend test. These tubes are loaded until 19mm of displacement per the rulebook, then the force vs. displacement curve is integrated using trapezoidal method to find total absorbed energy. The results of this test are shown below in Figure 121, with the derived properties found in Figure 122

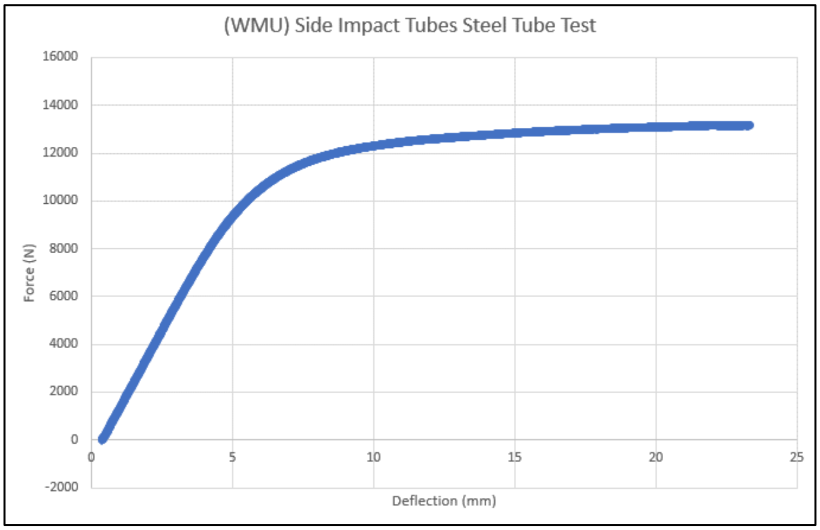
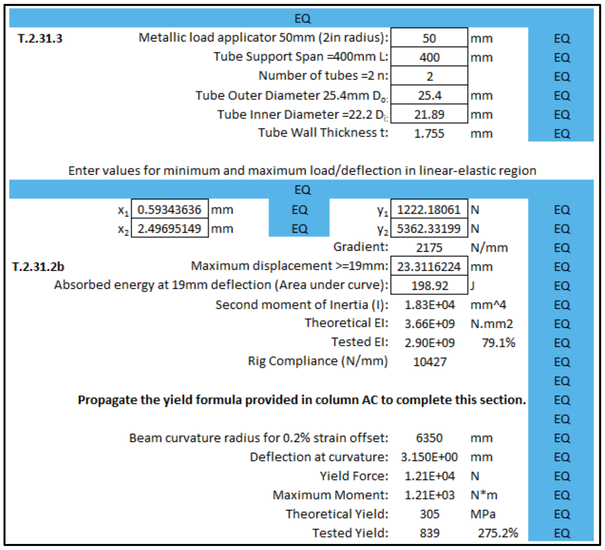


Figure 121 - Side impact tube three-point bend test force vs displacement



				EQ				
T.2.31.3					Metallic load applicator 50mm (2in radius):	50	mm	EQ
					Tube Support Span =400mm L:	400	mm	EQ
					Number of tubes =2 n:	2		EQ
					Tube Outer Diameter 25.4mm $D_{o:}$	25.4	mm	EQ
					Tube Inner Diameter =22.2 $D_{i:}$	21.89	mm	EQ
					Tube Wall Thickness t:	1.755	mm	EQ
	Enter values for minimum and maximum load/deflection in linear-elastic region							
				EQ				
	x_1	0.59343636	mm	EQ	y_1	1222.18061	N	EQ
	x_2	2.49695149	mm	EQ	y_2	5362.33199	N	EQ
					Gradient:	2175	N/mm	EQ
T.2.31.2b					Maximum displacement >=19mm:	23.3116224	mm	EQ
					Absorbed energy at 19mm deflection (Area under curve):	198.92	J	EQ
					Second moment of Inertia (I):	1.83E+04	mm^4	EQ
					Theoretical EI:	3.66E+09	N.mm2	EQ
					Tested EI:	2.90E+09	79.1%	EQ
					Rig Compliance (N/mm)	10427		EQ
								EQ
	Propagate the yield formula provided in column AC to complete this section.							EQ
								EQ
					Beam curvature radius for 0.2% strain offset:	6350	mm	EQ
					Deflection at curvature:	3.150E+00	mm	EQ
					Yield Force:	1.21E+04	N	EQ
					Maximum Moment:	1.21E+03	N*m	EQ
					Theoretical Yield:	305	MPa	EQ
					Tested Yield:	839	275.2%	EQ

Figure 122 - Side impact tube derived properties

This test is also used to find the compliance of the testing setup. To do this, the theoretical stiffness of the tubes is calculated and compared to the linear-elastic region of the tube compression. The difference is used in the spring-series equation derived previously to calculate jig compliance.

5.2.2.3 Vertical Side Impact Structure / Main Hoop Bracing Support

The vertical side impact structure and main hoop bracing support both utilize the same laminate design. This reduced the need for additional panels to test, while still meeting all functional requirements.

This laminate was tested and met all SES requirements. The force and displacement chart can be seen in Figure 123, and the derived panel properties can be seen in Figure 124. The VSIS region is also required to meet energy absorption equivalency to the tested steel tubes. The VSIS narrowly met this requirement as well. The use of aluminum core in energy absorption can be clearly seen in Figure 123 as effective, where the laminate skin failure leads to the aluminum core slowly crushing as the panel is displaced. In comparison to Figure 119 of the FBHS, where the first laminate skin failure leads to a massive drop in applied load per displacement.

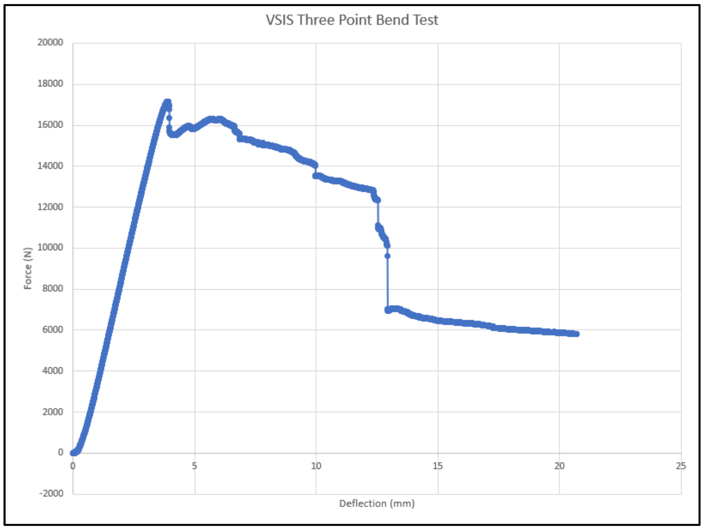
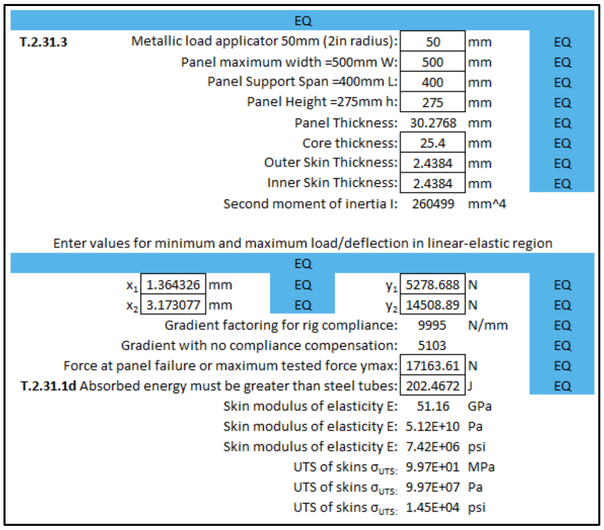


Figure 123 - VSIS three-point bend test force vs displacement



EQ

T.2.31.3	Metallic load applicator 50mm (2in radius):	50	mm	EQ
	Panel maximum width =500mm W:	500	mm	EQ
	Panel Support Span =400mm L:	400	mm	EQ
	Panel Height =275mm h:	275	mm	EQ
	Panel Thickness:	30.2768	mm	EQ
	Core thickness:	25.4	mm	EQ
	Outer Skin Thickness:	2.4384	mm	EQ
	Inner Skin Thickness:	2.4384	mm	EQ
	Second moment of inertia I:	260499	mm^4	

Enter values for minimum and maximum load/deflection in linear-elastic region

EQ

x_1	1.364326	mm	EQ	y_1	5278.688	N	EQ
x_2	3.173077	mm	EQ	y_2	14508.89	N	EQ

	Gradient factoring for rig compliance:	9995	N/mm	EQ
	Gradient with no compliance compensation:	5103		EQ
	Force at panel failure or maximum tested force ymax:	17163.61	N	EQ
T.2.31.1d	Absorbed energy must be greater than steel tubes:	202.4672	J	EQ
	Skin modulus of elasticity E:	51.16	GPa	
	Skin modulus of elasticity E:	5.12E+10	Pa	
	Skin modulus of elasticity E:	7.42E+06	psi	
	UTS of skins $\sigma_{UTS:}$	9.97E+01	MPa	
	UTS of skins $\sigma_{UTS:}$	9.97E+07	Pa	
	UTS of skins $\sigma_{UTS:}$	1.45E+04	psi	

Figure 124 - VSIS derived properties

5.2.2.4 Horizontal Side Impact Structure

The horizontal side impact structure laminate was tested and met all stiffness and panel requirements. The force and displacement chart can be seen in Figure 125, and the derived panel properties can be seen in Figure 126.

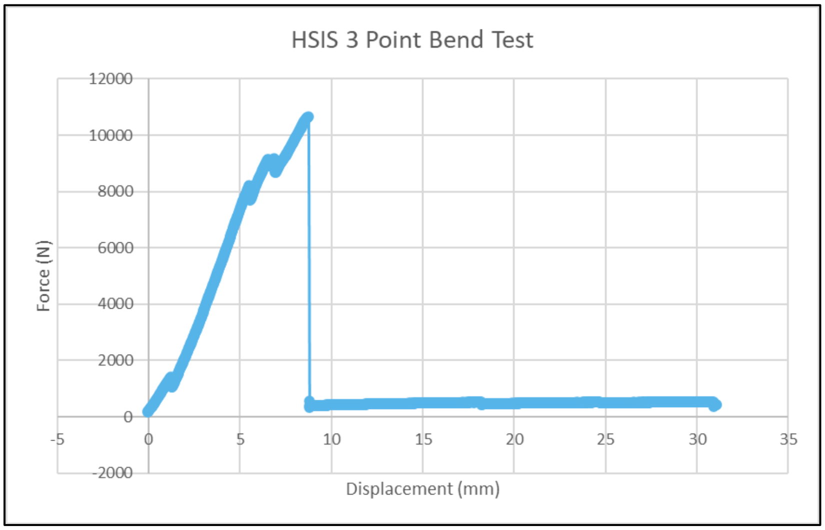
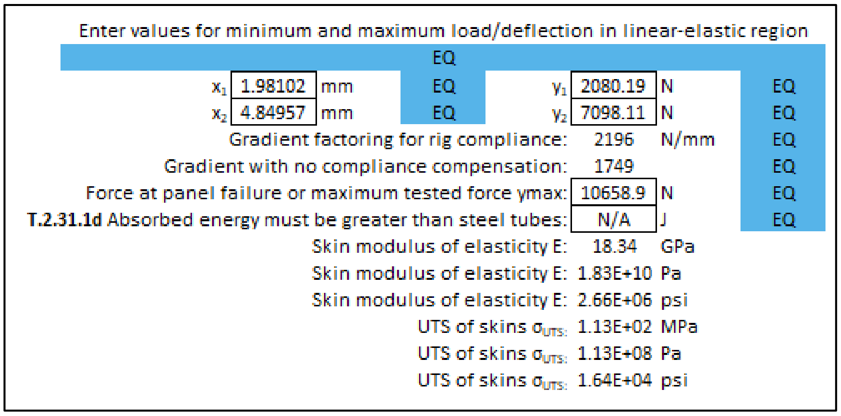


Figure 125 - HSIS three-point bend test force vs displacement



Enter values for minimum and maximum load/deflection in linear-elastic region

EQ

x_1 1.98102 mm EQ y_1 2080.19 N EQ

x_2 4.84957 mm EQ y_2 7098.11 N EQ

Gradient factoring for rig compliance: 2196 N/mm EQ

Gradient with no compliance compensation: 1749 EQ

Force at panel failure or maximum tested force ymax: 10658.9 N EQ

T.2.31.1d Absorbed energy must be greater than steel tubes: N/A J EQ

Skin modulus of elasticity E: 18.34 GPa

Skin modulus of elasticity E: 1.83E+10 Pa

Skin modulus of elasticity E: 2.66E+06 psi

UTS of skins σ_{UTS}: 1.13E+02 MPa

UTS of skins σ_{UTS}: 1.13E+08 Pa

UTS of skins σ_{UTS}: 1.64E+04 psi

Figure 126 - HSIS derived properties

The results of all the three-point bend tests can be seen in Figure 127. It can be seen in the figure that the stiffness between the ANSYS simulated stiffness and the actual stiffness have a strong correlation, which verifies that the ANSYS simulations are correct. As seen below, the corrected stiffness of the panel correlates much closer to the ANSYS results. This is due to the compliance of the testing jig. Using an equation identical to the equation in Figure 90 for the torsional stiffness calculations, the actual stiffness of the panel was found considering it in series with the jig. This yields the actual stiffness value, removing the element of jig compliance.

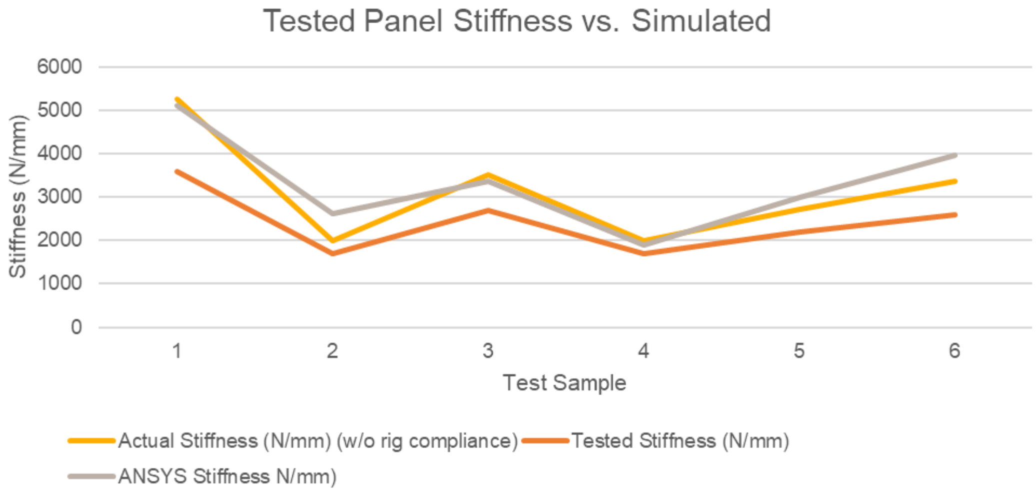


Figure 127 - Three-point bend test and simulation correlation

5.3 Perimeter Shear Test

The perimeter shear test was conducted to demonstrate that each laminate region met the rules regulated perimeter shear requirements. These testing setup for the perimeter shear test is regulated by the FSAE Rulebook, therefore the testing jig from the previous monocoque design was used.

5.3.1 Setup

The testing setup uses a 105mmx105mm square composite panel, loaded by a 25.4mm diameter flat ended punch. The panel is set on a rigid base with a hole cutout to allow for the second skin perimeter shear to be calculated without moving the panel. Figure 128 below shows the testing setup for the perimeter shear test.

Figure 128 - Perimeter shear test setup

5.3.2 Results

5.3.2.1 Front Bulkhead Support

The front bulkhead support laminate was tested using the setup defined above and found to meet all perimeter shear requirements. Figure 129 shows the resulting test data, while Figure 130 shows that it meets all SES and rulebook requirements. It should be noted that the perimeter shear of the second skin exceeded the capabilities of the MTS locking jaws at 12kN, so the test was ended. This did not affect the results as it had already met the requirements at this point.

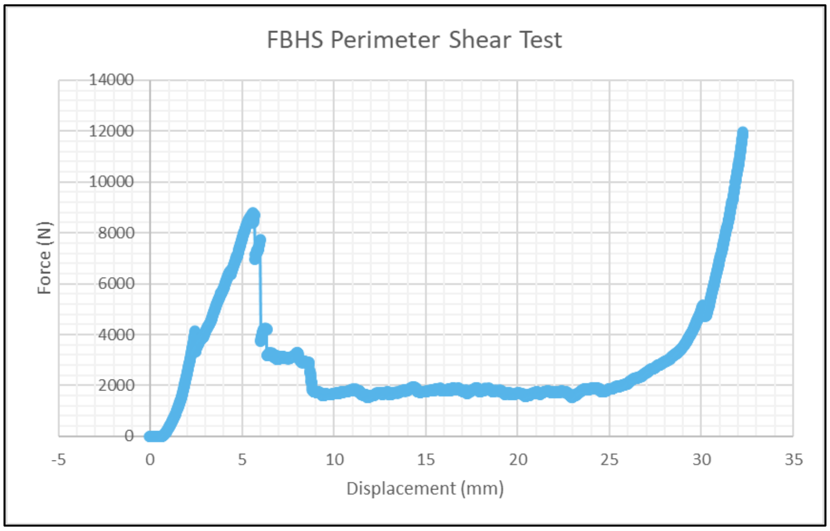
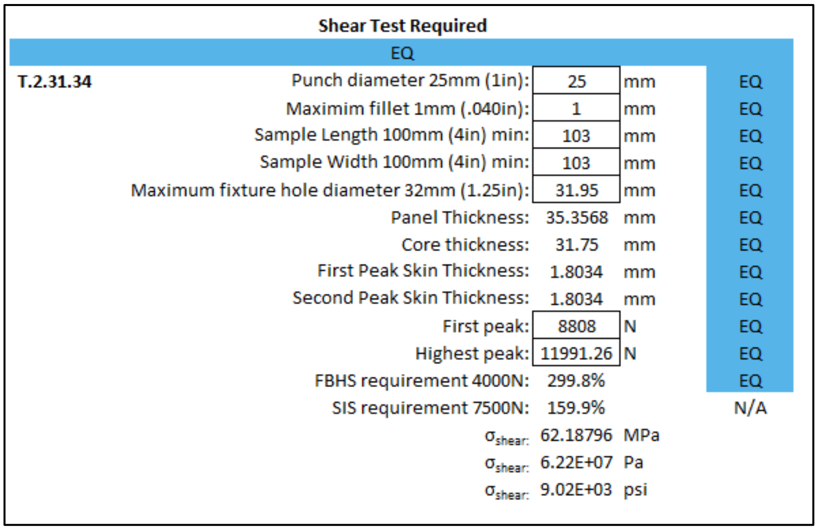


Figure 129 - FBHS perimeter shear test force vs displacement



Shear Test Required

EQ

T.2.31.34	Punch diameter 25mm (1in):	25	mm	EQ
	Maximim fillet 1mm (.040in):	1	mm	EQ
	Sample Length 100mm (4in) min:	103	mm	EQ
	Sample Width 100mm (4in) min:	103	mm	EQ
	Maximum fixture hole diameter 32mm (1.25in):	31.95	mm	EQ
	Panel Thickness:	35.3568	mm	EQ
	Core thickness:	31.75	mm	EQ
	First Peak Skin Thickness:	1.8034	mm	EQ
	Second Peak Skin Thickness:	1.8034	mm	EQ
	First peak:	8808	N	EQ
	Highest peak:	11991.26	N	EQ
	FBHS requirement 4000N:	299.8%		EQ
	SIS requirement 7500N:	159.9%		N/A
	$\sigma_{shear:}$	62.18796	MPa	
	$\sigma_{shear:}$	6.22E+07	Pa	
	$\sigma_{shear:}$	9.02E+03	psi	

Figure 130 - FBHS perimeter shear test meeting SES requirements

5.3.2.2 Vertical Side Impact Structure / Main Hoop Bracing Support

The shared vertical side impact structure and main hoop bracing support laminate was tested and found to meet all perimeter shear requirements. Figure 131 shows the resulting test data, while Figure 132 shows that it meets all rulebook requirements.

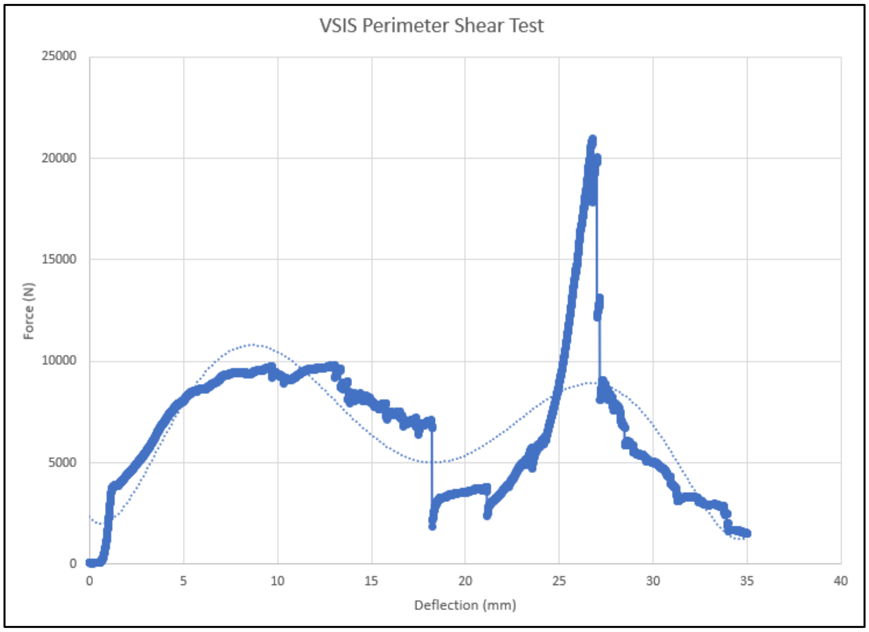
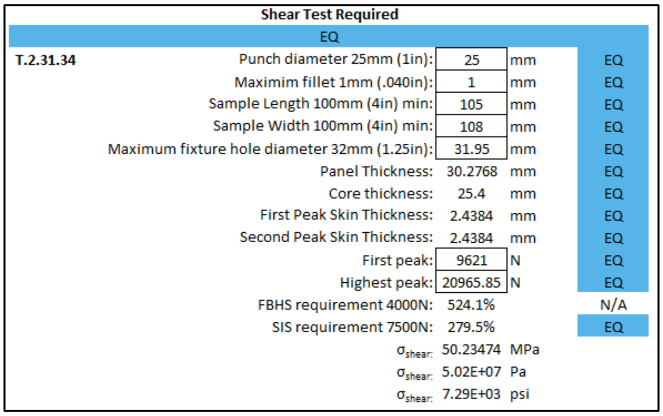


Figure 131 - VSIS perimeter shear test force vs displacement



	Shear Test Required			
	EQ			
T.2.31.34	Punch diameter 25mm (1in):	25	mm	EQ
	Maximim fillet 1mm (.040in):	1	mm	EQ
	Sample Length 100mm (4in) min:	105	mm	EQ
	Sample Width 100mm (4in) min:	108	mm	EQ
	Maximum fixture hole diameter 32mm (1.25in):	31.95	mm	EQ
	Panel Thickness:	30.2768	mm	EQ
	Core thickness:	25.4	mm	EQ
	First Peak Skin Thickness:	2.4384	mm	EQ
	Second Peak Skin Thickness:	2.4384	mm	EQ
	First peak:	9621	N	EQ
	Highest peak:	20965.85	N	EQ
	FBHS requirement 4000N:	524.1%		N/A
	SIS requirement 7500N:	279.5%		EQ
	σ_{shear}:	50.23474	MPa	
	σ_{shear}:	5.02E+07	Pa	
	σ_{shear}:	7.29E+03	psi	

Figure 132 - VSIS perimeter shear test meeting SES requirements

This laminate crushed in an atypical fashion. Instead of piercing a clear hole through the laminate, the entire panel's core failed before the punch pierced the skin. Even with this occurring, the minimum perimeter shear was met. This atypical crushing can be seen in Figure 133.

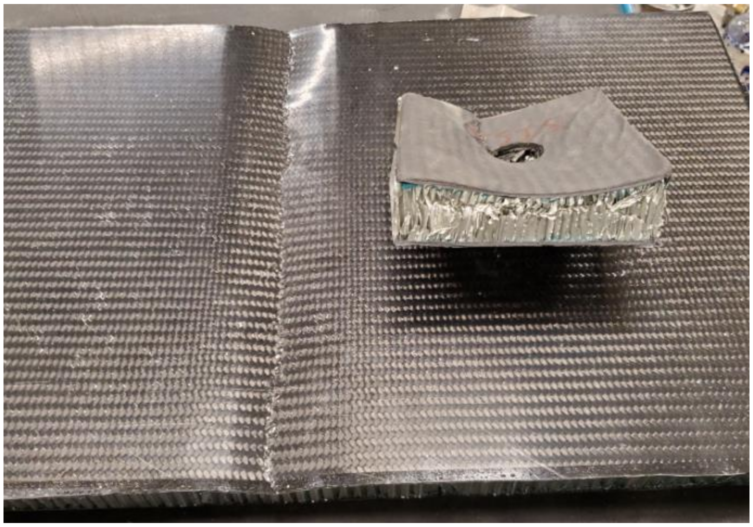


Figure 133 - VSIS perimeter shear test crushed panel

5.3.2.3 Horizontal Side Impact Structure

The horizontal side impact structure was the final laminate tested and found to meet all perimeter shear requirements as well. Figure 134 shows the resulting test data, while Figure 135 shows that it meets all rulebook requirements.

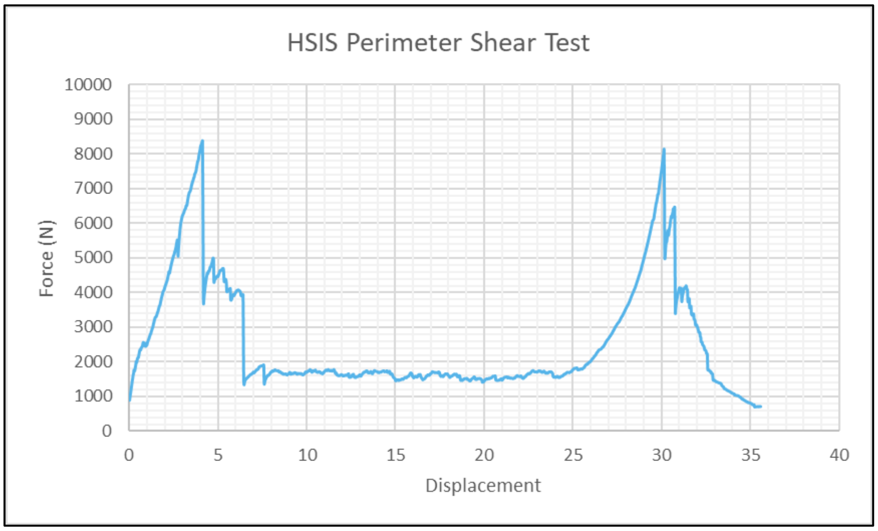
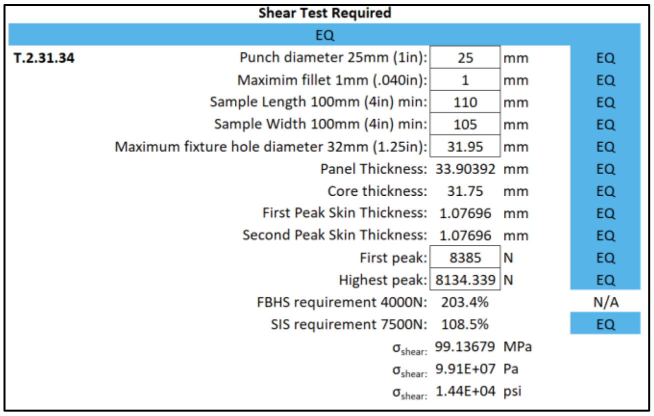


Figure 134 - HSIS perimeter shear test force vs displacement



Shear Test Required

EQ

T.2.31.34	Punch diameter 25mm (1in):	25	mm	EQ
	Maximim fillet 1mm (.040in):	1	mm	EQ
	Sample Length 100mm (4in) min:	110	mm	EQ
	Sample Width 100mm (4in) min:	105	mm	EQ
	Maximum fixture hole diameter 32mm (1.25in):	31.95	mm	EQ
	Panel Thickness:	33.90392	mm	EQ
	Core thickness:	31.75	mm	EQ
	First Peak Skin Thickness:	1.07696	mm	EQ
	Second Peak Skin Thickness:	1.07696	mm	EQ
	First peak:	8385	N	EQ
	Highest peak:	8134.339	N	EQ
	FBHS requirement 4000N:	203.4%		N/A
	SIS requirement 7500N:	108.5%		EQ
	$\sigma_{shear:}$	99.13679	MPa	
	$\sigma_{shear:}$	9.91E+07	Pa	
	$\sigma_{shear:}$	1.44E+04	psi	

Figure 135 - HSIS perimeter shear test meeting SES requirements

5.4 Harness Mount Test

Similar to the horizontal side impact perimeter shear test, a test was conducted to test the tear out strength of the driver harness, as well as the strength of the mount itself. This test was done by bolting an angled composite plate to a rigid mount. The angle of the plate simulates the direction of applied when connected into the MTS. This jig was first made for development of the BR19 harness mounts as they were of similar construction. Shown in Figure 136 is the harness test setup.

Figure 136 - Harness mount test setup

The composite panel used match the HSIS laminate as this is the region that the harness mounts to. The sample was then loaded to find the failure force required to cause failure of either the mount of composite. Shown in Figure 137 is the resulting force vs displacement chart.

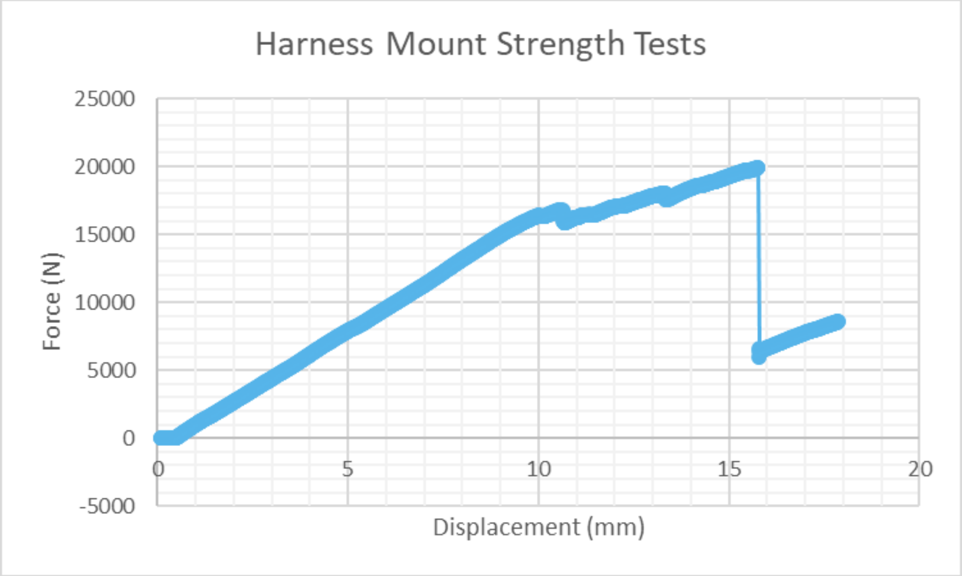


Figure 137 - Harness mount strength test force vs displacement

The test was ended once the composite panel experienced core shear. As seen in the plot, the peak force before failure was 19.9kN, passing the minimum requirement of 19.5kN.

5.5 Lap Joint Test

The lap joint tensile test was used to determine the failure load and overall strength of the lap joint. This test is necessary to ensure that the upper and lower halves of the monocoque are bonded in a laminate that is stronger than all other structure laminates.

5.5.1 Setup

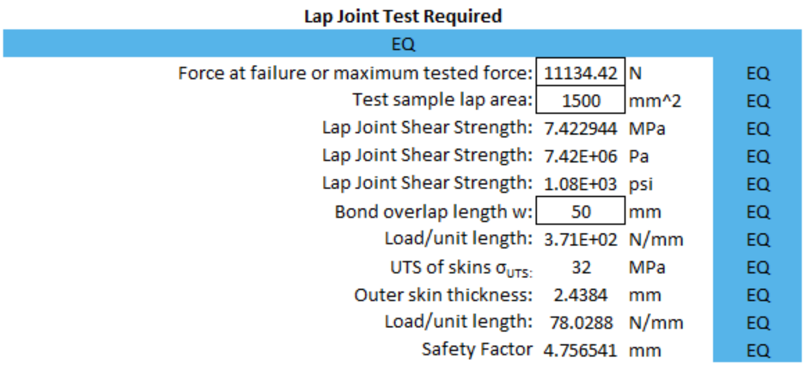
To test the strength of a potentially viable lap joint, multiple samples were made. The samples used a 20mm wide by 50mm long overlap region. To create the sample, two extremely thick pieces of pre-cured prepreg carbon fiber were bonded together. Then, the surfaces were sanded and cleaned. Wet layup carbon fiber was then applied along the desired shear area. Once vacuum bagged and cured, the samples were trimmed.

For the test setup, it was necessary to provide the MTS a grabbable surface to prevent poor results. Pieces of aluminum were bonded to the prepped sample surface using Loctite EA9430. These pieces of aluminum were tapered at the ends to adequately distribute the load without affecting test results. Once cured, a 0.25” diameter clearance hole was drilled through the sample. A bolt was then passed through a clevis and the sample, with washers added to keep the sample straight. This was then bolted to a fixture, and the MTS load arm. This setup can be seen in Figure 138 below.

Figure 138 - Lap joint test setup

5.5.2 Results

The resulting lap joint laminate used demonstrates a safety factor of at least 4.756 N/mm throughout the structure. The other properties of the lap joint can be seen in the SES excerpt shown in Figure 139.



Lap Joint Test Required

EQ			
Force at failure or maximum tested force:	11134.42	N	EQ
Test sample lap area:	1500	mm^2	EQ
Lap Joint Shear Strength:	7.422944	MPa	EQ
Lap Joint Shear Strength:	7.42E+06	Pa	EQ
Lap Joint Shear Strength:	1.08E+03	psi	EQ
Bond overlap length w:	50	mm	EQ
Load/unit length:	3.71E+02	N/mm	EQ
UTS of skins σ_{UTS}:	32	MPa	EQ
Outer skin thickness:	2.4384	mm	EQ
Load/unit length:	78.0288	N/mm	EQ
Safety Factor	4.756541	mm	EQ

Figure 139 - Lap joint test meeting SES requirements

Where the resulting data was calculated from the data collected on the third trial of lap joint samples. This test data can be seen in Figure 140 below. The lap joint is capable of supporting 11134.42N of force before massive failure occurs.

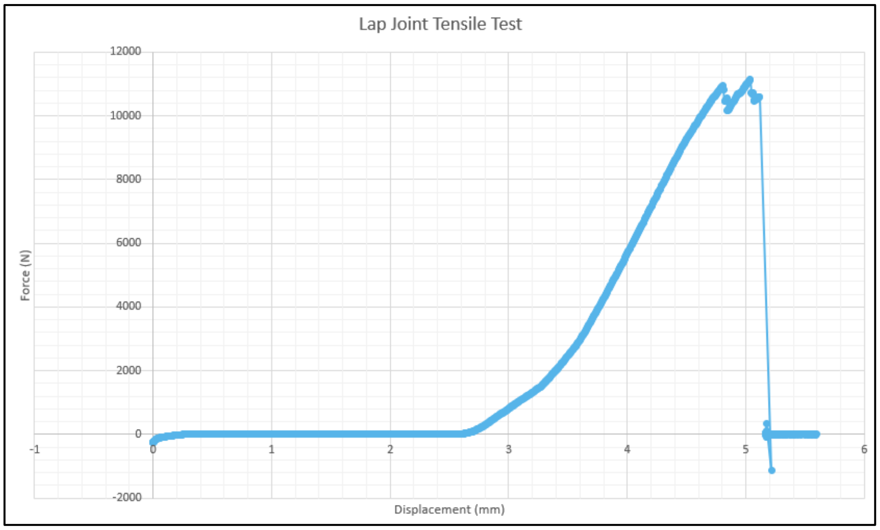


Figure 140 - Lap joint tensile test force vs displacement

6 Overall Chassis Results

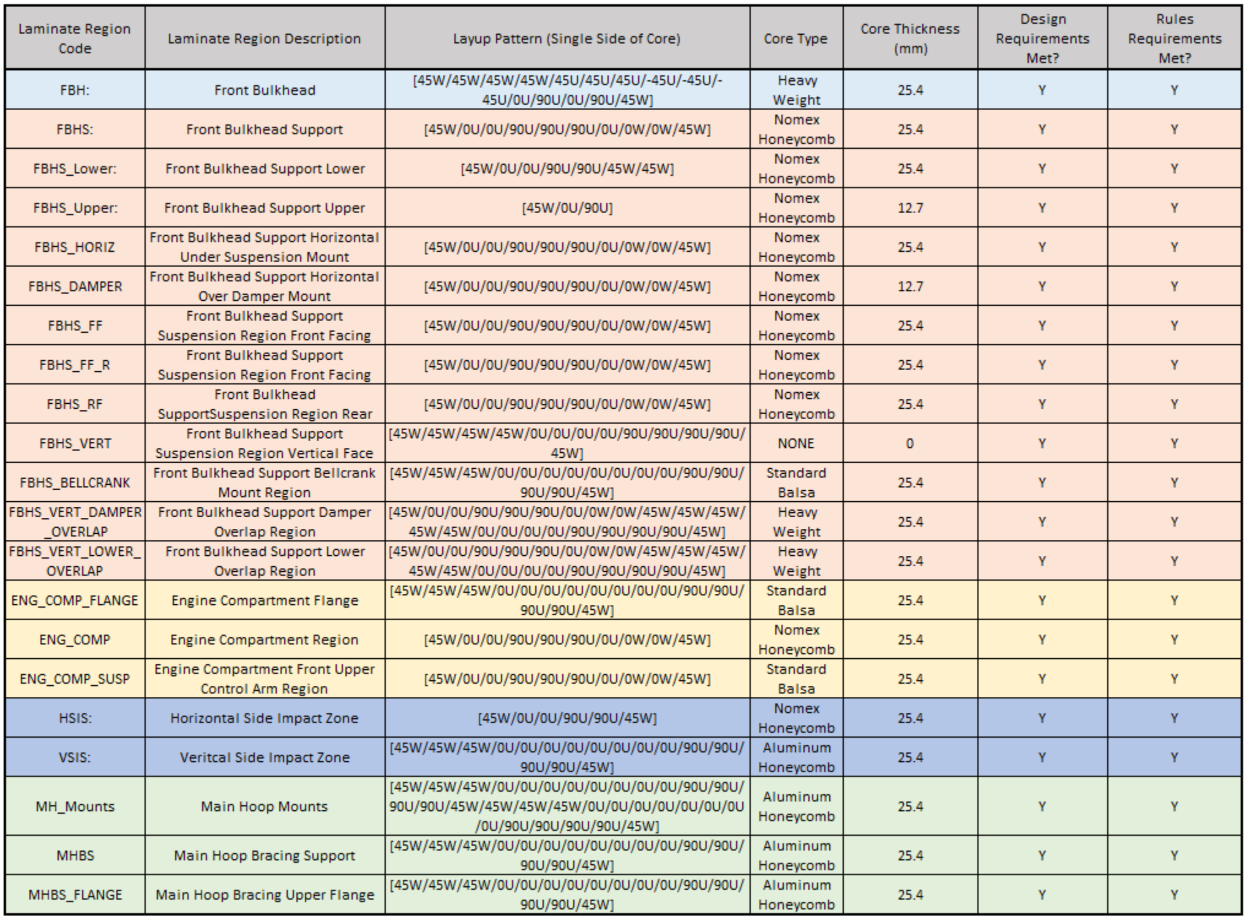
The final monocoque design meets and exceeds the previous BR20 monocoque in packaging, weight, cost, and manufacturability. This demonstrates a successful design that will increase the overall performance of the Bronco Racing vehicle.

6.1 Packaging Improvements

There were many important packaging changes made to BR21. These not only improved the weight and ergonomics of the vehicle but also decreased the complexity of assembly and maintenance. The front suspension was mounted normal to the monocoque surface which ensured the FBHS would not need to be over built. The front ARB was repositioned and redesigned to account for this. The cockpit opening was made to match the size of the provided template, increasing driver comfort and ergonomics. In the rear, the drivetrain and rear suspension was moved forward 6 inches until the drivetrain was close enough to the powertrain to be directly mounted to it, all while keeping the desired wheelbase. This not only decreased the unused space in the engine bay but also allowed for a much more reclined driver position while still maintaining the 7 feet of visibility seen in the previous model. The optimal steering wheel position was found and imported into the model so the drivers can comfortably pilot the vehicle. Finally, due to the rear suspension moving forward and a smaller roll envelope needed as well as the decrease in cockpit opening size, the main roll hoop size was drastically decreased.

6.2 Final Laminate Breakdown

The laminate has been shown to meet the worst-case loading parameters in ANSYS ACP, as well as meeting all Formula SAE Rulebook and SES requirements through physical testing. The resulting laminates are shown in Table 9 below. Recall that the 0° laminate direction references the longitudinal axis of the vehicle, or the vertical axis on regions with no longitudinal component (excluding the MHBS).



Laminate Region Code	Laminate Region Description	Layup Pattern (Single Side of Core)	Core Type	Core Thickness (mm)	Design Requirements Met?	Rules Requirements Met?
FBH:	Front Bulkhead	[45W/45W/45W/45W/45U/45U/45U/-45U/-45U/-45U/0U/90U/0U/90U/45W]	Heavy Weight	25.4	Y	Y
FBHS:	Front Bulkhead Support	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb	25.4	Y	Y
FBHS_Lower:	Front Bulkhead Support Lower	[45W/0U/0U/90U/90U/45W/45W]	Nomex Honeycomb	25.4	Y	Y
FBHS_Upper:	Front Bulkhead Support Upper	[45W/0U/90U]	Nomex Honeycomb	12.7	Y	Y
FBHS_HORIZ	Front Bulkhead Support Horizontal Under Suspension Mount	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb	25.4	Y	Y
FBHS_DAMPER	Front Bulkhead Support Horizontal Over Damper Mount	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb	12.7	Y	Y
FBHS_FF	Front Bulkhead Support Suspension Region Front Facing	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb	25.4	Y	Y
FBHS_FF_R	Front Bulkhead Support Suspension Region Front Facing	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb	25.4	Y	Y
FBHS_RF	Front Bulkhead SupportSuspension Region Rear	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb	25.4	Y	Y
FBHS_VERT	Front Bulkhead Support Suspension Region Vertical Face	[45W/45W/45W/45W/0U/0U/0U/0U/90U/90U/90U/90U/45W]	NONE	0	Y	Y
FBHS_BELLCRANK	Front Bulkhead Support Bellcrank Mount Region	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Standard Balsa	25.4	Y	Y
FBHS_VERT_DAMPER_OVERLAP	Front Bulkhead Support Damper Overlap Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W/45W/45W/45W/45W/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Heavy Weight	25.4	Y	Y
FBHS_VERT_LOWER_OVERLAP	Front Bulkhead Support Lower Overlap Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W/45W/45W/45W/45W/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Heavy Weight	25.4	Y	Y
ENG_COMP_FLANGE	Engine Compartment Flange	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Standard Balsa	25.4	Y	Y
ENG_COMP	Engine Compartment Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb	25.4	Y	Y
ENG_COMP_SUSP	Engine Compartment Front Upper Control Arm Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Standard Balsa	25.4	Y	Y
HSIS:	Horizontal Side Impact Zone	[45W/0U/0U/90U/90U/45W]	Nomex Honeycomb	25.4	Y	Y
VSIS:	Veritcal Side Impact Zone	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Aluminum Honeycomb	25.4	Y	Y
MH_Mounts	Main Hoop Mounts	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W/45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Aluminum Honeycomb	25.4	Y	Y
MHBS	Main Hoop Bracing Support	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Aluminum Honeycomb	25.4	Y	Y
MHBS_FLANGE	Main Hoop Bracing Upper Flange	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Aluminum Honeycomb	25.4	Y	Y

Table 9 - BR21 monocoque laminates by region

6.3 Cost

The new chassis design is also cheaper than the BR20 chassis system. The cost values of both monocoques were calculated by using the overall laminate region surface area in the mold, considering excess. A 30% waste factor was considered to account for manufacturing wastes during the carbon fiber trimming process, as well as overlap regions. The cost was then calculated using the sponsor discounted rates for the width and length of carbon fiber roll required. The BR20 subframe cost was determined from the VR3 sponsor order receipt. Mounts for the BR21 vehicle are approximated based off the Bronco Racing Torlon insert minimum order requirement. Figure 141 below shows the cost summary of the BR20 and BR21 vehicles.

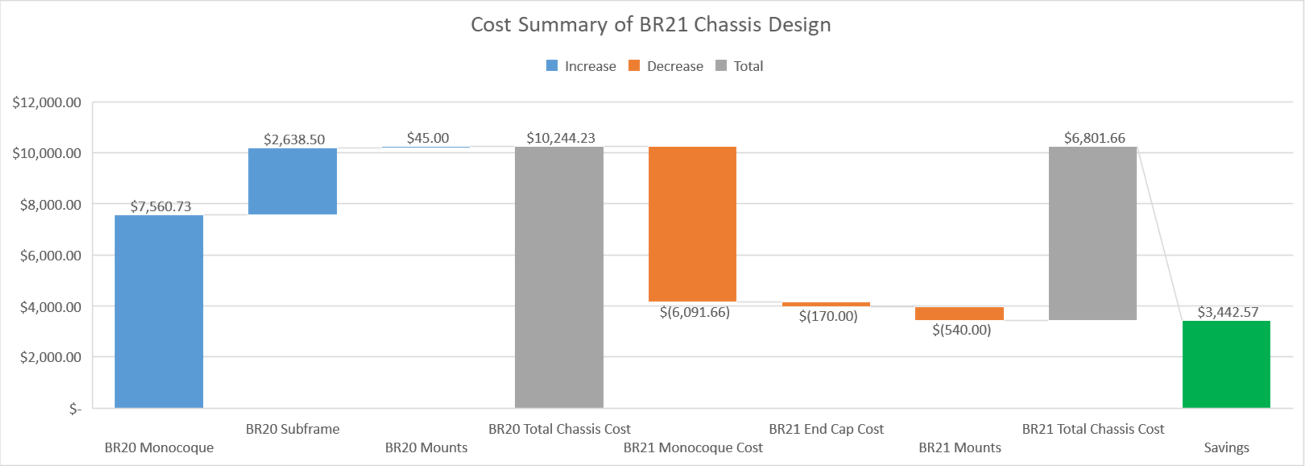


Figure 141 - BR21 cost summary compared to BR20

6.4 Mass

The overall mass of the vehicle was found through similar means as the cost. The overall area weight of each type of carbon fiber, film adhesive, and core was used with the known total surface area and quantity of layers to calculate the total mass of the chassis. The new chassis design will save 8.24kg assuming a final rear end cap design of 5kg. Figure 142 below shows the cost summary of the BR20 and BR21 vehicles.

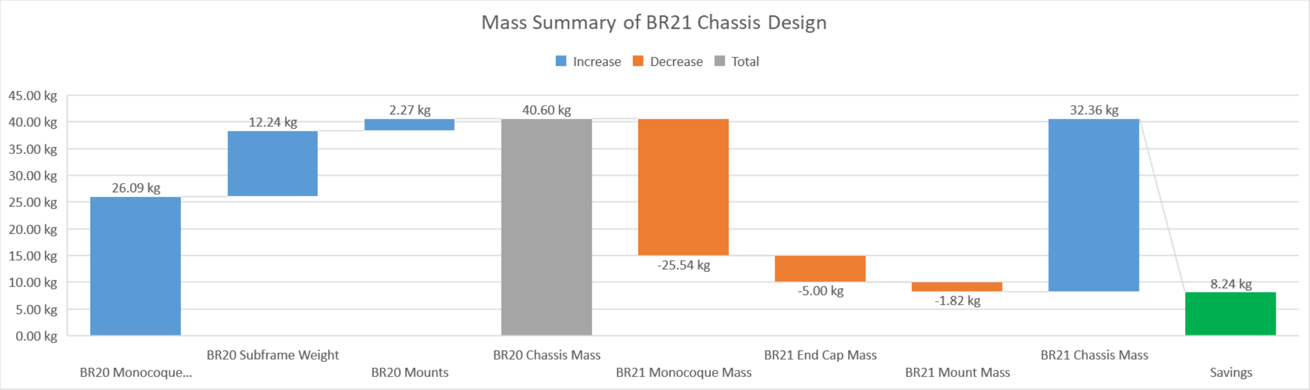


Figure 142 - BR21 mass summary compared to BR20

7 Conclusions

The new design of the BR21 chassis decreases weight by 8.24kg and cuts cost by $3,442.57 while meeting all design requirements and Formula SAE Rulebook requirements. This demonstrates a design that meets the requirements of the Bronco Racing Formula SAE team. In addition to the new design, a comprehensive manufacturing report has been created and can be seen in Appendix A. This report meets the final Bronco Racing requirement in that it demonstrates the methodology needed to successfully manufacture the proposed design.

Acknowledgements

We would like to thank the following people and sponsors; without their support this project would not have been possible.

- Mitch Macdermaid
- FSAE Team Members
- Dr. Daniel Kujawski
- Suraj Nikam
- Dr. Mitchell Keil

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Appendices

Appendix A – Manufacturing Report

Manufacturing of a Carbon Fiber Composite Monocoque Chassis for a Formula-Style Vehicle

WMU Bronco Racing

Alex Carline, Mitchell Hiller, Riley Masters

Spring 2020

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1 Introduction

1.1 Overview of Process

The manufacturing of a carbon fiber monocoque is completed in a series of steps. Outlined below are the general processes and available deviations depending on time constraints, budget, and human resources availability for construction of the vehicle. Manufacturing methods are described in a general way to allow for this report to be used across multiple generations of monocoque designs.

1.2 Personal Protective Equipment

Throughout the manufacturing process of the monocoque, personal protective equipment (PPE) is necessary for the safety of all involved in manufacturing. Heavy machinery, power tools, dangerous chemicals, and particulate dust will be present throughout the process. Safety Data Sheets (SDS) should be read and understood, as well as lab procedures and processes.

2 Mold Creation

The monocoque is created using a female high temperature fiberglass mold. However, to make this mold a male polyurethane tooling board mold is needed. This is due to the complex geometry of the monocoque, requiring a three axis CNC to cut the desired shapes and contours. Additionally, the lighter weight fiberglass molds allow for easier transportation of the molds as the polyurethane molds require a forklift to move.

2.1 Polyurethane Tooling Board Male Mold

The first step in the creation of the monocoque is the creation of the first mold. The monocoque is constructed in two halves, an upper and lower mold. To create the monocoque, the mold must first be created in CAD. Figure 143 shows an example of these molds for the BR21 monocoque with the cut lines shown in blue.

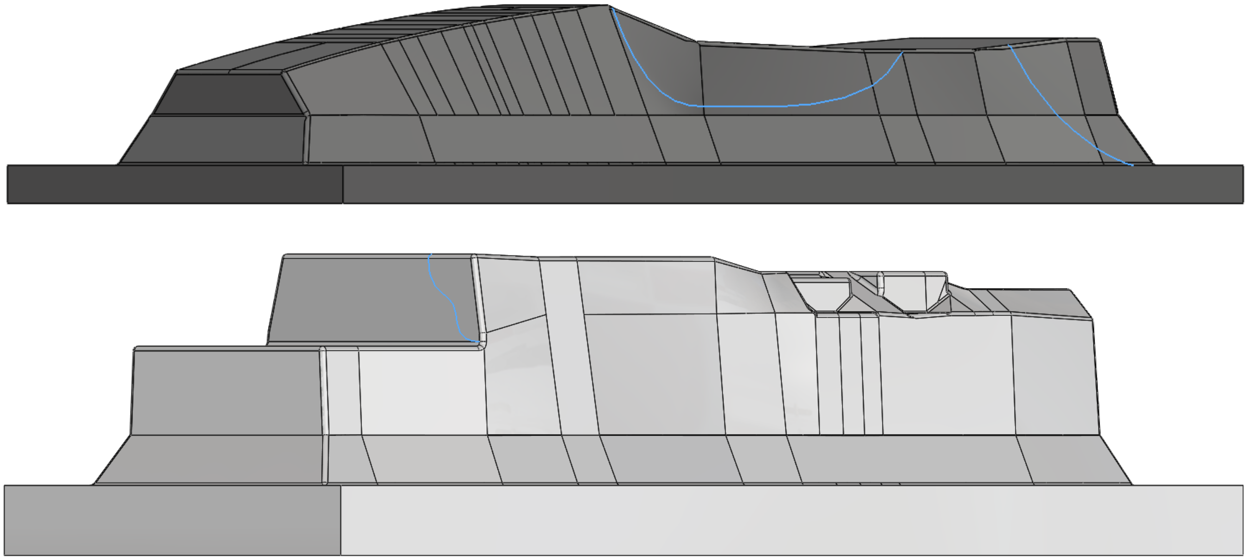


Figure 143 - Example CAD model of upper and lower molds

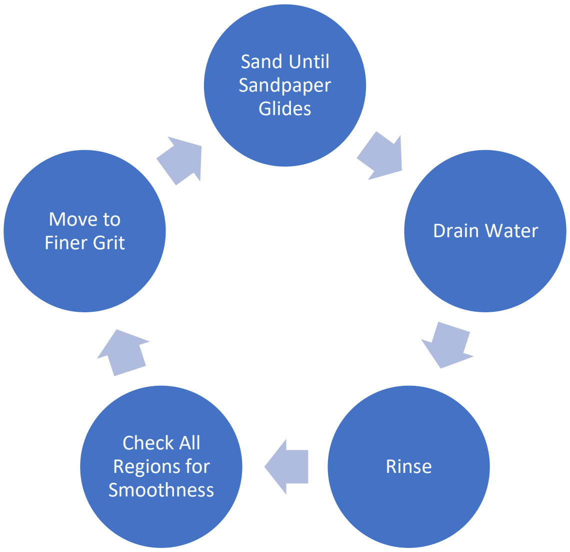
To create this geometry, the polyurethane tooling boards must be stacked to a height of 600 millimeters for the lower mold and 460 millimeters for the upper mold. Figure 144 shows the available supply of tooling board from Coastal Enterprises, currently stored at the Battle Creek airport. This material can be accessed by talking with Mike Konkel.

Figure 144 - Stack of tooling board at Battle Creek airport

To create a stack of sufficient height, the pieces of tooling board should be stacked from largest and most complete sheets to smallest. The largest 4’ x 8’ sheets will be used as the base of the tooling board stack, on top of a pallet for transportation. Smaller pieces will then be arranged in a Tetris-like style. All pieces will be bonded together until the desired height is reached and exceeded by 25mm. The additionally 25mm allows for removal of dirty material or possibly damaged areas. To properly adhere each sheet together, the epoxy should be brushed onto each side of the sheets. Then, large wood screws should be used to clamp the two sheets together while the epoxy dries. These screws can be removed after the initial set time of the epoxy is reached. Repeat this process until the mold height plus 25mm is reached. Once the stack of tooling board is created, the material can be moved using a pallet jack, and placed inside the

Formula Team's trailer for transportation to the machining sponsor. For the male mold, Total Tooling Concepts (TTC) will be the machining sponsor. The contact window for this company is Jared Walejewski of the BR FSAE Powertrain subteam.

Once the male molds are machined, the molds should be sprayed with automotive primer, then sanded to a smooth surface finish. Before this is done, note the density of the exposed tooling board. This will be useful in the female mold creation later on. The surface finish of the male mold will match that of the female mold created, therefore additional effort in this step will save effort later in the building cycle. In addition to just the mold surface, a perimeter of 70mm around the base of the mold should be prepared as this will serve as a flange around the top of the mold. The entire mold should be sanded smooth to 3000 grit, following the below process:



Finally, preparation of the male mold is the application of the mold release. Frekote 770-NC will be used throughout the monocoque build process. Frekote 770-NC comes in wipe-on form or spray form. Through previous monocoque build cycles, only the spray form should be used as the wipe-on form yields unreliable results. Application of the Frekote should follow the instructions provided on the can. After application, avoid contact with the mold surface. Frekote

770-NC is a semi-permanent mold release and should not be affected by occasional contact, however erring on the safe side can prevent many issues later on.

2.2 Fiberglass Female Mold

The female mold is the usable mold for creation of the monocoque. A quality construction of the female mold will prevent many possible issues in the assembly and final cleaning of the monocoque. Special attention should be taken in the layup of the fiberglass, as well as the construction putty used after.

To begin the fiberglass layup, materials must first be purchased. All mold materials can be found at SC Enterprises in Vicksburg, Michigan.

Dry cloth fiberglass can be draped over the mold and cut to approximate sizing before the wet layup occurs. The EL-336 resin and hardener mix ratios should be understood, as well as the process for mixing the construction putty.

The mold geometry is shown in Figure 145. Note the large flange present in the mold. This flange is critical to the success of the mold as it provides stiffness and a region for the core dams to attach into later. Each edge of the mold should have 100 mm from the widest part of the monocoque, as shown below.

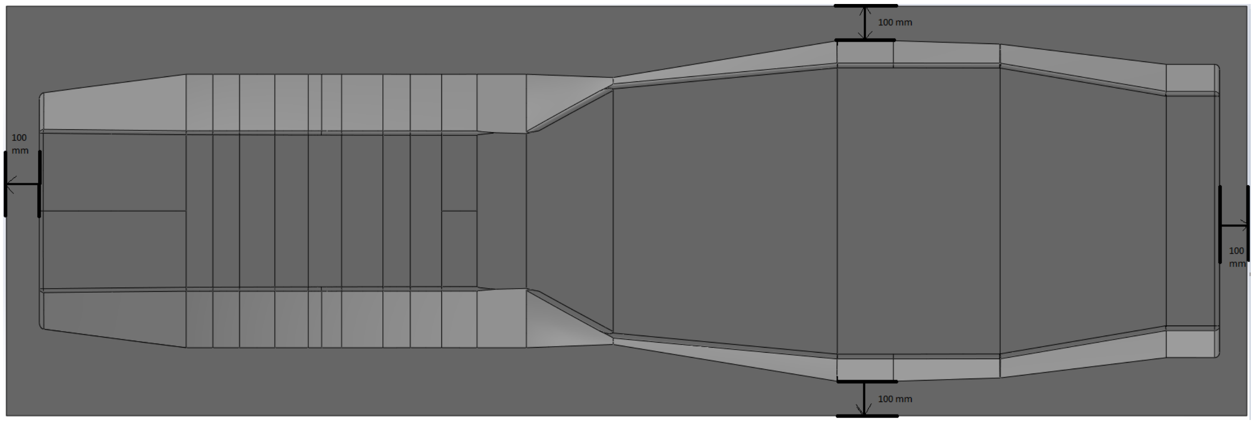


Figure 145 - Mold flange dimensions

Workstations should be made for the fiberglass layup. A team of two should be responsible for mixing and supplying resin. Teams of five on each mold will be responsible for placing and saturating the fiberglass, and one person on each mold should be available to bring supplies and carryout miscellaneous tasks throughout the manufacturing.

The inner surface of the female mold must be extremely smooth; therefore, gel coat is used. To begin the creation of the female fiberglass mold, gel coat must be brushed onto the mold. This layer should be at least 2mm thick to allow for some variance in the mold without reaching the fiberglass underneath. Next, the resin must be thickly brushed onto the surface of the male mold. Following this, the veil fiberglass must be draped over each region of the mold. The process of draping the cloth is very critical to a good surface finish of the monocoque. The center of the cloth should be lowered and pressed into the resin on the mold surface. Then working outward, the rest of the cloth will be pressed into the mold surface. Using BONDO spreaders, the layer of veil will be continuously worked until no dry spots are seen. This method prevents air bubbles from being generated between layers of resin and fiber. The resin is pressed up through the fiber, therefore if the fiber is saturated everywhere, there will not be any air bubbles. After the resin has completely saturated the fiberglass, more resin must then be brushed onto the surface for the next layer of fiberglass.

The above process should be used for all fiberglass used in the female mold. Following the layer of veil fiberglass, a thicker layer of fiberglass should be used. Mid-grade fiberglass is recommended for this step as it is still very flexible but will absorb more resin and is stronger than the veil. Two layers of this thicker fiberglass should be used for strength.

Next, the construction putty will be used to provide a thick outer shell to the mold. The construction putty must be mixed in a concrete mixer. This concrete mixer can be rented from

Scot at SC Enterprises. Once the putty is mixed with the hardener in the concrete mixer, it will be applied to the still-wet fiberglass mold. The putty must be at least 30mm thick around the surface of the mold, except the edges of the flange surface. This can be applied in chunks; however, care should be taken to avoid air bubbles. Once a general thickness of 30mm has been created, the putty should be smoothed to provide a good base of the last layer of fiberglass.

The last layer of fiberglass should be applied using the process mentioned previously. However, this fiberglass will be much thicker and the initial brushing of resin must be extremely thick to ensure total saturation. The last layer of fiberglass should be much thicker fiberglass. After total saturation, any burrs or existing fiberglass hairs should be removed and smoothed. The outside of the mold will be in contact with vacuum bagging, and must be smooth to avoid popping it. Finally, the fiberglass mold can be vacuum bagged to remove air bubbles and smooth out the mold, however this is optional. Previously fiberglass monocoque molds were created without vacuum bagging with varying success. An example of a completed mold without bagging can be seen in Figure 146.

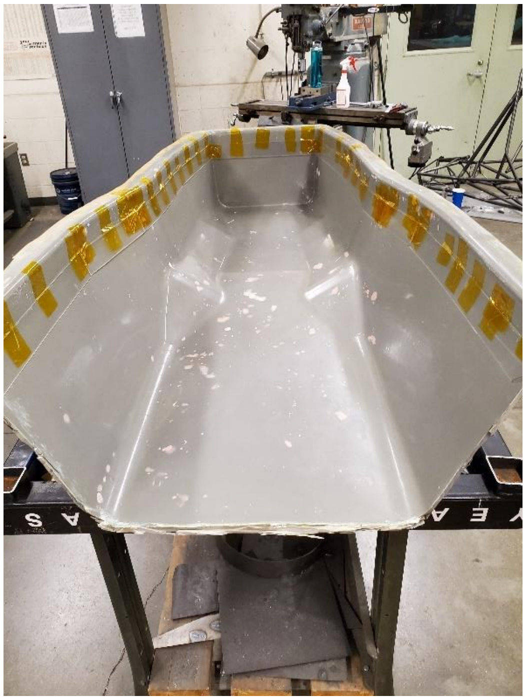


Figure 146 - 2019 fiberglass mold

Bagging both fiberglass molds will be difficult due to the size and weight of the tooling board supporting the molds. To avoid this issue, the bagging of the molds will be single sided.

First, cut nylon peel ply to cover the entire mold surface and upper surface of the tooling board stack. Peel ply will prevent any resin from bonding to the breather cloth and vacuum bag. Next, cut breather cloth to cover the same regions as the peel ply. If there is an excess of resin, consider using two layers of breather cloth. Breather cloth allows for the vacuum to pull even pressure throughout the mold, but also doubles as a saturation cloth for resin. If too much resin is present, the vacuum pressure may be affected. Doubling the amount of breather can avoid this issue. Finally, vacuum bagging must be cut and butyl tape run along the edges of the bag. As this is a single sided bag, the butyl tape will be applied along cleaned edges of the base of the polyurethane tooling board stack on the upper surface. The vacuum puck will then be set on this surface with excess breather under it. This allows the bag to be smaller while the tooling board can remain stationary. Figure 147 shows a diagram of the layout using the BR19 chassis molds.

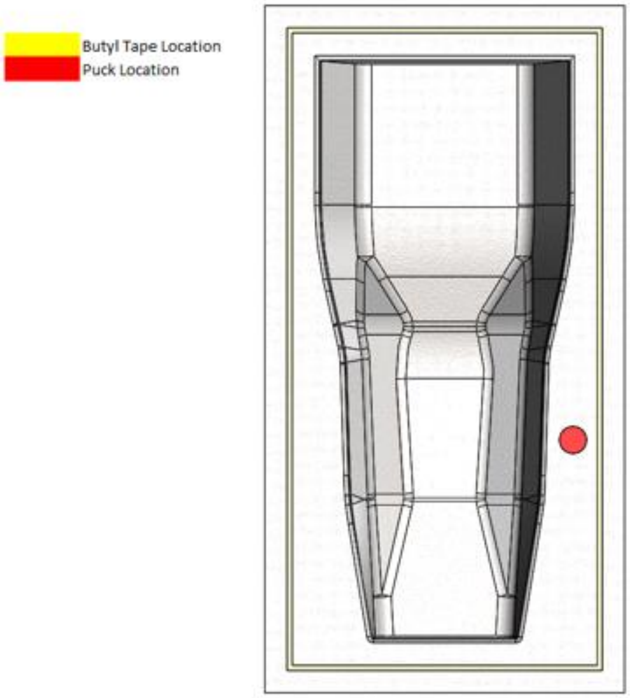


Figure 147 - BR19 mold tape and puck locations

Finally, the vacuum pump can be attached. Due to the varying densities of the polyurethane tooling board, care must be taken to avoid crushing the mold with the pressure. Using the noted tooling board densities recorded previously, control the overall vacuum pressure to a comfortable level. For high density board 29 inches of mercury can be used. For tooling board that can be indented easily, 15 inches of mercury should be the peak. The mold can be now be left until the cure cycle has been completed. This can be seen on the can of resin and hardener.

If the bagging method was used, the molds can be removed from the vacuum and bagging. The female molds must now be removed from the male bucks. Care must be taken to avoid breaking or damaging both the male bucks and female molds, as reuse or sale of these parts is ideal.

Starting around the flange area, use a small pry bar to separate the flange from the upper surface of the tooling board stack. Moving around the entire flange, continue this until the flange surface is lifted. Using constant pressure, keep pressure around the flange while tapping the mold surface area with a small mallet. The added pressure and impulse from the mallet will demold the remaining areas of the mold until it can be removed from the male buck.

After demolding both molds, each must be heat cycled to prevent warping of the carbon fiber monocoque. Figure 148 shows the difference between proper heat cycling between the same laminate layups. Notice the warping and pinching in the front of the BR19 chassis laminate.

Figure 148 - Comparison of BR19 warped layup vs successful layup

To heat cycle the mold, follow the instructions on the can of the EL-336 resin. However, in addition to these instructions, both molds must be vacuum bagged. Vacuum bagging the inner and outer surface of the molds simulates the pressures seen in the autoclave when the mold is being used during monocoque creation. During the cure cycle, two things are happening. The first is the cross-linking of bonds throughout the epoxy resin matrix in the mold. Secondly, air bubbles are being removed before it affects the monocoque.

2.3 Repairing the Fiberglass Mold

The second thing happening is the expanding of air bubbles in between layers of the fiberglass in the mold. As the part heats up, the air expands towards the inner surface of the monocoque. Without a vacuum bag, this would result in a protrusion. Indentations towards the monocoque surface result in deformed part geometry and is not acceptable for a quality final unit. To fix this type of issue, the protruded area must be pierced, then removed using a dental pick. The removal of this area leaves a hole in the mold, that must then be fixed with body filler.

Therefore, the vacuum bag is used to cause the expanding air cavities to collapse away from the monocoque surface mold. This type of defect allows for easier repair, in which no areas have to be removed, and it can be instead fixed with body filler.

BONDO has been used as a cheap alternative to high temperature body filler. BONDO is effective in filling any surface defects, but must have proper surface prep before and after repair. Before BONDO is used, the defected area must be sanded with 320 grit sandpaper until the gel coat is dull. The surface must then be cleaned with water, dried, then BONDO can be applied. This must be done to all defect areas at once. After application and drying, the inner gelcoat surface must be sanded from 600 grit to 3000 grit in the same process used in the male mold preparation.

The last step of female mold repair and preparation is the coating of mold release. Frekote 770-NC must be applied to all gelcoat surfaces and upper flange following the instructions provided on the can.

3 PHASE 1 – INITIAL LAMINATE LAYUP OF MONOCOQUE

The initial phase of monocoque construction will occur in nine parts. These parts are shown in Figure 149 shown below.

1. Creating the Trim Templates
2. Cutting Prepreg Carbon Fiber
3. Offsetting the Lap Joint Region
4. Placing the First Layer
5. Bagging the Molds
6. Running the Vacuum Cycle
7. Placing the Remaining Layers
8. Bagging the Molds Again
9. Transportation of the Molds
10. Autoclave Cure Cycle

Figure 149 - Monocoque construction process

3.1 Trim Template Creation

To properly cut the carbon fiber laminate to fit in the desired regions of the mold, templates must be created. To create the template, purchase a roll of construction paper at least 30” wide. Then drape the paper into the mold and trim until it matches the size of the laminate region. Note the direction of the 0 degree direction on the template. Figure 150 demonstrates the 0 degree direction on the BR20 mold.

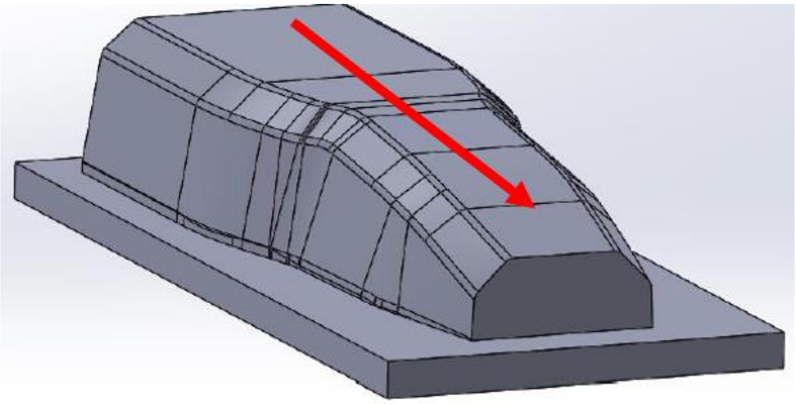


Figure 150 - BR20 mold with 0° direction marked

The laminate region must be accurately placed to ensure that stress concentrators have enough laminate strength. To measure out the laminate regions, use the front bulkhead as an X-direction datum point, and the top of the flange as the Z-datum point. To ensure each laminate evenly distributes stress into other regions, a 20mm overlap between laminates is needed. The laminate should also wrap over the lip of the flange to help reduce warping. Finally, note the regions layup pattern on the template for record keeping during the layup process.

3.2 Cutting Prepreg Carbon Fiber

With the templates created and the layup patterns marked out, cutting prepreg carbon fiber can be done. First, layout a large cardboard sheet that is wider than the roll of AS4 carbon fiber. Remove the prepreg from the freezer, and unroll the length of the carbon sheet, preferably over 40” for ease of cutting. Working in a team of two, one person should mark out the regions being cut, taking note of the weave direction of the carbon fiber roll. In woven twill carbon fiber, the 0 degree direction is in the direction that the roll unravels. However, 0 degree direction and 90 degree direction are the same, and can be used to reduce wasted carbon fiber. For unidirectional carbon fiber (the TR50S) the 0 degree direction is not the same as 90. When marking the cuts to be made, a tolerance of 5 degrees is acceptable in region direction. Any more change risks compromising the strength of the chassis in critical areas. Miscuts into the region area are not allowable, as cut areas of laminate reduces strength along the fiber direction. Once pieces are cut, they should be labeled with the type of carbon fiber cut, and direction on the roll it was cut. For example, “45W” indicates 45 degree cut of the woven carbon fiber. Figure 151 shows the 0 degree direction difference between weave twill and unidirectional carbon fiber.

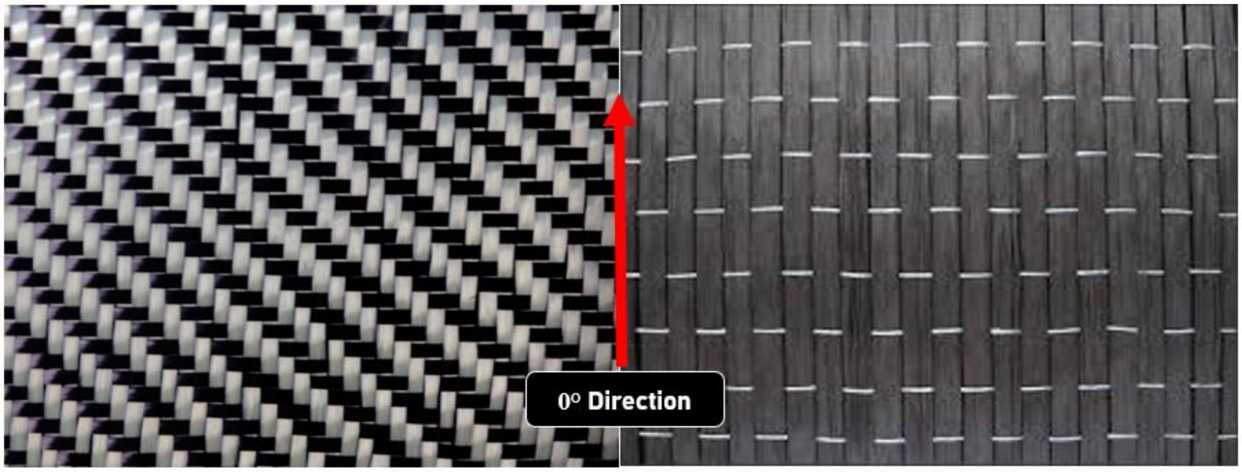


Figure 151 - Difference in 0° for weave and unidirectional

3.3 Offsetting Lap Joint Region

The final step before laying carbon fiber into the mold is the creation of the offset region for the lap joint. The expected thickness of the lap joint is 1.27mm, however finding material of this thickness proves difficult. Additionally, having excess depress makes final surface finishing easier. Previously, 2.03mm thick acrylic plexiglass was used. The plexiglass is cut into strips 50 mm wide, along the length of the upper and lower mold, 50mm from the upper flange. To ensure accurate placement of this plexiglass, a scoring jig must be created to mark the correct Z-location. This location is critical as it also shows the cut line for the bonding of both halves. To create this jig, drill a hole in sheet steel large enough to snugly hold a scoring tool. Then, cut this plate such that the vertical distance between the tip of the scoring tool matches that of the lap joint vertical displacement from the fiberglass flange. Weld a baseplate onto the jig, ensuring it is perpendicular. The upper surface of the baseplate can now be placed on the flange, and the scoring tool will always point to the correct offset.

To place the plexiglass, high temperature tape must be used. The plexiglass will remain in the mold until the final demolding process; therefore, it must be able to perform under heat and vacuum load. Kapton high temperature tape is recommended in the 25mm wide form. The tape must only be applied along the upper surface of the mold where the excess material exists. This is due to the imprinting of the tape onto the laminate. If the plexiglass bows over the mold surface, break it into smaller pieces loosely taped along the seams to prevent resin from pooling in the cracks. Confirm that the upper surface of the plexiglass follows the scoring line, then Frekote the plexiglass and tape, and the remaining mold again, following the instructions on the can. Figure 152 shows the prepared lap joint offset on the BR20 monocoque.

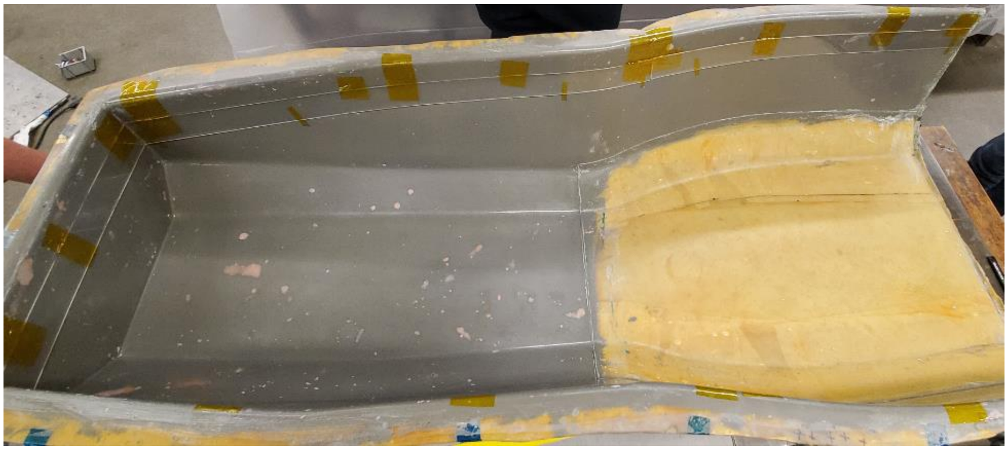
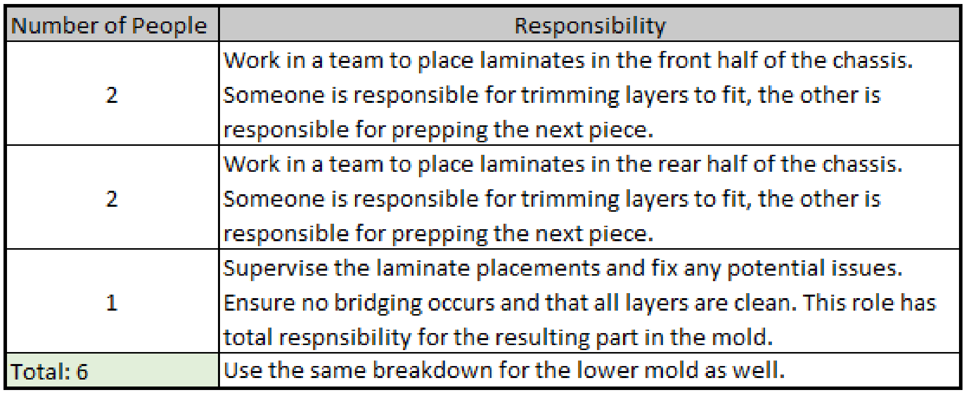


Figure 152 - BR20 prepared lap joint offset on upper mold

3.4 Initial Layer of Carbon Fiber

With the lap joint offset in place and other prep work complete, the cut carbon fiber can be placed into the mold. Assemble a team of twelve people for this step in the process. Refer to Table 10 below for workstations and manpower distribution.



Number of People	Responsibility
2	Work in a team to place laminates in the front half of the chassis. Someone is responsible for trimming layers to fit, the other is responsible for prepping the next piece.
2	Work in a team to place laminates in the rear half of the chassis. Someone is responsible for trimming layers to fit, the other is responsible for prepping the next piece.
1	Supervise the laminate placements and fix any potential issues. Ensure no bridging occurs and that all layers are clean. This role has total respnsibility for the resulting part in the mold.
Total: 6	Use the same breakdown for the lower mold as well.

Table 10 - Twelve responsibilites for intial layup

To prepare the laminate for placing, remove the backing paper. For the woven AS4, remove the pink front facing film first with a pick, then the white backing paper once it is ready to be placed. The carbon fiber should not be frozen when placing, as this will create excess moisture in the mold. The carbon fiber should be at least 50°F before beginning layup.

When placing each laminate, the same steps must be taken as that of the fiberglass layup for the mold. The carbon fiber should be draped horizontally over the region of layup, then the middle pressed into the mold surface first, gradually working out to the edges of the piece of carbon fiber. For larger pieces, work in teams of two to keep the carbon fiber from sticking to itself or other undesired regions. While placing the laminate, ensure bridging does not occur by pressing material firmly into mold contours. When draping, avoid pulling on the fiber as it will stretch and result in a narrower and longer piece. Ensure that the 0 degree direction of the carbon fiber is still along the longitudinal direction of the chassis before placing. This first layer is the most visible layer; therefore, the best looking pieces and correct orientation need to have extra care placed on them to ensure a beautiful final part. Additionally, the team responsible for the front bulkhead support regions should place their laminate first, so the visible overlap is on the front bulkhead region, hidden by the anti-intrusion plate.

For unidirectional carbon fiber, avoid holding the material along the 90 degree direction as it is very easy to rip apart. Holding the material in the 0 degree direction is advised.

If the material will not lay flat around contours of the mold, relief cuts may be necessary. First, press as much of the laminate into the mold as possible. The remaining triangular lifted regions will require relief cuts. Using scissors, create a slice from the top of the largest arc lifted, into the laminate until reaching the end of the lifted portion. After this, press one side of the lifted region down and underneath the other portion. Push the other half down over top of this region, and smooth out.

After the material has been set in place, check over the region for bridging. The easiest way to spot bridging is by following contours of the mold. If the contour suddenly becomes less pronounced, then bridging is likely occurring at that region. To check for bridging, use the handle of a plastic pair of scissors and press while rolling along the contour of the handle. If the laminate depresses inward, or makes an audible stretching noise, it is bridging. Figure 153 shows an example of extreme bridging. In reality, it is likely that the air gap will be less than 1mm.

Figure 153 - Extreme bridging of BR20 front bulkhead

3.5 Proper Bagging Strategy

After each region has its first layer of carbon fiber, bagging is necessary to ensure that it is pressed firmly into the mold. Vacuum bagging comes in a variety of types. For the monocoque, high temperature bagging material is used.

To begin the bagging process, clear a large workspace at least 250cm by 125cm. Cover the area in the plastic sheeting. Doing this keeps a clean workspace free of debris that could create pinholes in the bag. Tape the edges down and prevent anything besides bagging materials from being placed on the plastic sheet.

Next, the vacuum bag must be created. In general, the vacuum bag should be larger than the part with plenty of excess for removing bridging. To find the proper cut length, add the length of the part and the height of the largest vertical section of the mold, then multiply by 2 for the inner and outer surfaces, and add 1 meter for excess. The width of the part must be considered as well. The tube bagging is used as it can be cut down one seam, creating a 72” wide sheet of vacuum bagging. Check that the width of the bag is large enough by cutting a 20mm wide section along the width of the bag. Use this strap of bagging by butyl taping the ends together to create a loop. Place the loop around the mold and ensure that the bagging can reach every surface of the mold at once.

After unrolling and cutting the bagging to the correct length, layout the bagging flat along the plastic sheeting. Place yellow butyl tape along both ends of the width of the roll, longitudinal of the roll direction leaving the white wax paper on the butyl tape. The tape should begin halfway along the length of the sheet and continue to one end. Next, fold the sheet in half to reduce the length of the sheet. Line up the ends of the sheet so they are square, then begin removing the white wax paper from the butyl tape. Work slowly along the butyl tape, pressing the upper layer of bagging into the butyl tape attached to the lower layer of bagging. Continue this until the bag is sealed along the fold and both sides of butyl tape. At this point, the bag will look similar to Figure 154, however it will not have molds inserted yet. Use this method to create the vacuum bag for each mold.

Figure 154 - Vacuum bag for monocoque

The vacuum bags can now be folded carefully and placed in a clean location. Nylon peel ply can now be cut and placed into the mold. The peel ply can be cut at a length of half the length used for the bagging material. This is because the peel ply is only applied to the inside surface of the mold. The peel ply can then be draped into the mold. Peel ply should be placed in the same method as the carbon fiber laminate. Bridging must be watched and avoided during this step. If bridging occurs, it will not be found until the final step of vacuum bagging and will be extremely difficult to fix. Therefore, all steep angles and corners should be checked for bridging before moving to the next step. As peel ply does not stick as easily as carbon fiber, it may be necessary to hold multiple corners down to ensure that the peel ply does not become too tight under vacuum. Once the peel ply is in place, use high temperature tape to hold the peel ply to the mold. Duct tape can be substituted for high temperature tape if the mold is not experiencing cure temperatures during the vacuum cycle. Tape should only be applied to the outside surface of the mold as it is possible to imprint into the carbon fiber. Additionally, any folds in the peel ply will be visible in the laminate after bagging. These folds create wrinkles; however, this is only aesthetic and does not affect strength.

Following the peel ply, the entire mold must be wrapped in breather cloth. The breather cloth should be cut at the same length as the vacuum bagging. To begin the process, lay breather cloth on the plastic sheet clean workspace. Set the mold on top of the breather cloth, then fold the excess into the mold and spread out evenly onto the inner surface of the mold. Use the breather on the plastic sheeting to fold from the outside up the sides of the mold and draping into the inner portion of the mold. The draping portion of the breather cloth should be overlapping the spread out breather cloth on the inner surface. Tape the draped breather cloth to the inner surface breather cloth using high temperature tape. This tape can again be substituted for duct tape if the mold will not experience high temperature during the vacuum cycle. If any areas of exposed peel ply are visible, cut patches of breather cloth to cover these areas. Tape down any patches to ensure they stay in place during bagging. The breather cloth does not need to be checked for bridging as it is sufficiently stretchy to mold into any crevices. However, ensure that there is enough breather to prevent overstretching as this will reduced the ability of the breather cloth to transport air.

Finally, the mold can be inserted into the vacuum bagging. Have two people hold the prepared mold off to the side of the clean workspace. Another person should retrieve the prepared bagging, laying it out such that the unsealed end is easily reachable. Next, two people should spread the unsealed side of the bag while the two people holding the mold push it into the bag. The mold should be pressed into the bag front end first, so the wider rear end is toward the unsealed edge. When pressing the mold into the bag, take care to avoid pinching anywhere on the bag. Additionally, avoid sliding the mold along the lower surface of the vacuum bagging as this can create tears. Instead, have someone provide lifting support to the mold to reduce the sliding force. If someone is needed over the mold during this process, remove shoes before climbing onto the plastic sheet clean workspace to reduce contaminates on the surface. Press the mold into the bag until it is approximately 0.5m from the end of the bag.

With the mold in the bag, locate the desired position for the vacuum puck. Ideally, this puck will be placed somewhere that is not on the laminate and flat. This location also needs to be somewhere in which the bag will not move much while preventing bridging in the last step of bagging. When the location is determined, fold a 30cm by 60cm rectangle of breather width-wise and place at the puck location. Check over the inner and outer surfaces of the mold to ensure that it is covered by breather cloth and that nothing shifted during placement.

Using tan butyl tape, close off the unsealed end of the vacuum bag in the same method as previous with the yellow butyl tape. However, leave a 20cm strip still covered with the white wax paper near the puck location. The tan butyl tape is less sticky than the yellow and can be removed without ruining the bag, allowing the bag to be used multiple times. Next, place the receiving end of the vacuum puck onto the placed breather cloth through the unsealed section of bagging. Now, have all available hands press the bag into the mold to remove as much excess air as possible. Once the bag has been depressed, the 20cm opening can be sealed.

Final steps of bagging can now begin. First, use a razor blade to pierce a small “X” over the puck’s interior hole in the bag. Use extreme care to avoid piercing outside of this hole area as this will create a leak in the bag. Next, press the upper portion of the puck into this hole while screwing it into the lower portion. The action of spinning and grabbing the threads of the lower portion will cut a circular hole in the bag. Once the threads have engaged significantly, remove the upper portion and the circular cut of plastic from the vacuum path of the puck. The upper and lower portions of the puck can now be screwed together firmly.

Connect the vacuum pump quick disconnect to the puck and turn on the pump. Air will start being removed from the bag and gradually the bag will collapse. If the bag collapse isn’t obvious within 5 minutes of engaging the pump, a large hole must exist in the bag. Check all seams for leaks. Vacuum bag repair is covered more later in this section. As the bag begins to collapse, ensure that all harsh corners have enough bagging to prevent over-tightening the bag. If the bag is tightening too fast to prevent bridging or over tightening, stop the vacuum pump and make the necessary adjustments. This will likely have to occur multiple times as the bag gets closer to pulling full vacuum. Spread the vacuum bag evenly throughout the mold. It is much more advantageous to have excess bag rather than too little.

Once there is a sufficient amount of bagging throughout the part, and the bag is around 15inHg vacuum pressure, check all harsh concave corners for bridging. The bridging is similar to that of the carbon layup process. However, the vacuum bagging cannot be stretched to fit into the corners. Instead, vacuum pressure must be reduced, and more bagging shifted to the corner in need. To verify that a corner has sufficient bagging, press hard into the corner of question. If the corner feels soft or the bag stretches slightly, then there is a bridge. For the first layer of laminate, a properly bagged corner should feel as hard as the mold surface. After checking all bridges inside the mold, check the outer flange and any outer corners of the mold for bridging. Figure 155 shows the difference between a bridged and correctly bagged corner. The left-hand upper part of the mold is bridging, while the right-hand side is not.

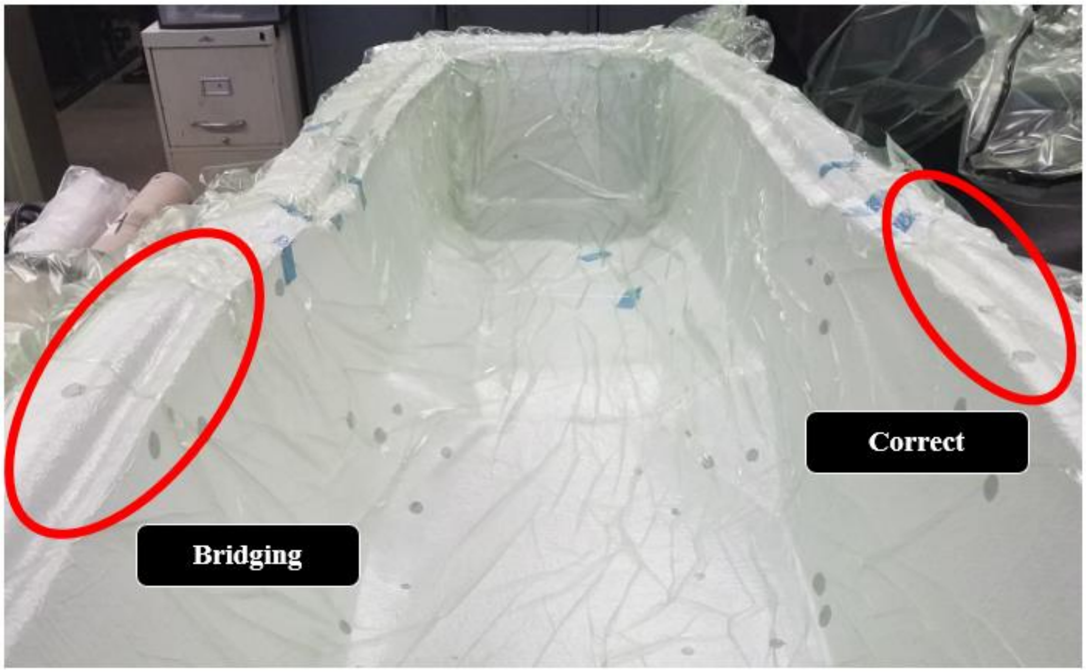


Figure 155 - Correct bagging vs bridged bagging

Once the bagging has been checked for all possible bridging, proper cleating can now occur. For even pressure distribution, the excess bagging must be spread out over the mold. This is accomplished by making “cleats” throughout the mold surface. Figure 156 shows an improperly sized cleat and a correctly sized cleat.

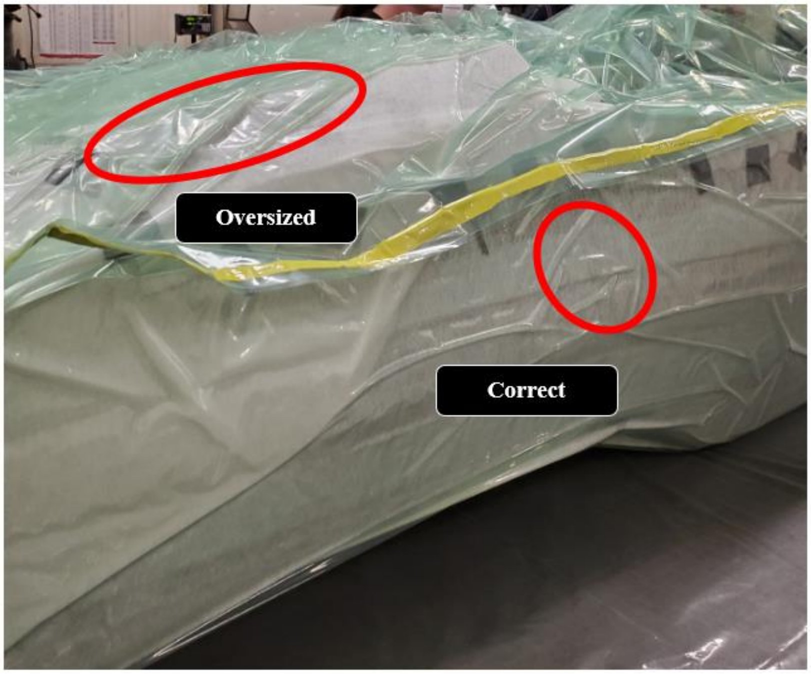


Figure 156 - Correct vs incorrect sized cleats

With the bag at around 15inHg, slide the bag along the mold in areas with excess bag or oversized cleats. Doing this will move the excess bagging throughout the part. Areas of extreme excess will be present, and should be moved to the edges of the flanges as this location has little effect on the final product. Be cautious to not reintroduce bridging to harsh corners in the part. Once this has been completed, the bag can be brought up to maximum possible vacuum pressure.

The minimum allowable vacuum pressure for structural parts on Bronco Racing vehicles is 25inHg, however highest vacuum pressure possible is desired. If the bagging is not reaching at least 25inHg after running the pump for 8 minutes, holes in the bagging must exist. Figure 157 shows the proper order for checking for holes in the bagging.

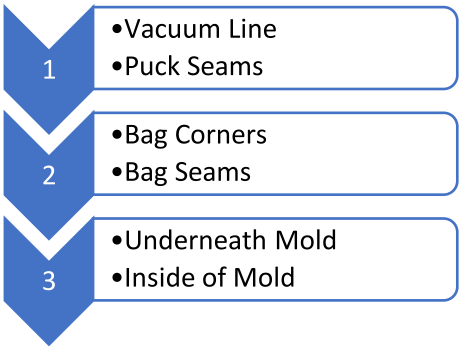


Figure 157 - Checking for holes in bagging procedure

All leak diagnosis should occur in a quiet and clean environment. The primary method of finding leaks is through audibly hearing air entering the bag. This usually sounds like a squealing noise, and can change in pitch and volume depending on the position of excess bagging around the leak. Additionally, air can usually be heard traveling through narrow regions of excess bagging, typically without breather cloth. This sound can be used to follow the path of the air to the actual leak in the bag.

Leaks can also be visible. Visible holes are detectible around the seams in the bag where the butyl tape is used as sealant. Small channels are sometimes missed in the pressing process of the butyl tape. These channels are easily seen through the bag.

If the hole has not yet been found, the use of specialized equipment may be needed. This is common if the hole is in the bottom of the mold. Holes in the bottom of the bag occur from bagging on an unclean surface. The weight of the mold and movement during bagging causes small pinholes to appear in the bag. These holes are easily fixed using a small piece of butyl tape to plug the hole. However, the difficulty is in finding the hole. Equipment similar to a stethoscope may be needed to magnify the sounds of the leak. Ideally, an ultrasonic leak detector will be purchased for hole detection as this product exists for this purpose. Once the bagging has achieved at least 25inHg, the next step can occur. If this pressure is unreachable with the current bagging, a new bag may be needed.

3.6 Vacuum Cycle and Checking the Laminate

As this vacuum cycle is only used to press the initial layer into the mold, it can be relatively short. For the carbon fiber to adequately stretch and embed itself onto the mold, approximately one hour is needed under pressure.

After the vacuum cycle, the pump can be turned off and puck unscrewed from the lower receiving end. Mark in sharpie the hole location for the puck so it is easy to identify later. Next, separate the bagging from the tan butyl tape at the sealed end of the bag. Use even and distributed force when separating the bagging. Localized stress may cause the bag to rip. This bag will be reused to save material and labor, rips in it will cause additional work for repair.

Once unsealed, remove the mold from the bagging. Carefully fold the bagging and set aside in a clean and safe location. Attach the lower portion of the vacuum puck back to the vacuum line for safe keeping. Remove the breather cloth from the mold as well. The breather cloth should not be saturated with resin. If it is saturated, trim and discard the affected area and replace with new breather cloth. Remove all tape from the breather cloth. Any leftover tape may create imprinting issues with the final part. Additionally, if low temperature tape was used, the next bag will be used in an autoclave, causing any leftover tape to melt into the part. Fold the breather and place in a clean and safe location. Finally, remove the peel ply and all tape attached. Fold this and place in a clean and safe location. When removing the peel ply, be cautious to not pull the laminate too hard as it may separate from the mold. Ideally, the laminate will stay attached to the mold for the remainder of the layup process.

Check over the mold for any areas that were not properly bagged. These locations are obvious as the peel ply would not have properly imprinted into the laminate. Figure 158 shows an area that experienced bridging. Note all areas where bridging occurred, so they can be accounted for in the next bag.

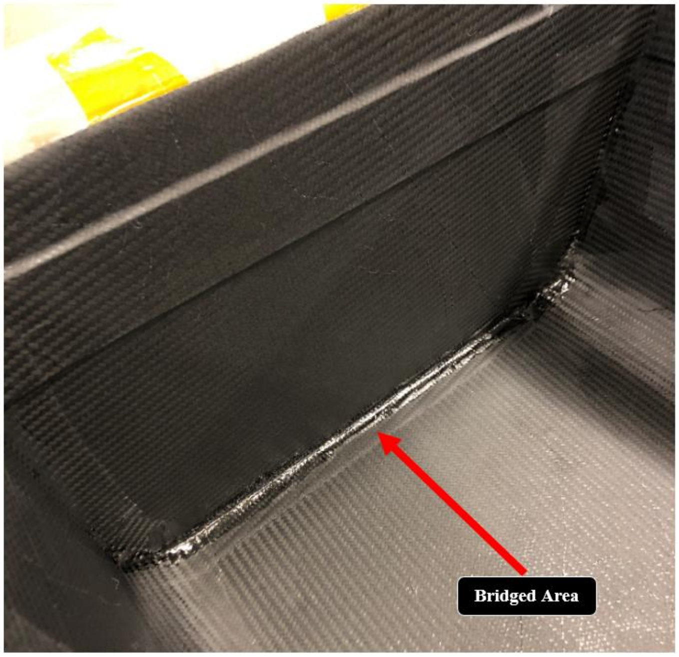


Figure 158 - Wet spot area from bridging

Check over the rest of the laminate for any particulate matter. Dust, dirt, plastic, and oil between layers of laminate will lead to delamination between carbon fiber layers. If this occurs, the entire part must be scrapped or major repair must occur. If any regions of the part had direct contact with breather cloth under vacuum, it is likely that this is now embedded into the resin of the first layer. Remove all traces of the breather cloth as this can also lead to delamination.

3.7 Remaining Layers of Laminate

With the initial layer clean and embedded into the mold, the remaining layers of the initial laminate can be placed. The process to lay in the individual pieces of carbon fiber are identical to that of the first layer covered in Section 3.4, however the quantity of pieces in each region is vastly different. Therefore, the below placement schedule in Table 11 should be followed.

Laminate Region Code	Laminate Region Description	Layup Pattern (Single Side of Core)	Core Type
FBH:	Front Bulkhead	[45W/45W/45W/45W/45U/45U/45U/-45U/-45U/-45U/0U/90U/0U/90U/45W]	Heavy Weight
FBHS:	Front Bulkhead Support	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb
FBHS_Lower:	Front Bulkhead Support Lower	[45W/0U/0U/90U/90U/45W/45W]	Nomex Honeycomb
FBHS_Upper:	Front Bulkhead Support Upper	[45W/0U/90U]	Nomex Honeycomb
FBHS_HORIZ	Front Bulkhead Support Horizontal Under Suspension Mount	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb
FBHS_DAMPER	Front Bulkhead Support Horizontal Over Damper Mount	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb
FBHS_FF	Front Bulkhead Support Suspension Region Front Facing	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb
FBHS_FF_R	Front Bulkhead Support Suspension Region Front Facing	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb
FBHS_RF	Front Bulkhead SupportSuspension Region Rear	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb
FBHS_VERT	Front Bulkhead Support Suspension Region Vertical Face	[45W/45W/45W/45W/0U/0U/0U/0U/90U/90U/90U/90U/45W]	NONE
FBHS_BELLCRANK	Front Bulkhead Support Bellcrank Mount Region	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Standard Balsa
FBHS_VERT_DAMPER_OVERLAP	Front Bulkhead Support Damper Overlap Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W/45W/45W/45W/45W/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Heavy Weight
FBHS_VERT_LOWER_OVERLAP	Front Bulkhead Support Lower Overlap Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W/45W/45W/45W/45W/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Heavy Weight
ENG_COMP_FLANGE	Engine Compartment Flange	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Standard Balsa
ENG_COMP	Engine Compartment Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Nomex Honeycomb
ENG_COMP_SUSP	Engine Compartment Front Upper Control Arm Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Standard Balsa
HSIS:	Horizontal Side Impact Zone	[45W/0U/0U/90U/90U/45W]	Nomex Honeycomb
VSIS:	Veritcal Side Impact Zone	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Aluminum Honeycomb
MH_Mounts	Main Hoop Mounts	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W/45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Aluminum Honeycomb
MHBS	Main Hoop Bracing Support	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Aluminum Honeycomb
MHBS_FLANGE	Main Hoop Bracing Upper Flange	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Aluminum Honeycomb

Table 11 - Placement schedule of each region

The above placement schedule is the overall laminate pattern. Each region should be staggered during the laminate process, where thicker laminates have more layers placed at one time than thinner layers. Doing so allows the stress in each fiber region to smoothly spread to the next region. Hard edges inside of the laminate leads to stress concentrations. Best practice would be to start with the largest pieces in the region, then move to the smallest, creating a gradient of layers with approximately 10mm between edges. However, the minimum overlap of 20mm must be followed.

Workstations for the remaining layup should be created. First, the precut carbon fiber should be organized by layup schedule and region and placed onto an open working area. Next, the molds should be placed onto separate tables at waist height to allow for access to the inner mold from all sides. In the WMU Student Projects Lab, the welding table and table saw table work well for this application. However, make sure these areas are clean of debris before placing the molds as contaminates could be brought into the bag from the mold bottom. Tooling should be laid out in a separate area from the carbon fiber.

Placing each laminate must be done carefully, and each layer verified and marked on the template layout listing. Each team should start when their placement region is next. First, they must verify the layer they are about to place is correct per the laminate schedule. Then they must verify that the laminate direction matches that of what is written on the carbon fiber laminate. Placement of the fiber should follow the instructions given in Section 3.4. Now that an initial layer is already placed, and carbon fiber now skins the mold, following contours should be easier. However, prepreg carbon fiber sticks very easily to other prepreg, so the placement of the laminate must be deliberate and accurate the first time. Separation of prepreg pieces is very difficult and can result in warped or perforated laminate.

During the placement of the carbon fiber by each team, the supervisory role is responsible for verifying layup pattern is followed, placement of carbon fiber is correct with no bridging, and no contaminants are present in the laminate. The supervisory role will also fix issues such as folded carbon fiber, relief cut locations, and workflow problems. Throughout the process, the supervisory role should also verify that the carbon composite regions are remaining centered by checking the X and Z coordinates of the laminate edges, similar to the template creation covered in Section 3.1. This role is crucial to the final product of the monocoque and should be fulfilled by someone with previous composites experience.

At this stage in the manufacturing process, the part will look similar to Figure 159 from BR20.

Figure 159 - B20 molds with first laminate finished

3.8 Proper Bagging Strategy

Once the laminate is finished and all regions are placed and verified, the molds can be bagged once again. This bagging method is very similar to the bagging strategy used in Section 3.5, with a few additions and changes.

Firstly, the bag created in Section 3.5 can be used with small changes. The tan butyl tape seam must be trimmed off and replaced with a yellow butyl tape. This is due to the transportation process being too rough on the less sticky tan butyl tape, usually resulting in leaks. Next, the peel ply and breather cut previously can be reused. However, high temperature tape must be used, and cannot be substituted with duct tape. Application of the peel ply and breather is identical to that of Section 3.5.

Once the molds are inside the bag, but not yet under the vacuum, additional vacuum line fittings should be attached to the mold. These fittings should match those of Pratt and Whitney's autoclave fittings. Figure 160 shows the difference in quick disconnect fittings between those used in the puck connection for Bronco Racing's vacuum pump, and the fittings available at Pratt and Whitney.

Figure 160 - Our quick disconnect fitting vs Pratt & Whitney's

The additional vacuum lines will be placed on the outside of the mold underneath the flange. The fittings used are "flute" fittings. These fittings are simple perforated steel tubes with a quick disconnect at one end, and a crushed but open end on the other. The entire exposed steel tube shaft is wrapped in breather cloth and taped with high temperature tape, leaving 25mm of exposed metal shaft. Figure 161 shows the vacuum flute properly set up.

Figure 161 - Properly set up flute

To place the flutes into the part effectively, carefully separate the yellow butyl tape seam on the left and right of the mold. Slide the flute breather first into the opening, and place the excess breather over the flange, into the inner portion of the mold. Seal the butyl tape around the exposed metal shaft of the flute. Position the quick disconnect end of the flute to be easily accessible, at least 25mm from the mold surface. Place a flute on both the left and right side of the mold, so there are a total of 3 vacuum fittings for each mold. Follow Section 3.5 to achieve at least 25inHg before moving to the next step of manufacturing. Figure 162 shows a properly bagged mold for this stage of manufacturing.

Figure 162 - Properly vacuum bagged mold for this stage

3.9 Transportation of Bagged Molds to Autoclave Sponsor

Pratt and Whitney is Bronco Racing's autoclave sponsor for the monocoque chassis. To schedule a time to use the autoclave, Giuseppe Messina at Pratt and Whitney must be contacted at least two weeks before the desired dates of use. Pratt and Whitney's process for autoclave usage approval takes multiple days, therefore knowing all days the autoclave is needed in advance is beneficial as it can all be approved at once. Once dates of use are approved, a university heavy duty truck must be checked out for each date from Richard Sackett in the Auto Lab at the Parkview Campus. Typically, Fridays are used for Pratt and Whitney days due to the availability of Bronco Racing Members.

The afternoon before traveling to Pratt and Whitney, the truck keys must be picked up from Richard Sackett. Next, a trailer must be attached to the truck and emptied. Any of the available trailers in the Parkview Lot are sufficient for mold transportation. Once empty, the bagged molds must be secured inside the trailer.

To properly secure the molds in the trailer, a soft base is required for strapping the molds down onto. The molds cannot be strapped directly down to the trailer floor as any shock impulse from potholes in the road risk cracking the fiberglass molds. Previously, spare tires were used as the base for the molds. To follow this method, four spare tires are needed. Each tire should be covered in plastic to prevent popping holes in the bagging. The tires can be placed into the trailer, then the molds can be brought out while still under vacuum. The mold should remain under vacuum during the movement to the trailer to prevent shifting of material under the bag. Once the mold reaches the trailer, the vacuum pump can be turned off and disconnected. The puck quick disconnect fitting should be blocked with butyl tape to slow the loss of vacuum pressure. Then the front of each mold is placed into one tire, with the rear settling into another rearward tire. To hold the molds down, ratchet straps must be used. However, ratcheting directly to the bag will create holes. The strap locations must be determined based off of how smooth the bagging is around the contact area of the flange. Folded bagging that is then compressed creates pinholes at the seams and corners of the fold. After finding smooth areas to pass the ratchet strap, tape doubled over breather cloth to these locations to act as cushions. Carefully tighten the ratchets, ensuring the molds are not bowing under the force of the straps. The straps must be tight enough to prevent movement, as even a small amount of movement can lead to rubbing through of the vacuum bagging.

With the molds secured, the tooling needed for Pratt and Whitney can be collected and placed in the trailer. Table space in Pratt and Whitney is limited, therefore a clean quilt or thick blanket should be brought to lay out on the floor to set the molds onto inside of the building. An adjustable wrench is needed to swap out the puck quick disconnect fitting to the size used at Pratt and Whitney.

After the tools have been collected, all equipment has been gathered for Pratt and Whitney. As for personnel, 4 people are needed to attend Pratt and Whitney. One person will continue the supervisor role to ensure that the molds are taken care of and solve any prevalent issues throughout the day. This person should again have previous composites experience. The remaining three people are support members and will assist in carrying the molds, finding holes in the bagging, and interacting with members of Pratt and Whitney. All members attending Pratt and Whitney must bring a valid U.S. passport or original copy of their birth certificate with a raised seal. This documentation is needed as Pratt and Whitney is a military contractor and has stringent security requirements. Pratt and Whitney keeps a log of all people who have attended their compound over the last year. If documentation has already been provided earlier in the year, documentation is not required, however this has been found to be unreliable, and it is advised to always bring documentation. Separate from the documentation, any other materials supporting personnel want to bring to fill time during the cure cycle is encouraged as there will be approximately four hours of waiting after putting the molds in the autoclave.

With personnel and equipment loaded into the truck and trailer, the molds can be carefully driven to Pratt and Whitney's Lansing, MI location. Typically, the truck and trailer leaves the Parkview campus at 5:00am to arrive at Pratt and Whitney at 6:30am when the engineers arrive. This allows the entire day to problem solve if issues arise with the molds. Once at Pratt and Whitney, check-in through security is required where Giuseppe or another supporting engineer will arrive to take Bronco Racing members to the autoclave to be used.

Once at the plant where the autoclave is housed, the truck and trailer can be brought to the nearest bay door and unloaded. Take care to unload the molds onto the soft quilt or blanket near the autoclave.

3.10 Autoclave Preparation and Cure Cycle

Once unloaded, the pucks on each mold should have the quick disconnect fittings swapped with larger fittings to match Pratt and Whitney’s. Two vacuum gauges should then be collected from Pratt and Whitney’s clean room after talking with plant personnel. The vacuum gauges should be connected to each puck, and vacuum lines from outside of the autoclave connected to one of the flute fittings in each mold. Each mold should then be inspected again for leaks. The vacuum pressure at Pratt and Whitney is lower than that of the pumps used previously. A reading of 24inHg is sufficient for a single vacuum line at Pratt and Whitney.

If a hole is suspected but not easily found, take the mold into the clean room. The clean room is much quieter, and vacuum leak equipment is available to use. Find any remaining holes to achieve over 25inHg (if using multiple vacuum lines). If holes are not able to be found, Pratt and Whitney has bagging, breather, and peel ply on hand for a new bag. Ideally this will not be used as Bronco Racing should remain as minimally invasive as possible to protect for future sponsorships.

With the molds properly bagged and ready for the autoclave, retrieve four long strips of breather cloth from Pratt and Whitney’s supplies. Layout these pieces of breather on the metal rails inside the autoclave as a cushion for the molds to be set on. Carefully lift the molds into the autoclave and across the rails on the breather cloth cushions. Thermocouples are hanging on either side of the autoclave. Using the high temperature tape, tape the thermocouple to a region of bagging over the carbon fiber laminate. On the other mold, tape the thermocouple to a region of bagging over thick fiberglass on the mold. The reason for the two different locations is to compare the temperatures of the mold vs laminate during the cool down period of the cure cycle. A high discrepancy in these temperatures indicate that the mold is not ready for removal as warping would occur.

To enable the vacuum lines inside the autoclave, notify the supporting engineer that you are ready for an autoclave operator. Getting an autoclave operator available may take over an hour if they are busy on another assignment. Once the autoclave operator is available, they will enable all of the vacuum lines, connect each fitting with autoclave rated vacuum lines, and verify the vacuum line and thermocouple functionality. With these items verified, all nonessential items will be removed from the autoclave, and the door shut and locked.

From this step, the autoclave operator will program the cure cycle into the autoclave. Pratt and Whitney's autoclave can control ramp up temperature, but not cool down speed. For BR21 chassis, the cure cycle is 2C/min ramp up temperature to 120C. Once at 120C, the temperature will be held for 90 minutes, then cooled as slow as possible. This is accomplished by turning off the autoclave and letting it sit while monitoring the temperature. Do not open the door to the autoclave until the carbon fiber temperature and mold temperatures are below 40C. If the door is prematurely opened, the carbon fiber laminate will warp and the monocoque will be too damaged to repair.

During the cure cycle, vacuum pressure must remain on, however no added pressure will be used. Added pressure makes the laminate thinner and squeezes out more resin. This typically makes laminate stronger, however WMU does not have an autoclave available to use during the creation of test panels, so actual effects are unknown.

Once the cure cycle is complete and parts allowed to cure sufficiently, the autoclave operator can open the autoclave door. Depending on the outdoor temperature, the molds could be transported directly to the trailer. However, if it is extremely cold out, it is advisable to allow the parts to get closer to room temperature before moving out into freezing conditions in the trailer. The molds can be secured in a similar fashion as previously, but care for piercing holes in the bagging is no longer needed as the bagging will not be used again.

Once back at Parkview campus, the molds can be cut free from the bagging. Then, using the peel ply, can be separated from the carbon fiber laminate. Proper PPE is required for this as freshly cured carbon fiber is extremely sharp. The process of pulling off peel ply can send particles into the air, skin, and eyes. Recollect all pucks, flutes, and fittings to store for later bagging. Similar to Section 3.6, check over the laminate and note any locations of bridging, and clean any areas of contaminated laminate. At this point, the cured laminate should look similar to Figure 163.

Figure 163 - First side of BR20 laminate cured

4 Phase Two of Monocoque Laminate Layup

4.1 Preparing the Hardened Laminate for Film Adhesive

With the cured laminate cleaned, the next stage of monocoque layup can occur. For the film adhesive to properly bond to the cured resin, the resin must be rough. Using 220 grit sandpaper, sand the entire carbon fiber laminate throughout both molds. These should be sanded until a dull finish is acquired. Care must be taken to not sand through the resin as the fibers underneath the laminate will be fray and compromise the strength of the part. Additionally, use the sandpaper to remove any sharp burrs or ridges in the laminate. After sanding the laminate, clean the composite with an acetone-dipped cloth. Ensure all dust is removed from the part as this will greatly affect the ability of the film adhesive to bond to the resin.

4.2 Cutting and Dry-Fit of Balsa Core

Balsa core is used in areas that require high compressive stress or shear stress. These areas are typically suspension hardpoints, pedal box mounting location, or steering rack mounting location. The balsa core needs to be positioned using the X and Z axis measurement method used in Section 3.1 for each corner of the balsa wood core. Once the position and orientation are found, the balsa can be cut to shape and dry-fit into the mold. To cut the balsa wood, a vertical band saw is needed. The balsa used is end-grain balsa and is very sensitive to ripping. Therefore, slow cutting on a vertical band saw is required. To accurately cut the balsa wood, print a 1:1 scale of the balsa inserts. Cut out this paper template and trace onto the balsa wood. When placing onto the balsa wood stock, avoid ridges and gaps in the balsa. End grain balsa is glued together to make sheets. This glue fails easier than the wood, and gaps can be found if inspected.

With the balsa wood cut, clean each piece with acetone to remove dust, then attach double sided tape to the wood. Place the core in the measured position and firmly press to ensure that it holds in place during the entire dry-fit process.

4.3 Cutting and Dry-Fit of Nomex Core

With the balsa core in place, the Nomex core can now be placed around the balsa. For the highest strength core at the lightest weight, minimize the number of pieces of core used. Each seam between pieces of core requires two layers of film adhesive, adding weight and reducing reliability. Plan out all cuts and individual piece sizes before cutting any Nomex.

To begin cutting core, first extend thin plastic sheeting to approximately the first size of the piece needed for placement. When determining which piece to start with, it is easiest to build from the bottom up to allow for the Nomex to rest on itself during the process. Trim the plastic off of the roll, and place over the area that the Nomex piece will be placed. Then mark with a sharpie the outline of the piece needed to fit snugly in place. Mark any edges that require fillets. Now trim the plastic sheeting to match the size of the piece marked.

Transfer the plastic sheeting over to the sheet of Nomex core received from Plascore. Take care to orient the plastic correctly on the Nomex sheet to account for the 0 degree direction of the sheet. Figure 164 demonstrates the 0 degree direction on Nomex core.

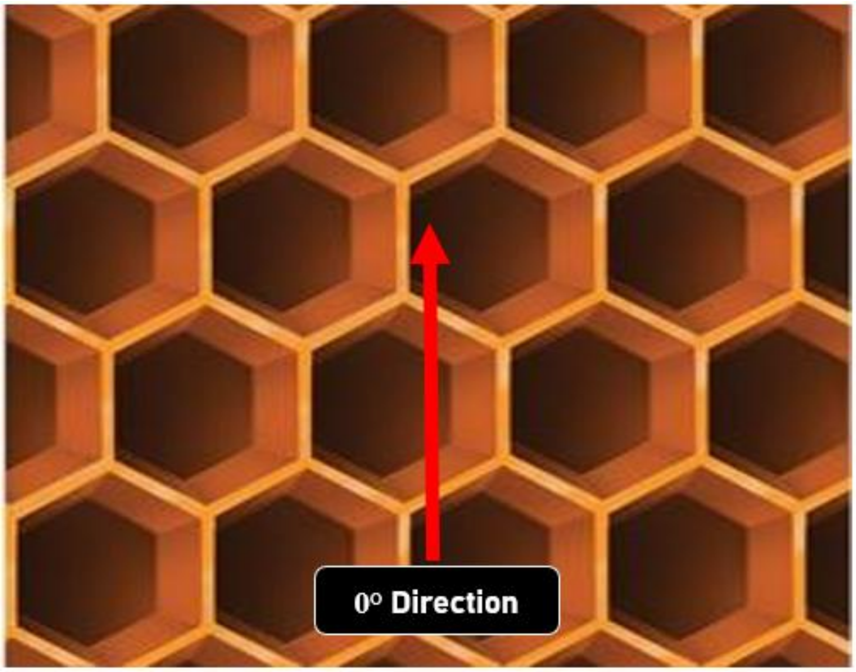


Figure 164 - 0° direction of honeycomb core

When the plastic sheeting is correctly oriented and placed to reduce waste, it can then be taped to the sheet of Nomex to hold it securely. Using an extendable knife with a blade of at least 1.25”, cut directly into the Nomex following the marked cut path. This may require multiple knife scores to get through the 1” thick honeycomb. To ease the cutting process, it can be advantageous to place the region to be kept on a higher plane than the remaining Nomex. This causes the Nomex to fall away from the cut edge, separating the honeycomb and making it easier to cut.

For BR21, all fillets are 3/8” inch radius. This standardization allows for a router to be used to trim all core pieces that butt up to the fillets. Additionally, BR21 was designed such that the core could be directly butt up against itself on the right angles of the mold.

Areas around the balsa should be a snug fit. If the fit is too tight, the film adhesive will not fit in place and more trimming will be required. To remove small quantities of Nomex, a disc sander can be used to remove individual cells of Nomex. The disc sander can also be used for sloping the Nomex to remove ridges between different pieces. Once all of the Nomex core is in place, it should look similar to front end of BR20 in the example shown in Figure 165.

Figure 165 - BR20 Nomex and balsa core placement

4.4 Cutting and Dry-Fit of Aluminum Core

With balsa and Nomex core placed, the final type of core can be placed. The aluminum core is cut and placed in a similar manner as Nomex core. However, aluminum core is much more susceptible to side crushing than Nomex core. Due to this, care must be taken when placing the core as to not crush too many cells. Crushing cells makes it easier to place into tight fit areas, but increases density and reduces local compressive loading ability. Additionally, a disc sander cannot be used to remove cells, as this will just create crushing. To remove individual cells, a knife must be carefully used. At this stage in the process, all core should be dry fit into both molds, looking similar to the example shown in Figure 166 for BR20.

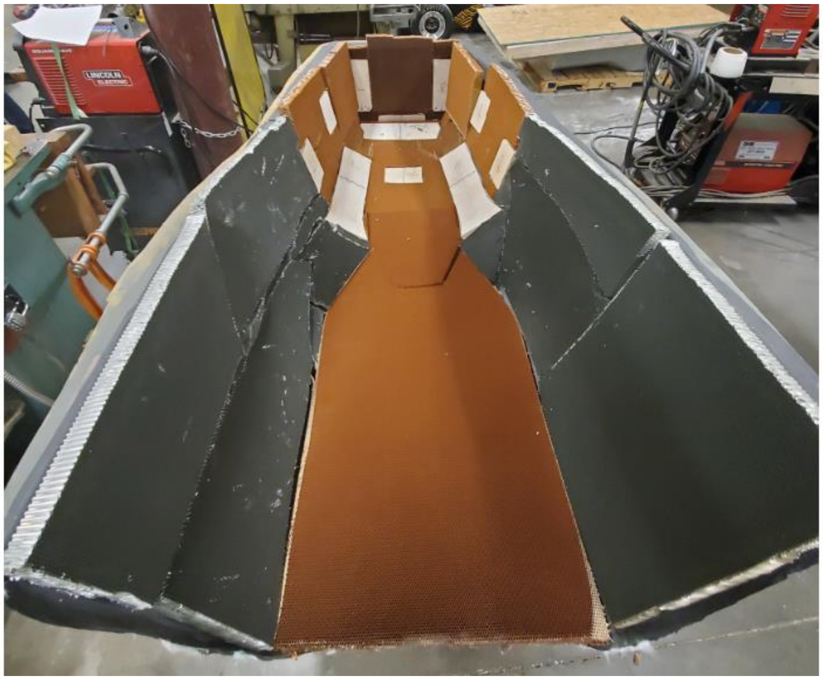


Figure 166 - BR20 dry fit of core materials

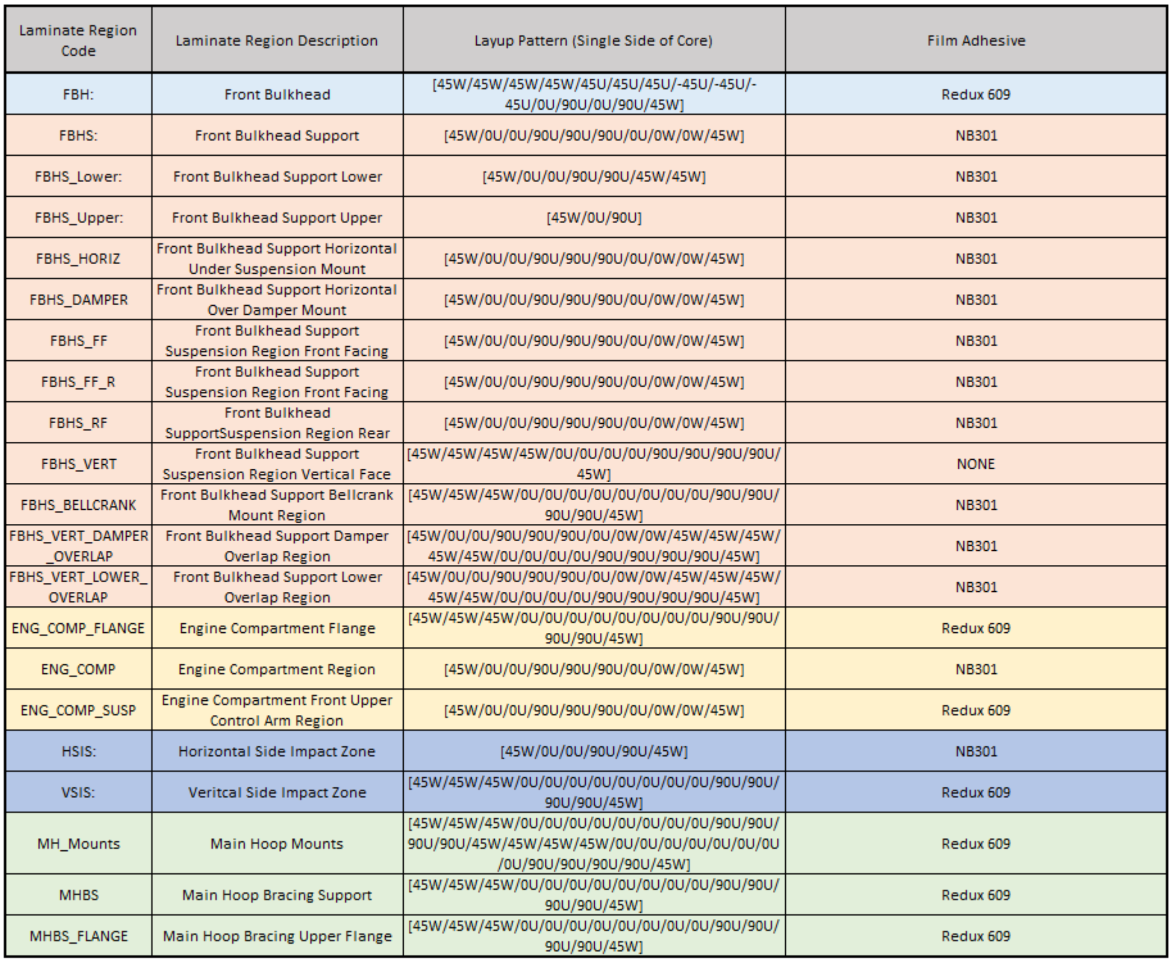
4.5 First Layer of Film Adhesive

With all of the core dry-fit into place, the film adhesive is now ready to be determined. The process of the placing the core likely caused dust to be generated onto the prepared laminate. Using masking tape, place a small piece onto each individual piece of core. Then number each piece around the inside of each mold. Take detailed pictures of the mold to capture the orientation and placement of each piece. Carefully remove all placed core and layout onto a clean area. Using compressed air, spray out each mold then wipe down with an acetone dipped rag.

The film adhesive can now be placed into the mold. The film adhesive used is dependent on the region of layup. Areas that use aluminum core require thicker film adhesive with an imprinted woven grid. Areas of Nomex core only require thinner homogenous film adhesive. For

BR21, Redux 609 is used for the regions of aluminum and balsa core, and NB301 is used for areas of Nomex core.

To properly place the NB301 film adhesive, the templates created for the carbon fiber cutting can be used. Use these templates to cut out the correct film adhesive per Table 12 for BR21.



Laminate Region Code	Laminate Region Description	Layup Pattern (Single Side of Core)	Film Adhesive
FBH:	Front Bulkhead	[45W/45W/45W/45W/45U/45U/45U/-45U/-45U/-45U/0U/90U/0U/90U/45W]	Redux 609
FBHS:	Front Bulkhead Support	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	NB301
FBHS_Lower:	Front Bulkhead Support Lower	[45W/0U/0U/90U/90U/45W/45W]	NB301
FBHS_Upper:	Front Bulkhead Support Upper	[45W/0U/90U]	NB301
FBHS_HORIZ	Front Bulkhead Support Horizontal Under Suspension Mount	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	NB301
FBHS_DAMPER	Front Bulkhead Support Horizontal Over Damper Mount	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	NB301
FBHS_FF	Front Bulkhead Support Suspension Region Front Facing	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	NB301
FBHS_FF_R	Front Bulkhead Support Suspension Region Front Facing	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	NB301
FBHS_RF	Front Bulkhead SupportSuspension Region Rear	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	NB301
FBHS_VERT	Front Bulkhead Support Suspension Region Vertical Face	[45W/45W/45W/45W/0U/0U/0U/0U/90U/90U/90U/90U/45W]	NONE
FBHS_BELLCRANK	Front Bulkhead Support Bellcrank Mount Region	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	NB301
FBHS_VERT_DAMPER_OVERLAP	Front Bulkhead Support Damper Overlap Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W/45W/45W/45W/45W/0U/0U/0U/0U/90U/90U/90U/90U/45W]	NB301
FBHS_VERT_LOWER_OVERLAP	Front Bulkhead Support Lower Overlap Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W/45W/45W/45W/45W/0U/0U/0U/0U/90U/90U/90U/90U/45W]	NB301
ENG_COMP_FLANGE	Engine Compartment Flange	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Redux 609
ENG_COMP	Engine Compartment Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	NB301
ENG_COMP_SUSP	Engine Compartment Front Upper Control Arm Region	[45W/0U/0U/90U/90U/90U/0U/0W/0W/45W]	Redux 609
HSIS:	Horizontal Side Impact Zone	[45W/0U/0U/90U/90U/45W]	NB301
VSIS:	Veritcal Side Impact Zone	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Redux 609
MH_Mounts	Main Hoop Mounts	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W/45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Redux 609
MHBS	Main Hoop Bracing Support	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Redux 609
MHBS_FLANGE	Main Hoop Bracing Upper Flange	[45W/45W/45W/0U/0U/0U/0U/0U/0U/0U/0U/90U/90U/90U/90U/45W]	Redux 609

Table 12 - BR21 film adhesive by region

Once cut, the NB301 film adhesive can be placed in the same manner used in Section 3.5. Take care to remove both sides of the backing material on both film adhesives. The backing material is difficult to remove and easily forgotten. To easily remove the backing material, dental grade picks can be used to separate the backing material from the adhesive. When placing the film adhesive, it should not extend past the top of the mold. Film adhesive that passes onto the flange is a waste and can result in unwanted bonding with layup materials.

For Redux 609, the film adhesive will be used by first wrapping the cut core, then placed into the mold. For film adhesive with an imprinted grid, the exposed grid must face towards the core, not the laminate. This allows the grid to embed itself into the pores of the core, yielding a stronger bond.

To ensure total coverage of the film adhesive, first remove the masking tape note with core number. Then take a 1.5” wide strip of film adhesive and wrap around the entire edge of the core piece. Cover both faces of the core with film adhesive to result in a completely covered core piece. Once covered, reattach the masking tape number note, and set aside for placement. Wrap all pieces of aluminum and balsa core using this method. Figure 167 shows a properly wrapped piece of aluminum core.

Figure 167 - Properly wrapped aluminum core

4.6 Final Placement of Core

Using the detailed pictures taken previously, replace all of the core back into the mold. First place the balsa core using the marked areas from previously. If these regions were covered with NB301 film adhesive, carefully remove the film adhesive from this area using a razor blade. Next, place the balsa wood core into the correct location by firmly pressing into place. The balsa wood should hold itself in place at this point. If it does not, heating the film adhesive slightly with a heat gun will cause the adhesive to transition to gel. Once pressed hard into place, the adhesive will cool into a hardened layer that will hold the core into place. After all the balsa is placed, use the same method of the aluminum core. For aluminum core, be cautious of the use of force around the edges to prevent collapsing the honeycomb cells. At this stage, the mold should look similar to Figure 168 of BR20.

Figure 168 - BR20 with all aluminum and balsa core materials bonded in place

Finally, the Nomex core can have film adhesive skinned around the edge similar to that of the aluminum and balsa core, however with NB301 used instead. The Nomex core can now be placed into the mold around the already placed core, starting from the bottom up again. If any regions are suspected to not have enough thickness of film adhesive to meet the core, double or triple the film adhesive in these local regions. This is likely to occur in areas of sharp fillets.

Check over the entire mold for gaps in the core or film adhesive. If a gap is too large to span with just film adhesive, trim a small sliver of Nomex or aluminum core, then skin in film adhesive and place in the desired location. Also check for ridges between pieces of core. If the core does not have smooth transitions between pieces, these ridges will be visible in the final part and can act as stress concentrations due to the bridged laminate. Figure 169 shows an example of a core ridge noticed in the final laminate of the BR20 chassis.

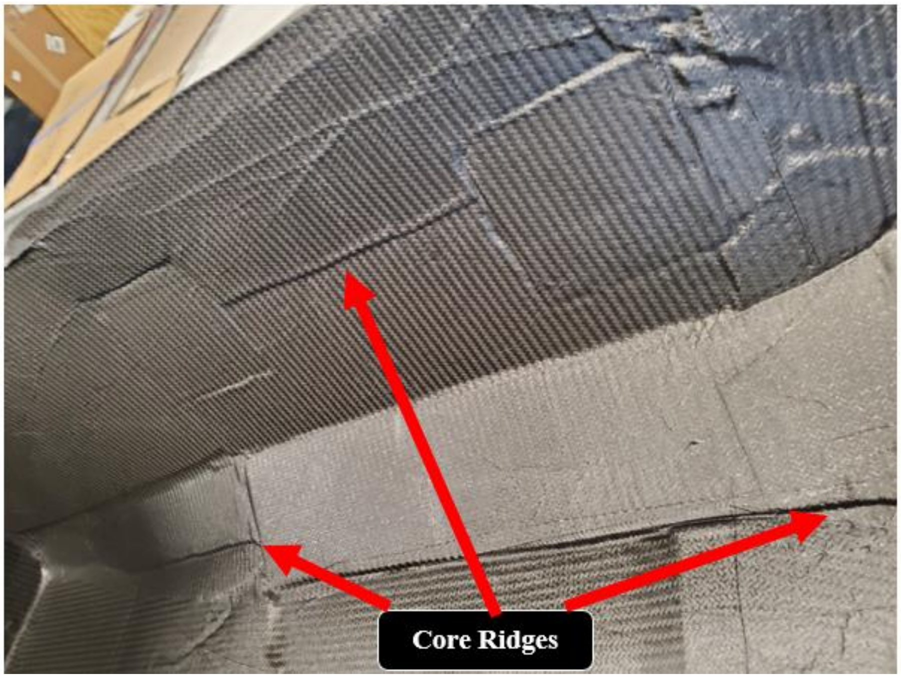


Figure 169 - Core ridges in final laminate of BR20

After the core has been checked over, the final layer of NB301 can be placed across the Nomex core upper face. Once this has been done, the laminate is ready for vacuum bagging.

4.7 Proper Bagging Strategy

The bagging strategy used in section 3.5 can be followed closely with only a few minor changes. Firstly, a perfectly unbridged bag will be very unlikely due to the rigid and jagged nature of the core. Secondly, extreme care must be taken to avoid crushing the aluminum core. Since this vacuum cycle will not see increased temperatures, it is unlikely the core will crush as it is supported by the film adhesive around the edges. However, to protect against inadvertent crushing, limit vacuum pressure to 20inHg. This can be accomplished by inserting a small syringe through the butyl sealant tape to create a regulated leak in the bag.

After the bagged molds have been allowed to sit for at least two hours, they can be carefully removed from the vacuum bagging following Section 3.6 closely. Save this bagging and material for the next cure cycle. Once removed from the bag, the compressed film adhesive and core will look duller, and be much more rigidly pressed in place. A before and after of the vacuum process can be seen in Figure 170, demonstrating this step on the front bulkhead front impact test piece.

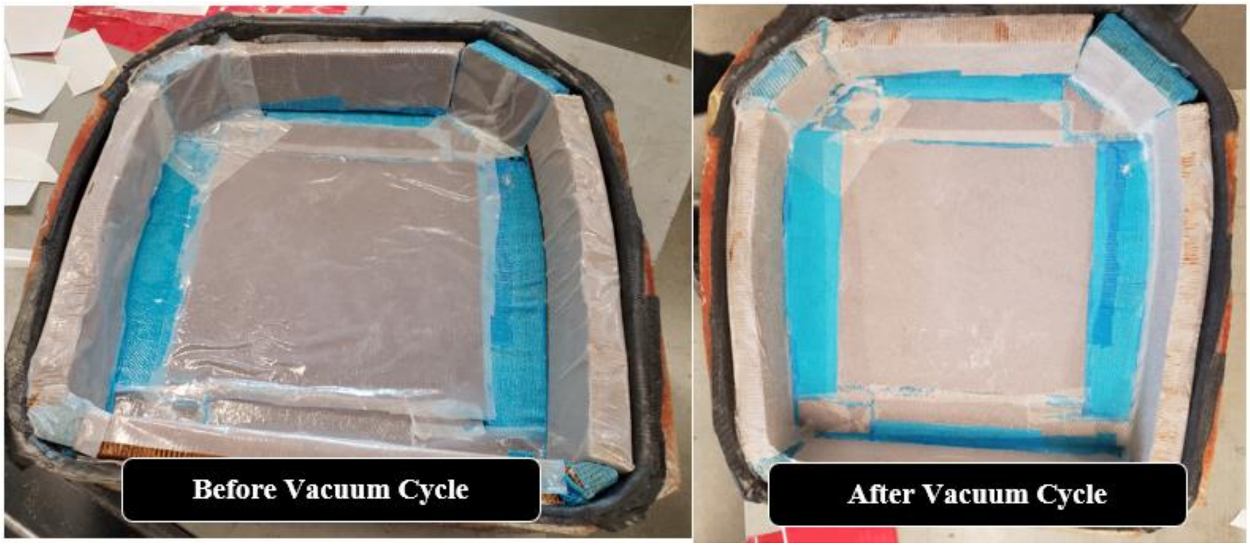


Figure 170 - Core before and after vacuum bagging

4.8 Core Repair

Once removed from the bagging, more gaps in the core may have appeared. This is intentional as the core is now no longer bridging over different areas of the mold due to the compression from the vacuum bagging. Repair any gaps in the core similar to the method defined in Section 4.6. After proper repair and confirmation of full coverage of film adhesive, the next step of manufacturing can be taken.

4.9 First Layer of Inside Laminate

The first layer of inner laminate can now be placed following the method defined in Section 3.1-3.4. Note that this layup will seem easier as the harsh corners of the mold have been naturally smoothed out during the layup process.

Be cautious again of bridging in all corners. This should be a much smaller issue now, however, care still needs to be taken to avoid the issue. Ridges should also be checked to ensure that the carbon is not peaking overtop of a core ridge. If this occurs, remove the laminate and level the core.

Now that the core is placed in the mold, the overall inner laminate surface is significantly smaller. This will create large amounts of excess with the current carbon fiber templates. Before marking and cutting carbon fiber, the template sizes should be reduced to keep a consistent 20mm overlap of carbon and enough to wrap over the upper flange. Without this step, the monocoque will be unnecessarily overweight. Once the first layer is placed, the monocoque manufacturing can proceed to the next step.

4.10 Bagging Strategy

With the first layer of the inner laminate placed, the molds can be vacuum bagged once again. Use the bagging created in Section 4.7, and method defined in Section 3.5, the molds can be successfully bagged. Note that bridging checks will now occur over core material. Therefore, the hardness of the mold surface will not be felt when checking bridges, but instead the core hardness. This is a minor but notable difference.

Once a successful bag is achieved, the vacuum cycle defined in Section 3.6 can be used to properly seat this layer of laminate into the core. Once the vacuum cycle is complete, carefully remove the molds as the bagging will be used again for the next step of the manufacturing process. Note any remaining bridged locations for consideration in the final autoclave bagging preparation.

4.11 Remaining Layers of Inner Laminate

The remaining layers of laminate can now be placed following the methods defined in Section 3.4 and 3.7 using the smaller templates created in Section 4.9. The harsh corners of the laminate should now be much smoother, and risk of bridging greatly reduced.

Extra care should also be taken in the placement of the last layer of laminate in the layup schedule. This final layer is visible on the inside of the monocoque and will not be covered by vinyl wrap at the end of the manufacturing process. Once all layers are placed, the mold should look similar to BR20 shown in Figure 171.

Figure 171 - BR20 lower mold with all laminate placed

4.12 Core Dams

Due to the low side loading abilities of the aluminum core, an upper dam is needed along the flange. Under vacuum it may appear that the core is sufficiently strong to support the pressure from vacuum. However, at higher temperatures the prepreg resin will begin to flow, and the laminate will lose stiffness. This loss of stiffness will allow the vacuum bag to begin crushing the core. If this were to happen, the final laminate removed from the oven would look like Figure 172, the upper mold of the BR20 chassis.

Figure 172 - BR20 deformed upper core

Aluminum dams have been designed and created to solve this issue. These dams will follow the outer flange of each mold, bolting through the flange to support it from deforming due to bridging from the vacuum load. Each dam should be waterjet by the Bronco Racing sponsor Kalamazoo Waterjet, then filed around the edges to ensure it will not pop the vacuum bag. Once the dams are bolted to the mold, each mold should look similar to Figure 173.

Figure 173 – BR20 Dams attached to molds

4.13 Bagging Strategy

At this stage, all laminate is placed into the mold with the dams attached. The vacuum bag removed from the molds in Section 4.10 can now be replaced following the methods defined in Section 3.5, with minor changes needed due to the addition of core and dams. Special care must be taken to ensure no bridging occurs along the underside of the dams. The dams are designed to minimize overhang and areas of bridging, but bridging is still possible in the seams near where the dam contacts the flange. This is the last bagging sequence to occur for a high temperature cure cycle. As such, extra caution should be taken to ensure the monocoque is bagged to sufficient quality. Any large cleats of bagging, or folded peel ply will be visibly imprinted into the inner surface of the monocoque. Care should be taken to minimize the quantity of imperfections.

4.14 Transportation of Bagged Molds to Autoclave Sponsor

The bagged molds can be transported to Pratt and Whitney in Lansing using the same method outlined in Section 3.9.

4.15 Autoclave Preparation and Cure Cycle

The autoclave setup and cure cycle can be conducted identically to Section 3.10. Note that this is the final autoclave cure of the laminate unless repair is needed.

4.16 Repairing Monocoque Laminate

After removing the cured molds from the autoclave and detaching the dams, the laminate should appear similar to the stage of the BR19 vehicle shown in Figure 174 below.

Figure 174 - Successful cure of B19 lower mold

If the dams were incorrectly or not at all used, then it is possible for core damage to have occurred. If this happens, the laminate will look similar to the first phase two cure of the BR20 vehicle chassis shown in Figure 175.

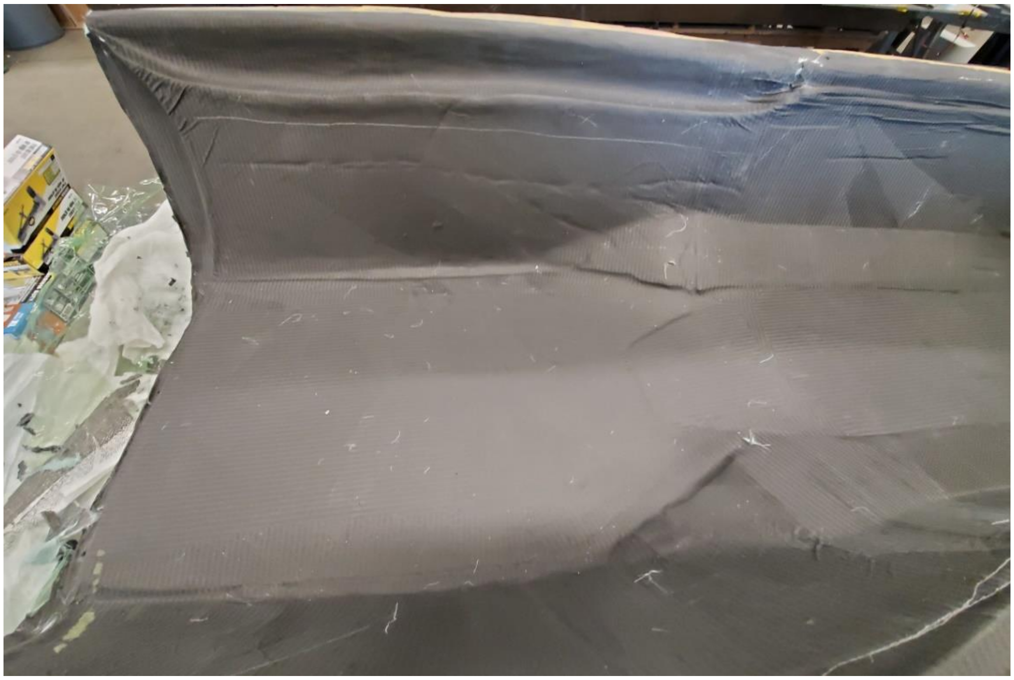


Figure 175 - Failed final cure of BR20 lower mold

This type of laminate damage is repairable, but caution and care must be expressed while doing so. To repair laminate with side crushed core, the following steps must occur:

Cut and Remove Affected Laminate → Remove Crushed Core → Remove Remaining Laminate Lip → Cut New Core → Cut New Carbon Fiber → Place New Laminate → Cure Repair

During the repair process, cutting, grinding, and sanding of the cured carbon fiber must be performed. When this occurs, wear respirators, gloves, Tyvek suits, and work in a well-ventilated area.

4.16.1 Cut and Remove Affected Laminate

To begin with laminate repair, the total affected areas must first be identified. To do this, take a small metal object, like a coin, and tap around the suspected areas of crush. The crushed core will make a deeper and more solid sound than the normal core. Once the regions have been identified, take heavy duty tape and mark out the perimeter of the area needing to be removed.

Next, use a small rotary tool with a cut-off wheel to trim around this perimeter. It is crucial that the disk does not reach the first layer of laminate, as this can risk compromising the monocoque and mold. Be sure to trim along the upper edge of the carbon fiber where it lays over the core as well. Along this edge, trim as close to the first layer of laminate as possible to save time later sanding away the resulting lip.

To remove the trimmed piece of laminate, use a small pry bar to pull the laminate away from the core. Work around the perimeter to carefully remove the trimmed piece. Be sure to avoid pressing the prybar into the unaffected core, as this can damage it and result in more repairs being needed. After the core is removed, it should appear similar to the stage of BR20 shown in Figure 176 below.

Figure 176 - BR20 with affected laminate removed

4.16.2 Remove Affected Core

Next, the damaged core must be removed. To easily and safely remove the core, use rotary air tools with flat bottom grinding bits. The bits must be flat bottom, otherwise the initial laminate will be damaged. Shown in Figure 177 are the bits used to repair the laminate on BR20.

Figure 177 - Grinding bits to remove core

Using the air rotary tool, cut through the core at a slight angle until the initial laminate is reached. Once reached, keep the bottom of the grinding bit parallel to the mold surface and slowly sweep through the damaged areas. Some areas of damaged cores may be much denser than others. If an extremely dense region is being grinded, take care to avoid heating the area by friction from grinding too much, as this can affect the initial laminate. Once all the impacted core is removed, it will look similar to the stage of BR20 shown in Figure 178 below.

Figure 178 - Removed core of BR20 lower mold repair

4.16.3 Remove Remaining Laminate Lip

After the core has been removed, the remaining shell of laminate will still be above the initial laminate. To remove this lip and smooth the initial laminate for the next step, a 150 grit or less sanding disc on a rotary air tool is preferred. The sanding disc should be approximately 50mm in diameter to allow it to be easily controlled. Using the disc, remove the lip of laminate until it is flush or near flush with the initial laminate. Be cautious to not sand the initial laminate as this will compromise the strength of the chassis. With the lip sanded off, use care to knock off any loose debris on the initial laminate surface. At this stage, the repaired monocoque should look similar to Figure 179.

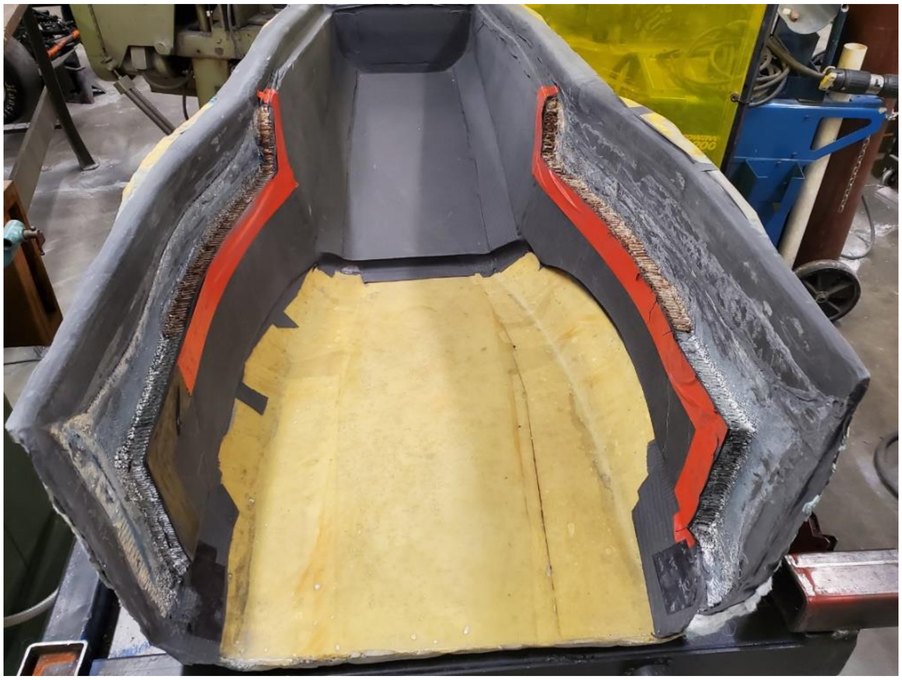


Figure 179 - BR20 with lip smoothed

4.16.4 Cut New Core

Use the same method described in Sections 4.2, 4.3, or 4.4 to cut the correct type of core to fit in the repair area. Once this step is complete, remove the tape around the perimeter of the repair area, and clean all surfaces with acetone.

4.16.5 Cut New Carbon Fiber

Using the template used in Section 4.16.4 for the core perimeter, use this template as the basis for the carbon fiber cut templates. These carbon fiber repair pieces can be made in the same fashion as Section 3.2, except for one change. Use the template from Section 4.16.4 for the first layer of laminate, then every layer after that must increase by 5mm from the perimeter. This will create gradually larger pieces to help distribute stress along the repair seam.

4.16.6 Place New Laminate

With all loose debris removed and the carbon fiber lip smoothed out, the laminate can be replaced. The laminate should be laid up using the same method used in Section 4.5, 4.6, 4.9, and 4.11 with some changes. There is no need to bag between the first and remaining layers as this is a smaller concentrated region. Additionally, the first layer of film adhesive should run halfway up the side of the perimeter around the core. This is to allow the two pieces of core to stick, without risking the film adhesive impeding the repair laminate.

The inside layer of laminate should be staggered to avoid creating a large lip or stress concentration at the seam of the repair. To properly stagger the layers, begin the inside laminate by placing it over the placed film adhesive, then over the trimmed perimeter of the repair area by 5mm. Place the next layer of the laminate 5mm from the perimeter of the last placed layer. Continue the 5mm perimeter offset until all layers of the laminate have been placed. The result will look similar to Figure 180 of the repaired BR20 chassis shown below.

Figure 180 - BR20 uncured repair

4.16.7 Cure the Repair

Once all layers of the laminate have been placed, the repair is ready to be cured. The bagging process is identical to that of Section 3.8, while the transport and cure cycle process is identical to Sections 3.9 and 3.10 respectively. After cure, the repaired region should be nearly indistinguishable from the surrounding laminate. Figure 181 shows the cured final repair of the BR20 chassis before the lap joint stage.

Figure 181 - BR20 cured repair

4.17 Demolding the Monocoque

At this stage, the monocoque has been cured and is now a solid unit still attached to the mold. To release the monocoque from the mold, the outer flange must be trimmed. As the mold will be used for many years, avoid cutting off excess amounts of the flange. The key is to only trim the areas that the carbon fiber is wrapped around the lip. The easiest method to cut the laminate from the flange is by using an angle grinder with a cut off wheel attachment. For safety, wear a respirator, Tyvek suit, gloves, and a respirator during this process.

While cutting the flange, stress relief from the thermal contraction will likely occur through the monocoque. This will become apparent by creaking or snapping. Use caution with the angle grinder as the retraction of the laminate may inadvertently move the blade of the grinder. After trimming all wrapped areas, the monocoque should be able to be removed from the mold.

If the monocoque is still stuck to the mold, use a long piece of plastic to slide between the composite and mold surface. Do this around the edge of the mold until all vertical parts of the monocoque are free. After this, the monocoque will be able to be removed from the mold using constant distributed force along different areas of the structure. With the monocoque removed, the acrylic lap joint offset can be removed from the composite. It may be necessary to use a pick to pull the acrylic from the outer monocoque surface. Once this has been done for the upper and lower parts of the monocoque, the monocoque should look similar to the stacked upper and lower BR20 halves shown in Figure 182.

Figure 182 - BR20 after demolding

5 Trimming and Lap Joint of Monocoque

At this stage of the manufacturing process, the monocoque composite has been completely constructed. Next, the upper and lower molds need to be bonded to create the designed structure. Throughout this process it is critical to wear the proper protective equipment to prevent personal damage from carbon dust and hazardous tools. For dust, a respirator, Tyvek suit, and gloves are needed. For any rotary tools, reciprocating saws, or angle grinders used, a full-face shield is required due to the dangers of the tool and risk of carbon fiber shrapnel.

5.1 Initial Sanding

The surface of the monocoque fresh from the mold may not be cosmetically appealing. It is likely that there will be bubbles of resin from where air in the fiberglass mold expanded then collapsed. These bubbles can be easily sanded out using the air rotary tool used in Section 4.16.3. Note that this will leave a dull surface finish on the outer carbon skin. This surface will be polished at a later step. Use caution to avoid sanding the actual carbon fiber weave. If the weave is damaged, it can risk compromising the strength of the chassis. Only the outer layer of resin should be sanded.

5.2 Trimming of Excess Material

Trimming of excess material will occur in two steps. The first is before the lap joint, with the second occurring afterwards and marked by a coordinate measuring machine (CMM). The first stage of trimming will include the material excess on the top of each upper and lower mold. Each mold has excess material, as shown by the lip caused by the acrylic lap joint offset. If the acrylic plexiglass followed the score line in Section 3.3, then this lip can be used as a cut line. Note that the cut line is the upper lip caused by the acrylic. If any uncertainty exists about the accuracy of the line or ability to closely follow the line with an angle grinder, then a margin distance should be added to be sanded away later.

To cut the laminate, use an angle grinder with a fresh cut-off disk. If budget allows, invest in a larger 7in angle grinder to make the process simpler and more reliable. Before beginning to cut, secure each mold to prevent movement. Each mold should be set so that it sits identical to its position on the vehicle. This may require propping wood or other solid objects underneath the mold. To verify the mold is horizontal, a square can be used from the mounting table to the front bulkhead of both molds as this surface is exactly vertical.

To begin the cut, first cut off the upper flange that overhangs the outer surface of the mold. Doing this provides more clearance for the cutting tool. Next, start at the open end of the structure and cut along the lip (or chosen margin line) from the outside surface. Move slowly along the cut lip, checking that the cutting tool is horizontal. Continue this until the entire upper excess is removed. It may be necessary to make multiple passes with a smaller angle grinder. At this stage, the two monocoque halves will look similar to Figure 183 of BR20.

Figure 183 - Trimmed BR20

To aid in the next step, it is also advised to trim the excess composite off the frontmost area of the cockpit opening, where the front roll hoop would sit. This region has a trim line ingrained into the mold for easier cutting. This region can be cut using the same method previously defined.

5.3 Leveling of Monocoque and Checking Dimensions

Now that both halves are trimmed, they need to be levelled together to match the design. Fitting the two halves occurs in two steps. The first step is to smooth out any waves caused by imprecise cutting. The second step is the sanding away any additional excess and confirming the trimmed shape matches the design.

To begin the leveling process, remove the monocoque halves from the secure horizontal mounts. Flip each half over and set on a smooth flat table that is at least hip height. Look from the rear end of the monocoque into the inside surface. From a low perspective, light can be seen coming through areas that are higher than the surroundings. Likewise, areas in contact with the table can be seen. Mark these areas using a paint marker. To remove the high spot, an angle grinder with a flat sanding disc works well for areas in need of a lot of material removal. For areas that need more fine tuning, a pneumatic palm sander works well. Flip the monocoque half over and sand the marked region until the high spot seems to disappear. It is important to keep the sander horizontal during this process. Continue doing this until no visible light is seen when viewing the upside down monocoque on the table. Do this process for both halves of the monocoque.

Next, secure the lower mold into its horizontal position. Place the upper half of the monocoque onto the trimmed and leveled surface of the lower. View the inside of the monocoque from the rear looking out, similar to that of the previous step. Light will be visible in areas that are not well mated. Mark these areas, but do not remove the upper half of the monocoque yet. First, measure the overall height of the front bulkhead structure. Then, measure the height of the top of the laminate directly in front of where the front roll hoop would sit, down to the floor of the monocoque. Compare the front bulkhead height and front roll hoop height with the designed model. If the measured values are larger than the designed, the leveling can continue. If these values are the same, then the next step can occur.

If the bulkhead height and front roll hoop heights are larger than designed, then the marked high spot areas should be leveled. To continue with the leveling process, it is recommended to keep the lower mold stationary in the mounted horizontal position and modify the upper mold. Remove the upper mold and sand the marked high spots. Continue marking high spots, measuring, and sanding until the measure values match that of the designed model. If small gaps still exist at this point, they will be filled with core in the next step.

5.4 Bonding Upper and Lower Molds

Before the lap joint is made, the two monocoque halves need to be bonded to prevent unwanted shifting in the structure during the bagging of the lap joint. First, place the upper half of the monocoque onto the lower. Ratchet strap the upper half to the lower half to prevent movement or use a heavy object set on top of the monocoque. Using pieces of scrap core, fill any large holes with the correct type of core for that layup region. Be sure to orient the core in the correct direction as specified in Section 4.3. With all the large holes filled, next fill smaller or uneven areas of the seam. It may be necessary to cut the core down its width to fit it into uneven areas of the seam.

Once all gaps are adequately filled, the two halves can be bonded together. First, line up the front bulkhead surface and corners. This surface must have a flush transition between halves and corners must line up. Once this has been set, check that the left and right sides of the monocoque have a flush transition between monocoque halves. A slight misalignment may occur due to the mold expanding or contracting from uneven vacuum load during the cure cycle, causing the halves to not have a flush transition. If the upper or lower halves do not line up, it may be necessary to use clamps or a ratchet strap to carefully press the monocoque into shape. However, do not overtighten the ratchet strap as this can risk the monocoque failing or being preloaded. An acceptable force to press the monocoque is 500N. Once alignment is confirmed, the next step can be taken.

Take off any ratchet straps, remove all fitted pieces of core (arranging them so they can be easily placed later), and separate the two monocoque halves. Use a pneumatic hose to spray out the exposed areas of core in the lap joint seam. Then clean this area with acetone to prepare it for the adhesive. Finally, use masking tape to cover the 50mm of carbon fiber underneath the seam on the inner and outer surface of the monocoque. This is used to protect it from the epoxy as the surface finish of the epoxy is poor for lap joint bond.

The adhesive used to bond both halves of the monocoque is Loctite EA9430. This epoxy is extremely strong when cured but takes 5 days until it is fully hardened. First put on gloves, long sleeves, and disposable clothing. Using a scale, measure out the designated hardener to resin ratio into a small cup and mix well. The epoxy hardens faster when the volume is much larger than the surface area as it builds heat, so it is recommended to mix small quantities at a time. Then, fill a wide tip syringe from the rear with the epoxy. Reinsert the plunger of the syringe, then generously apply the epoxy to the exposed core at the lap joint seam on both the upper and lower parts of the monocoque. At this stage, remove any gloves to prevent the spread of epoxy.

Next, lift the upper mold and place carefully onto the lower mold seam. Align the halves in the same method as previously. Now, tape small pieces of peel ply across the seam of the monocoque in the areas that previously had ratchet straps. Cut additional pieces as more ratchet straps will need to be added. Add the ratchet straps used for alignment and secure the monocoque into its aligned state. Add more ratchet straps as deemed necessary to prevent movement while providing a clamping load.

With the monocoque set in place, reapply gloves and reload more syringes with mixed epoxy. Use the premade core pieces to fill the gaps between halves. However, before inserting any piece of core, cover both sides in epoxy so all contacting surfaces are coated. Continue this until all large and small gaps are filled. If any areas appear to be low on epoxy, or have small gaps, use the syringe to fill the cavity. At this stage, the monocoque will look similar to Figure

184 below. Note that in this image, breather cloth is used between the ratchet straps and mold surface. Instead, peel ply should be used.

Figure 184 - B20 ratchet strapped together

The clamped halves must be left for 5 days to dry. Therefore, the monocoque should be placed somewhere that will result in little movement during the curing process. After moving to a safe location, reconfirm that the monocoque is aligned. Remove all masking tape and leave to cure.

5.5 Lap Joint

The lap joint process occurs in five steps. First, the monocoque must be prepared for the lap joint. Then, material needs to be cut to be used in the lap joint. Next, workstations need to be created for the lap joint. Once workstations are made, a large vacuum bag must be created. Finally, the lap joint can be made.

5.5.1 Preparing the Monocoque for the Lap Joint

To prepare the monocoque for the lap joint process, first remove all ratchet straps and peel ply. Then, use 220 grit sandpaper to sand the inner and outer surface in the offset region where the lap joint will be bonded. This region will begin with a mirror like finish. Sand it until the surface finish is dull, being careful to not sand into the carbon fiber weave underneath. Additionally, the lip where the acrylic plexiglass originally sat may have chipping where the resin built up around the edge of the material. Remove any areas that appear that they could chip or seem structurally weak. Clean the inner and outer surfaces of the monocoque with acetone. Then use wide roll masking tape to cover the lower 150mm of the monocoque below the lap joint seam. Using the same roll, cover 100mm above the upper lip of the lap joint region. The masking tape helps to prevent resin from spreading to undesirable parts of the vehicle, adding weight and hindering cosmetics.

5.5.2 Cutting Material for Lap Joint

To cut material for the lap joint, dry weave carbon fiber is needed. Typically, this is ordered from Composite Envisions as they provide Formula SAE teams a discount code. 3k carbon fiber is used in the process, and through the previous platform of monocoque design, it was found that 45° patterns yielded extremely poor quality. The 45° patterns would stretch during the resin impregnation process, making the piece too thin and long. Therefore, all the lap joint pieces are in the 0° and 90° direction.

To cut the carbon fiber, first lay out a plastic sheet to work on. This prevents dirt and debris from becoming embedded into the weave. Next, unroll the 50” wide roll along the table, and cut into strips along the length of the roll. These strips will be varying in width to allow for a gradient of edging leading to the upper and lower lap joint offset lip. The first strip will be 25mm wide, the next will be 30mm, then 40mm, 50mm, and 50mm again for a total of 5 layers on both the inside laminate and the outside laminate. These strips should be cut to a length that allows easy control of the piece, while minimizing seams. Through previous manufacturing phases, it was found to be easiest with the front bulkhead covered in one section, then the left and right sides broken into two sections each. This will yield strips that are 400mm long for the bulkhead, 10000mm long for the first section of the side, and 1200mm long for the second section of the side. These sections are slightly oversized to allow for overlap with pieces of a different section. The strips should be bundled and labeled for easy identification in the lap joint construction process.

To cut the dry weave fabric effectively, it is easiest to cut the Kevlar stitching material off the side, then carefully pull on one of the individual "weaves" of carbon hanging off the end. When done correctly, this single weave of fiber will slide out from the total fabric weave, leaving a clear and straight line to cut. As a note, dry weave carbon is easily warped, therefore the fabric should be checked for squareness every few cuts.

5.5.3 Lap Joint Workstations

Next, workstations need to be set up for the lap joint process. First, a large table is needed to be covered in plastic sheeting and taped down in place. Then, a smaller table with full 360° access to the monocoque will need to be covered in plastic. In WMU's Student Projects Lab, the welding table or table saw work well for this application. Ten people are needed for the lap joint process. Two teams of two people will be responsible for the left and right sides of the monocoque. One person is responsible for the outer front bulkhead. This person should also serve as the supervisor role outlined in Section 3.7. The last person working directly on the monocoque will be working inside of the chassis itself. They are responsible for placing lap joint pieces on the inside skin of the front bulkhead, and frontmost pieces of the sides. It is recommended that this person is small in stature to be able to comfortably place pieces. Two people will be working on the larger covered table in an area that is designated for fiber impregnation. These two people should be experienced in the wet layup process and will be responsible for resin impregnating the precut carbon fiber to give to the placing teams.

The larger table will be broken into two sections. The first will be sectioned off as an area where resin will be used. The other area is to be left open and remain clean. This area is prepared as a bagging area once the lap joint has been created and is also used in the construction of the vacuum bag.

5.5.4 Creating the Full Monocoque Vacuum Bag

To create a vacuum bag that can be used for the entire monocoque, it must be done differently than that of previous bags. The principles remain the same, but the bag sizing and puck location is different.

Using the large covered table, unroll a tube of green 36” wide tube bagging. This bagging can be purchased from SC enterprises, similar to the other bagging materials. Cut a 25mm strip laterally across the bag, then cut this strip along the pressed seam so it is 1” x 72”. Use this strip to check if the monocoque will fit in the bag at its widest point, the front roll hoop location. Check this by wrapping the strip around the monocoque. If the strip can be fully wrapped with at least 50mm of overlap, then the monocoque will fit. If not, then a section of bag the length needed to meet a 50mm overlap will be needed. This extra width will be required to be added to the width of the bag for the total length of the vacuum bag.

To accurately size the vacuum bag needed, measure the total length of the monocoque and the height of the front bulkhead. Use the below equation to find the length of the bag needed.

$$Length\ of\ Bag = 2 * [(2 * Length\ of\ Monocoque) + Height\ of\ Front\ Bulkead + 3\ Ft)]$$

The additional three feet of bagging gives space for the tacky tape seams, pump, and excess for reaching areas of possible bridging. Note that this length is effectively double the expected amount to be used. This is because the vacuum bag will cover the inner and outer surface of the monocoque. The remaining bagging construction can follow Section 3.5, but low temperature materials are usable as an autoclave is not necessary for the lap joint.

The peel ply should be cut in one large continuous piece for the outer surface, and another for the inner surface. The peel ply should be 250mm wide to accommodate the full lap joint and any possible excess resin.

Breather cloth will be required for the entire monocoque. All surfaces inside the vacuum bag must be covered in breather cloth, or warping is possible. Additionally, cut two 200mm by 200mm squares to be used at the puck location. Fold and place all cut materials into a safe area where they will not be disturbed or dirtied.

5.5.5 Constructing the Lap Joint

To begin the construction of the lap joint, the two people experienced in wet layup will mix the TCC-205 resin and 104 hardener to the specified mixture on the can. They will then take a piece of the precut carbon fiber, lay it onto the table, and drip resin across it. Using BONDO spreaders, the resin will be pressed into the fibers. The carbon fiber will be flipped to the other side where the weave will be saturated more. Once the fiber is thoroughly saturated to approximately 40% of the total laminate weight, it can be handed to one of the placing teams.

Each placing team must be careful to not stretch the laminate, while also being careful not to spread resin onto uncovered areas. The laminate should be held by each person, one on each end. The laminate should be placed into an area of interest first. For the frontmost side piece, the starting area is the overlap with the front bulkhead. For the rearmost side piece, it is the overlap with the frontmost side piece. This is to ensure that the laminate is covering all critical areas. When placing in a region of overlap, the ideal overlap matches that of the lap joint overlap in Section 5.5.2. Once the end is placed, the laminate should be pressed on from the already placed end, to ensure no air bubbles are trapped underneath the laminate. For the first layer of the lap joint, it is critical that the thinnest layer is centered over the seam of the monocoque halves and is not able to slide freely. If this layer moves off the seam, the chassis integrity could be compromised.

The supervisor role should keep track of all placed pieces on a written document to prevent confusion. Once all pieces of the first layer are placed, the next layer can begin. The supervisor role is also in charge of directing the resin impregnators of which pieces are next and when they should be done.

Continue the process until all pieces and layers have been placed. Then, using disposable scissors cut all loose fibers. It may also be necessary to use an acetone dipped rag to clean any excess resin that may be dripping down the masking tape. Once all fibers and drips have been fixed, gloves can be changed. It is important to swap to clean gloves at this stage to prevent accidental spreading of resin. At this stage, the masking tape can be carefully removed. Figure 185 shown below demonstrates the lap joint process, where the final layers have not yet been added for BR20.

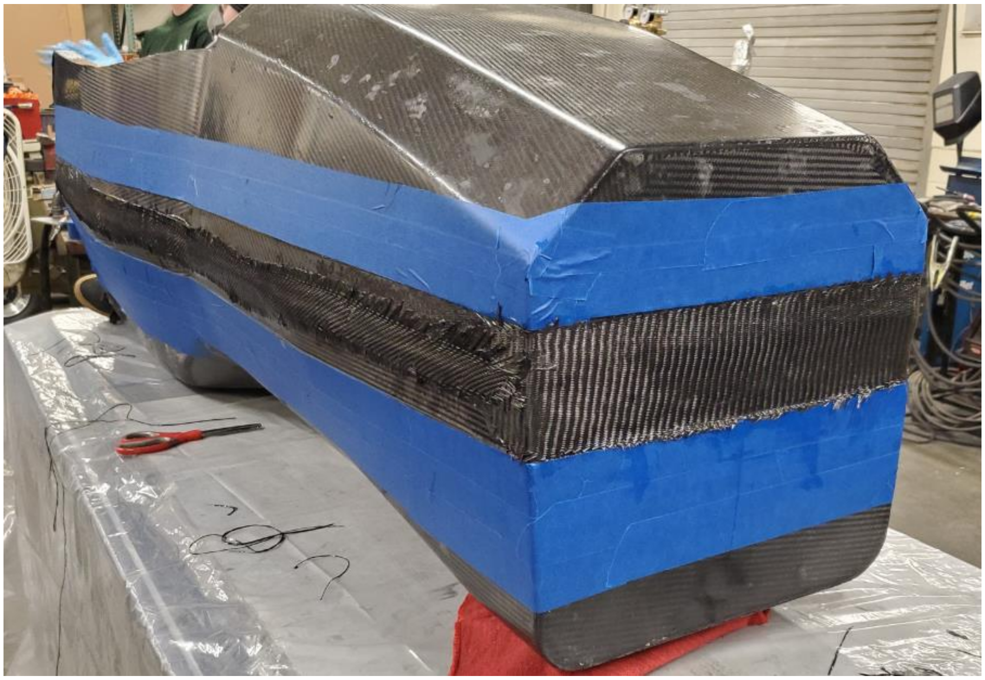


Figure 185 - BR20 uncured lap joint

To prepare for the bagging step, remove the plastic sheeting that was affected by resin and replace with new plastic sheeting. Clean off any dirt or contaminants on the covered table.

5.5.6 Vacuum Bagging the Full Monocoque

To properly vacuum bag the lap joint, the entire monocoque must be vacuum bagged. To begin this process, use the precut strips of peel ply to cover the entire lap joint laminate on both the inside surface and outside surface. It is critical to saturate the peel ply in resin by pressing it into the laminate. This helps the peel ply stay in place and prevent shifting. Next, tape the top and bottom of the peel to the monocoque using duct tape. Once the lap joint laminate is covered peel ply, the breather cloth can be used.

Take the precut breather cloth and spread out along the covered large table. Lift the monocoque over to this covered table and set on top of the breather cloth. Wrap the breather around the outside surface of the monocoque, then into and around the inside surface. Tape any seams where the breather cloth overlaps to prevent shifting. Ensure that all surfaces of the monocoque are covered and the breather cloth is secure.

Finally, the monocoque can be placed into the large vacuum bag. First, lift the monocoque off the table and have two people hold if off to the side. Unfold the premade vacuum bag across the large table so that the opening is facing the accessible end of the table. Insert the monocoque frontside first into the bagging, and carefully position in the bagging until it reaches 300mm from the front seam of the bag. This may require lifting the monocoque multiple times to pass vacuum bagging underneath. Take care to not drag the bagging with the weight of the monocoque as this can create tears in the bagging. Additionally, use care to not move or shift the breather cloth of peel ply during this process. With the monocoque at the front of the bag, seal the opening completely. Reopen a small 70mm diameter hole in the frontmost part of the bag to allow air to escape for the next step.

With the bag mostly sealed, invert the excess bagging in the rear of the monocoque towards the front. This step should be done carefully to avoid pinching any areas of the bag. The inverted bag must be pushed all the way to the inner surface of the front bulkhead. It may be necessary to climb into the monocoque during this step to continue placing the bagging. Anyone that gets into the monocoque must be wearing sweatpants or leggings as buttons and zippers found on other types of pants will easily rip the bagging under the person’s weight. Check all clothing before getting into the monocoque.

At this stage, the bagging is roughly in place. Now have all available hands press on the bagging to remove excess air through the small opening in the front. Place the two cuts of breather cloth against the bottom of the front bulkhead, but not on the lap joint. Center the receiving end of the puck here as well, then seal the hole. Cut a small hole for the puck using the same method defined in Section 3.5. The vacuum pump can now be started, and holes found in a similar manner to Section 3.5. Note that it is likely that someone will have to lay inside the monocoque to find holes in the vacuum bagging. Once complete, the monocoque full vacuum bagged will look similar to the stage of the BR20 chassis shown in Figure 186 below.

Figure 186 - Full BR20 monocoque bagged after lap joint

The bagged monocoque should be left for at least 24 hours to allow for full cure of the resin. Once cured, the bag should be carefully removed to be used later in the monocoque manufacturing process. Store the bagging in a safe place free from dirt and debris.

After removing the bagging material, the breather and peel ply can be removed. The resulting lap joint should look similar to Figure 187 of BR20. Note that the offset lip may not be completely gone. This will be corrected in the last step of manufacturing.

Figure 187 - BR20 with cured lap joint

6 Locating and Drilling Features in Monocoque

A critical part of ensuring a safe vehicle is constructing all mounting locations with excellent quality. To do this, a coordinate measuring machine (CMM) is required. If possible, it is also advised to have all of the holes drilled professionally, due to the capabilities of advanced machinery.

6.1 Locating of Holes and Cut Lines

A CMM must be used to locate all hole locations. This is due to the curved nature of the monocoque. It is not possible to accurately measure in three-dimensional space using tape measures and rulers. Previously, Bermont Gauge and Automation (contacted through Dante Dudek) in Fraser, Michigan has provided CMM and machining services for this stage of the monocoque.

To ensure the final quality of the monocoque is satisfactory and structurally adequate, it is advised to use datum points on only the lower half of the monocoque. This is due to the lap joint method of bonding the top to the bottom. This method leaves inherit inaccuracies, but by using only one half as the datum, it keeps relative consistency between the hole locations. The lower mold is used, as this houses most of the holes in the structure, and is also the more structural half of the chassis.

Cut lines can also be marked using the CMM. It is again ideal to use this method as hand measurements will yield poor results. Trimming around the cockpit opening is especially critical as this region only has 10mm of margin before it violates major side impact rules and compromises chassis structure.

6.2 Drilling of Holes and Trimming with Tooling Available

If tooling is available through a sponsor, it is highly recommended to use. However, many tooling companies have machinery that cannot handle the dust and splinters created by composite manufacturing as it infiltrates the cooling system. It is recommended to keep clear communication with any sponsor and confirm ahead of time that composite waste will not negatively affect their equipment. Additionally, composites are very hard and will dull cutting equipment faster. If the sponsor is unfamiliar with composites, be sure to notify them that high point loads like that of a drill press will fracture the carbon fiber before cutting it and should be avoided. High speed cutting with low force is ideal to prevent microtears in the laminate around each hole. Finally, clamping the composite structure in a fixture must be done carefully. Overtightening of a clamp could crush the core of the monocoque. If this were to happen, major repairs would have to occur.

For long sweeping cuts such as the cockpit opening and front bulkhead cutout, vibrating or harsh equipment should be avoided. Tooling like a reciprocating saw may be too violent for the laminate, causing delamination of the carbon fibers and core. This is especially worrisome in the aluminum core regions. Instead, a high-speed cutoff wheel is preferred. When using any high speed and friction heavy tooling, keep the laminate cool to avoid burning the resin along the cutline.

6.3 Drilling of Holes and Trimming without Tooling Available

If the holes and cut lines have been found with a CMM, but no sponsor is able to drill the holes or trim at the cut lines, then these things must be done by hand. Cutting and drilling these parts by hand is much less accurate but can be done.

To drill holes, it is critical to keep the drill bit perpendicular to the surface of the outer monocoque skin. All holes are located on flat panels to allow for easier drilling and mounting of tabs. To keep the drill bit perpendicular, first drill out a clearance hole into a steel rod on the lathe and face the end of the rod. Then, butt weld this rod to a plate. Use the rod as a guide to keep the drill bit straight and cut a hole into the plate. Now this plate can be used to place against the surface of the monocoque, and the rod with drill bit inside will always be perpendicular to the surface. When drilling, check that the hole size is accurate by test fitting a Torlon insert. The fit should be similar to a press fit, with the outer rim of the insert against the composite skin.

For trimming excess parts of the mold, use a large angle grinder, or multiple passes with a smaller angle grinder. The trimming can be done identical to that of Section 5.2. Use caution with the grinder, and repeatedly check that the angle grinder is oriented correctly for a horizontal or vertical cut. It may be helpful to use compressed air to clean the cut line so it is always visible during the trimming process.

Once completed, the monocoque should look similar to Figure 188 below, where BR20 is shown on the inside surface of the front bulkhead region. Note that this figure shows the BR20 monocoque with the holes sanded post drilling. This will not occur until the next step.

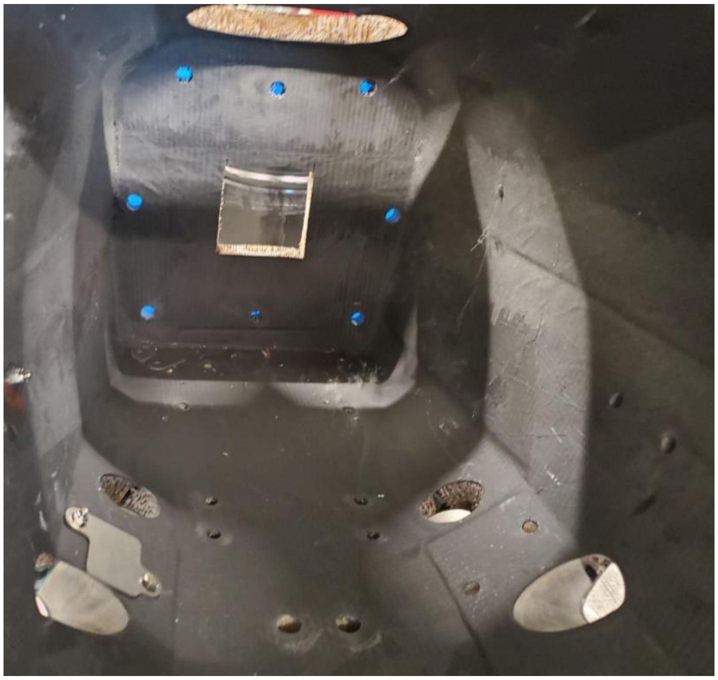


Figure 188 - BR20 with holes and trims

7 Creating Mount Points in Monocoque

To create structural mounts for the suspension of the vehicle, a lighter mount design was used compared to previous years. These new mounts incorporate a Torlon composite insert that is to be placed into the holes of the monocoque, then epoxied into place. To do this, multiple steps are needed for each hole. Figure 189 shows the type of Torlon insert used, a 1” long 0.257” through hole design.

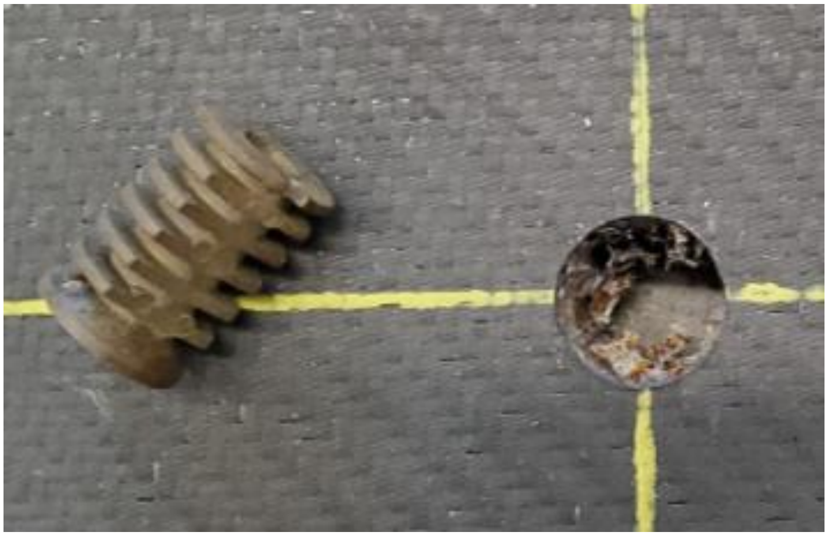


Figure 189 - Torlon insert and through hole

7.1 Removal of Core Material

First, the perimeter of the hole needs to be sanded with 220 grit sandpaper to remove any carbon fiber splinters. Once smooth, the core material may need to be bored out to increase perimeter shear area. To bore out the core, use a hex key wrench placed in a drill. The hex key should be trimmed such that the hole radius plus hex key horizontal distance is equivalent to the desired bore radius. Hook the horizontal portion of the key into the core. Then, turn the drill on and carefully proceed around the perimeter of the hole, also moving deeper into the hole to reach the other laminate skin. Once finished, remove as much core material as possible, spray with air to remove dust, and clean the perimeter with acetone.

7.2 Placement of Inserts

With this step complete, the insert can be placed. To do this, first slide the insert into the hole, and align so that the composite skin is centered and pressed onto the insert flange on both the inner and outer surface. Next, use masking tape to cover the inner surface of the laminate and insert face, to seal any epoxy from leaking out of the insert housing. Place the plastic cover that comes with the inserts on the outer surface side of the insert, aligned such that the epoxy entrance and exit holes are accessible.

To insert the epoxy into the composite, the epoxy gun must first be set up. The epoxy gun is similar to a caulk gun in that it applies pressure to the back of the epoxy tube, forcing it out. However, the epoxy used is Scotch-Weld EC-3542 B/A FR, which is a two-part epoxy. To mix the epoxy adequately before insertion, it is best to use a static mixing nozzle. This nozzle is screwed into the exit port of the epoxy. With this setup, it is possible to quickly and easily epoxy many inserts sequentially.

To ensure that the insert has been properly epoxied, first align the exit nozzle of the epoxy with one of the ports on the insert. Squeeze epoxy into this hole until the epoxy begins coming out of the other hole in the insert. At this point, the masking tape and outer plastic can be removed, and the epoxy left to dry. The insert will be cured in place after three hours but should not be fully loaded until seven days after the epoxy is placed.

8 Phase Three – Placement of Roll Hoops and Covering Exposed Core

As part of the Formula SAE rulebook, all exposed core material must be covered with a protecting layer of carbon fiber. This fiber also helps to transfer load from the outer skin to the inner skin, however this amount is very small. Another part of the Formula rules is the addition of the front and main roll hoops. For the BR21 design, the front roll hoop is lap jointed in place, with the rear bolted.

8.1 Roll Hoop Preparation

To prepare for the placement of the roll hoops, first sand the area around the placement of the front roll hoop with 220 grit sandpaper until dull, then clean with acetone. Do this for both the inner and outer skin at the top, and the inner skins for the side. The sanded region should be approximately 50mm wide. Before the next steps can occur, the front roll hoop must be completely welded and cleaned.

8.1.1 Placement of the Front Roll Hoop

To secure the front roll hoop to the chassis, it will undergo the same bonding process as the lap joint holding the upper and lower monocoque halves together. First, place the roll hoop against the front of the cockpit opening, such that it is perpendicular to the ground. It is advised to place the monocoque in the position that it will sit in the car to ensure it is correctly placed. Using ratchet straps, lightly compress the roll hoop so that it can fit past the cockpit opening and into the region where it is to be placed. Use clamps to lightly secure the front hoop in place. Mark all clamping locations with a marker, then mark the location that the roll hoop contacts the inner surface of the monocoque. Also mark the locations that the ratchet straps are needed to compress the roll hoop. Once placement is confirmed as possible, remove the front hoop from the vehicle.

To prevent the front hoop from shifting during the bagging process, it must be epoxied to the laminate. First, sand the entire front roll hoop with 220 grit sandpaper, then clean with acetone to promote bonding. Mix Loctite EA9430 in a small quantity and apply to the outer edge of front hoop, and along the marked locations of contact with the monocoque on the inner surface. Do not apply epoxy to regions that need to have ratchet straps for compression. Place the front roll hoop into the correct position. Use small pieces of peel ply to separate the clamps from the epoxy surface. If necessary, use a syringe to fill any other bond regions with epoxy, similar to Section 5.4. Once this has been completed, carefully move the monocoque to a safe and clean place. Do not move the monocoque for at least two days and wait five days until the next step.

8.1.2 Placement of the Main Roll Hoop

To place the main roll hoop in the correct region, use the predrilled holes as a guide for the path. The upper portion of the main roll hoop must be completely vertical. To aid in the placement process, it may be beneficial to jig and tack the main hoop supports and bolting area. Doing this will allow this rear area to be bolted in place with minimal freedom allowed in the front. This will essentially place the hoop in the correct position. Once placed, the main hoop mounts can be bolted through the inserts and tacked to the hoop. Full welding should occur outside of the monocoque to prevent heat from damaging the composite. It may be necessary to bolt in and remove the main hoop multiple times to ensure fitment of all welded pieces.

8.2 Lap Joint of Front Roll Hoop and Covering Exposed Core

To fully secure the front roll hoop in place, it must be lap jointed. The lap joint must cover the entire front roll hoop, except for a 25mm section on the bottom of the roll hoop on the righthand side. This uncovered region allows Formula SAE technical inspectors the ability to confirm the thickness of the roll hoop as matching that of the rules. The front roll hoop will be lap jointed in the same step as the covering of all the exposed core. Doing this saves time and bagging materials.

To construct the lap joint and cover the core, the same process can be used as outlined in Section 5.5. The dry carbon fiber cut lengths must change to match that of the length of the roll hoop, which should be broken into an upper and side sections. All exposed core can be covered in only one layer of laminate, except for the cockpit opening and rear engine cut, which should be covered in two, due to repetitive loading during ingress and egress, as well as maintenance. One layer of laminate is only sufficient if and only if it completely covers the exposed core. Use more layers if necessary but keep in mind each extra layer is extra weight of carbon and resin on the car. Additionally, peel ply should be cut in a manner to adequately cover all regions of wet layup and taped similar to that in Section 5.5. Once this process is finished, the completed monocoque should look similar to that of BR20 shown below in Figure 190.

Figure 190 - BR20 with front hoop lap joint and core coverage

9 Final Cleaning and Surface Finishing of the Monocoque

The final step in the manufacturing phase of the monocoque chassis is the preparation for vinyl wrap. While this step may seem simply cosmetic, it is very important as the appearance of the overall vehicle plays a strong role in Bronco Racing's ability to gain and keep sponsors. No sponsor wants to have their company name on a vehicle that looks to be poorly made. Monocoque surface finishing occurs in three steps. First, surface blemishes must be removed, then grooves must be filled. Finally, the monocoque can be clear coated.

9.1 Removing Surface Blemishes

The first step to increasing the overall look of the monocoque is to identify areas of the laminate that require little or no surface repair. Note these areas as they should be used as areas of exposed carbon fiber to show through the vinyl wrap. Once these areas have been identified, cover them in masking tape to preserve the appearance.

Next, use a pneumatic rotary tool with a 220-grit sanding disc attached to sand away any resin bubbles. Use caution to avoid sanding into the carbon fiber weave. Work around the monocoque to sand all resin bubble flush to the surrounding surface. For smaller bubbles, it may be easier to sand by hand with 220 grit sandpaper.

9.2 Remove Surface Grooves

After resin bubbles have been fixed, use the rotary tool to begin removing groves in the surface of the monocoque. There are only a few locations that will have grooves present. The first is the upper and lower lip of the lap joint offset. Carefully remove the sharp edge formed by the resin drying against the acrylic. It may not be possible to fully smooth this region. This will be taken care of shortly. The other region that may have grooves is the areas where wet laminate has been placed onto prepreg carbon fiber. Carefully sand these areas smooth so that there is an even transition.

If it is not possible to achieve an even transition, BONDO may be necessary to smooth over the groove. BONDO can also be used on any areas where resin bubbles have left a small crater. Before using the BONDO, mix glass beads into the putty at a 50% mix ratio by volume. This will make the BONDO lighter for a given volume needed. The hardener can then be kneaded into the putty, and spread across the grooved surface. Allow the BONDO to dry following the instructions on the can.

Once dry, sand the BONDO smooth. Reapplication and sanding may be necessary. All grooves and BONDO to carbon fiber transitions must be smooth to the touch. Sand all applied Bondo to 400 grit to keep the surface appearing smooth through the vinyl wrap.

9.3 Increasing Clarity of Exposed Carbon Fiber

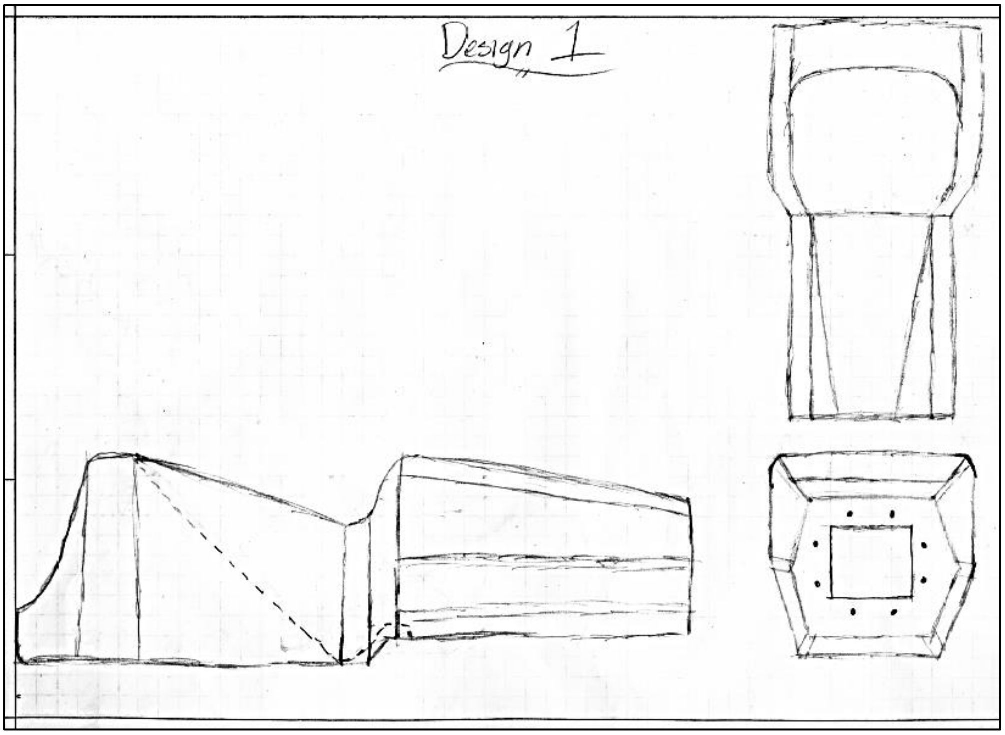
The final stage of monocoque construction can now occur. Remove the tape covering the concealed regions of carbon fiber. These regions will be the areas exposed by the vinyl wrap and should appear as pristine as possible. First, sand each area with 400-grit sandpaper until a slightly dull surface finish is acquired. Then clean the entire monocoque with an acetone dipped rag.

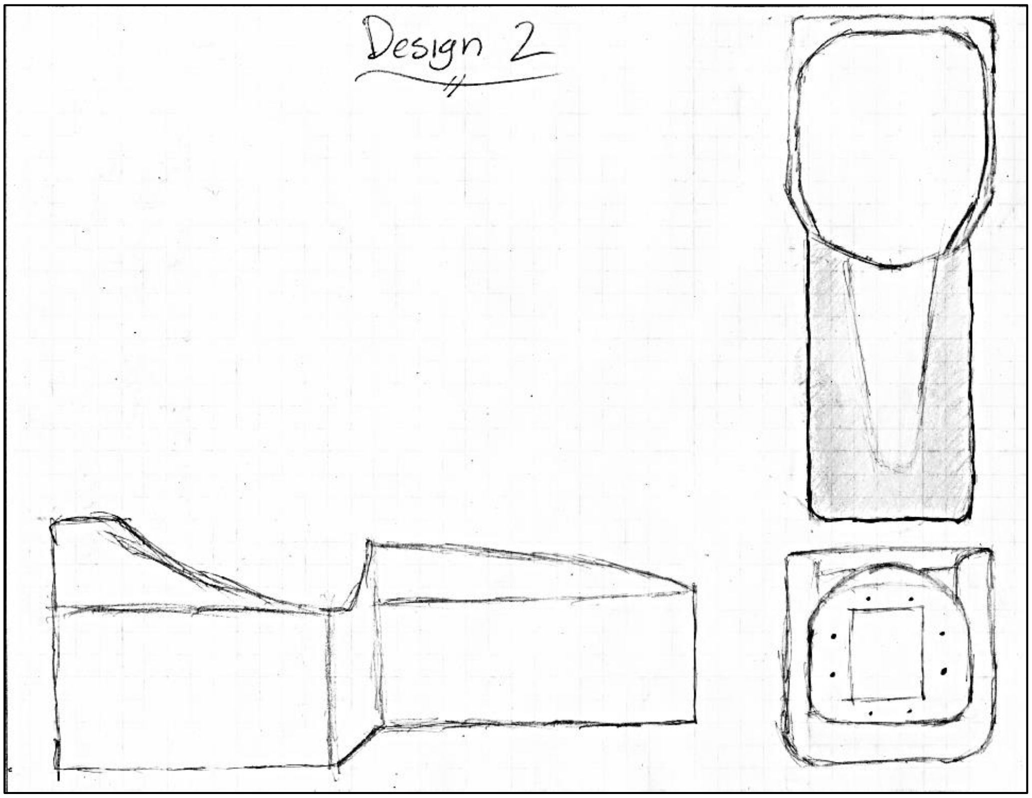
Carefully transport the monocoque into a clean, well ventilated room. Use gloss clear coat to spray to the exposed areas of carbon fiber. It is critical to work in thin and light coats to avoid having the clear coat run. After applying two light coats of gloss clear coat, leave the monocoque until fully dry. At this stage, the monocoque is ready for assembly into the Bronco Racing Formula SAE vehicle. Figure 191 and Figure 192 show the monocoque mounted to the vehicle, both before vinyl package addition and after.

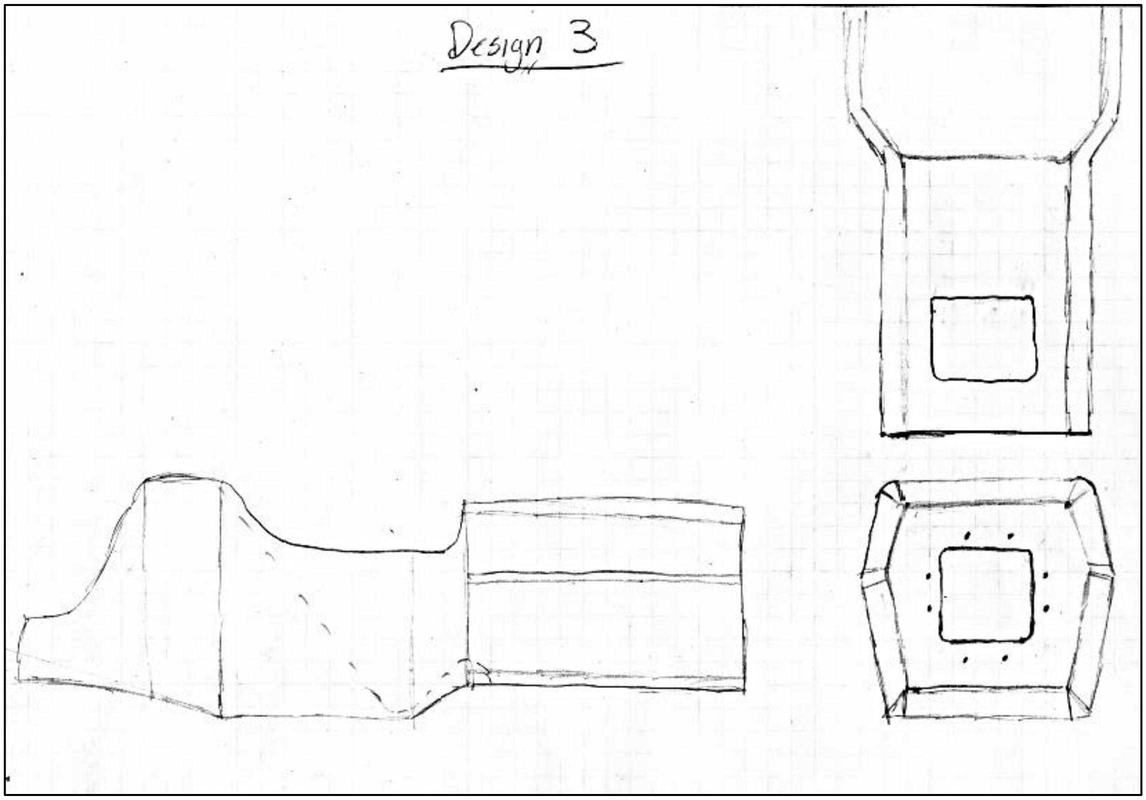
Figure 191 - BR19 monocoque before vinyl wrap

Figure 192 - BR19 monocoque after vinyl wrap

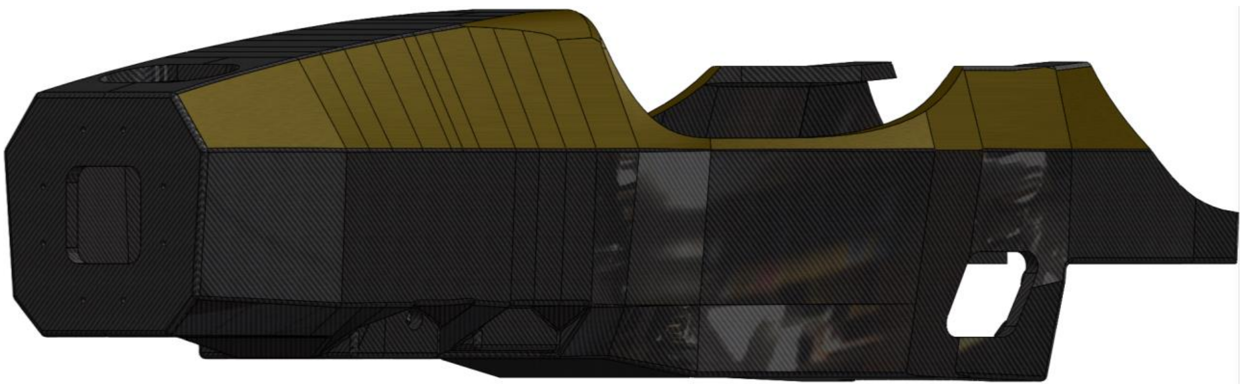
Appendix B – Initial 3 Design Sketches

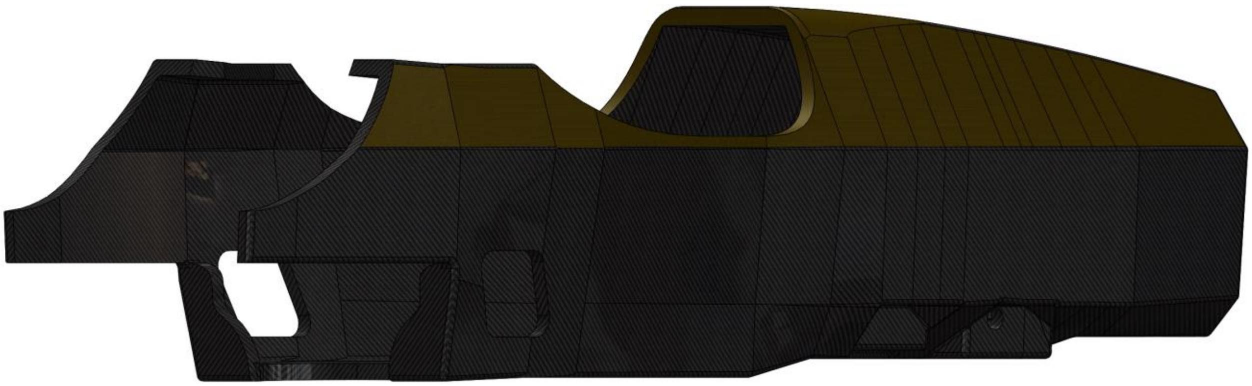


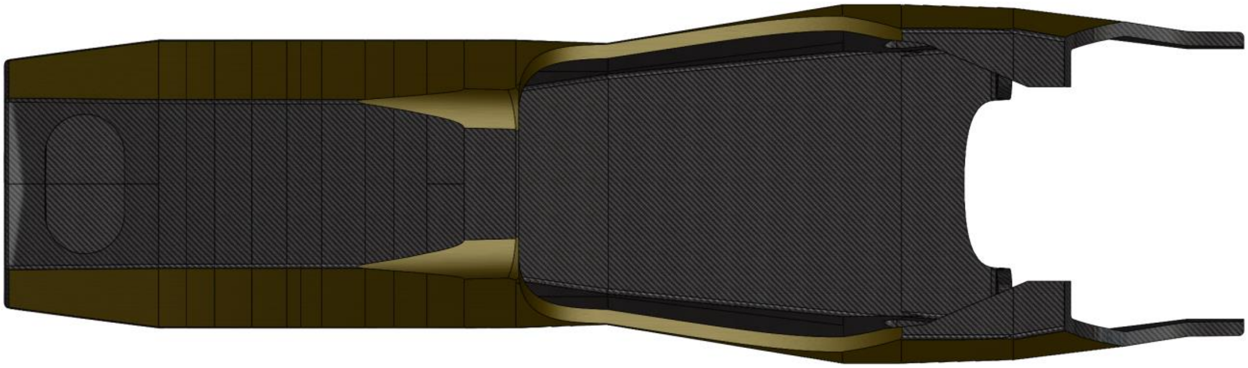


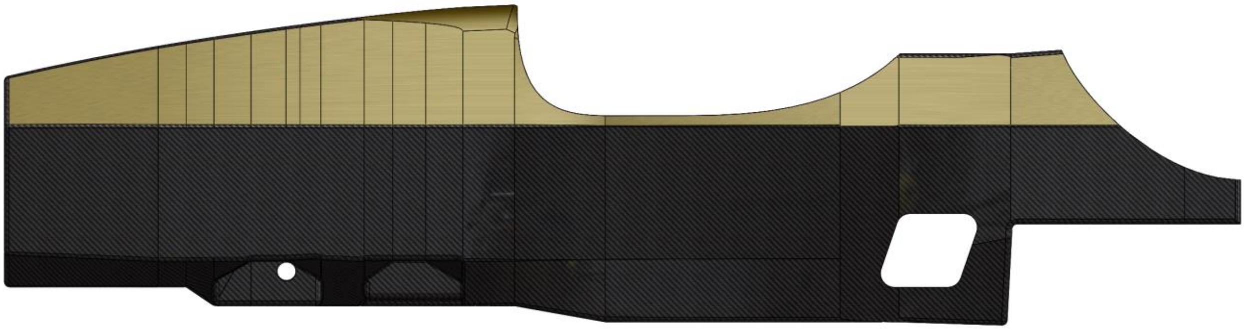

Design 3

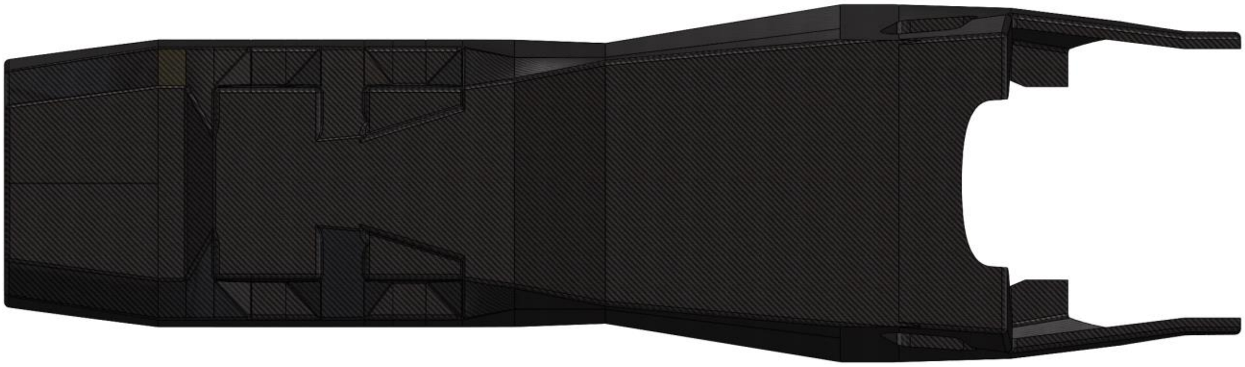
Appendix C – Monocoque Renders

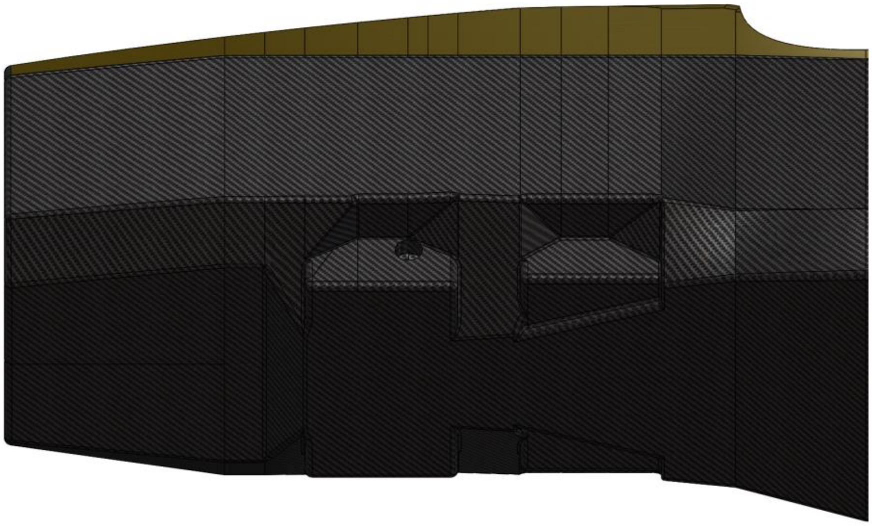


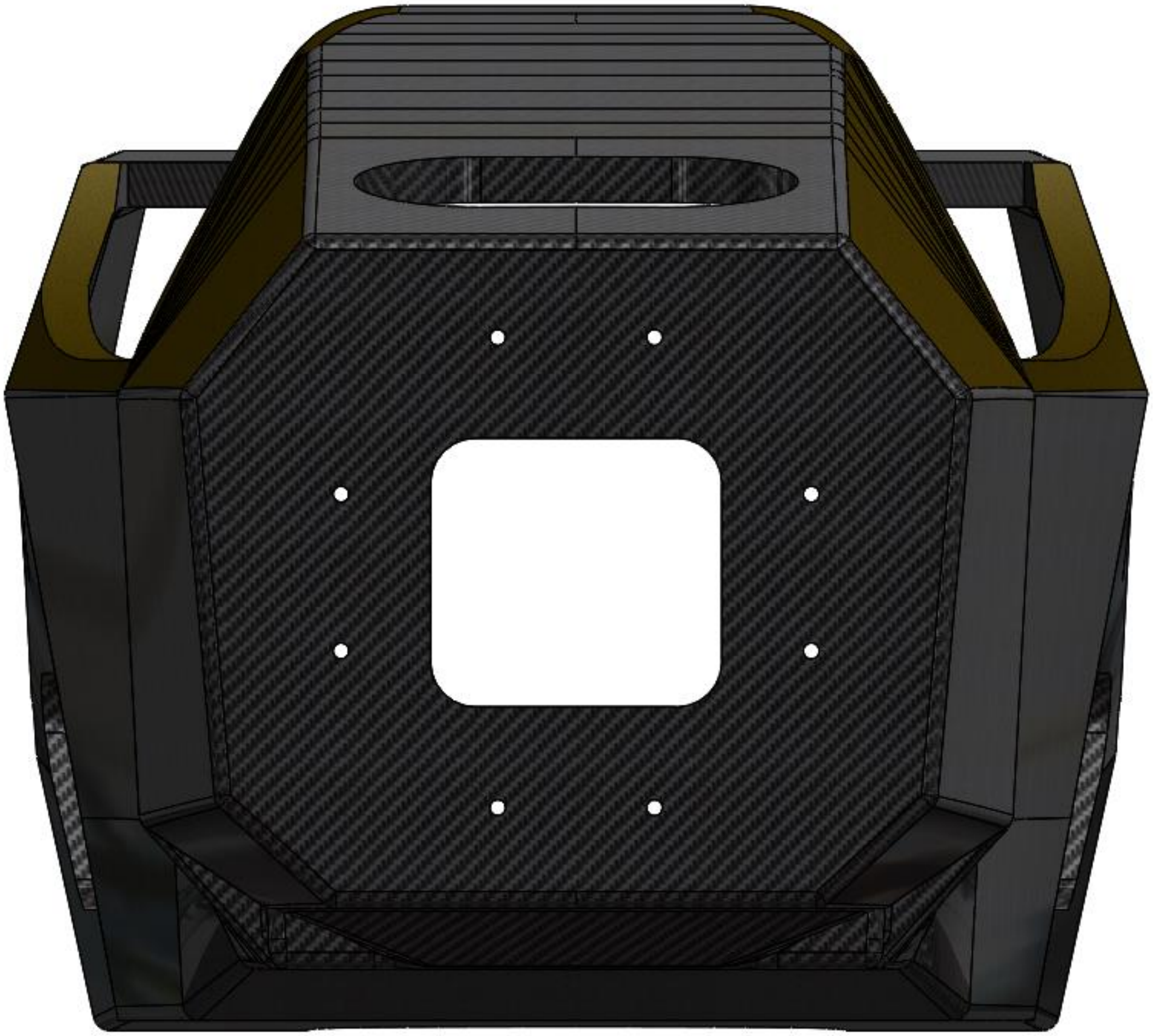


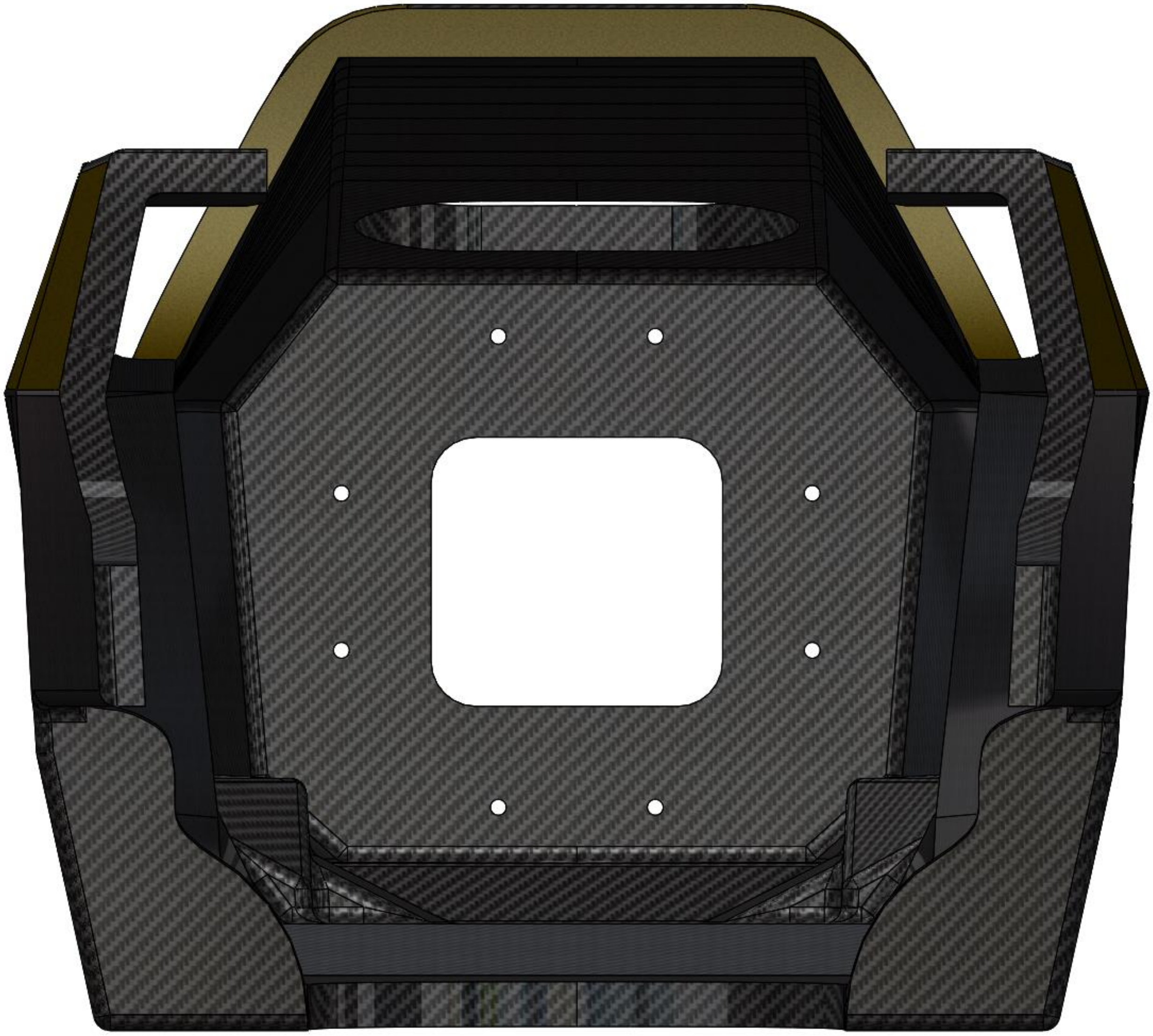




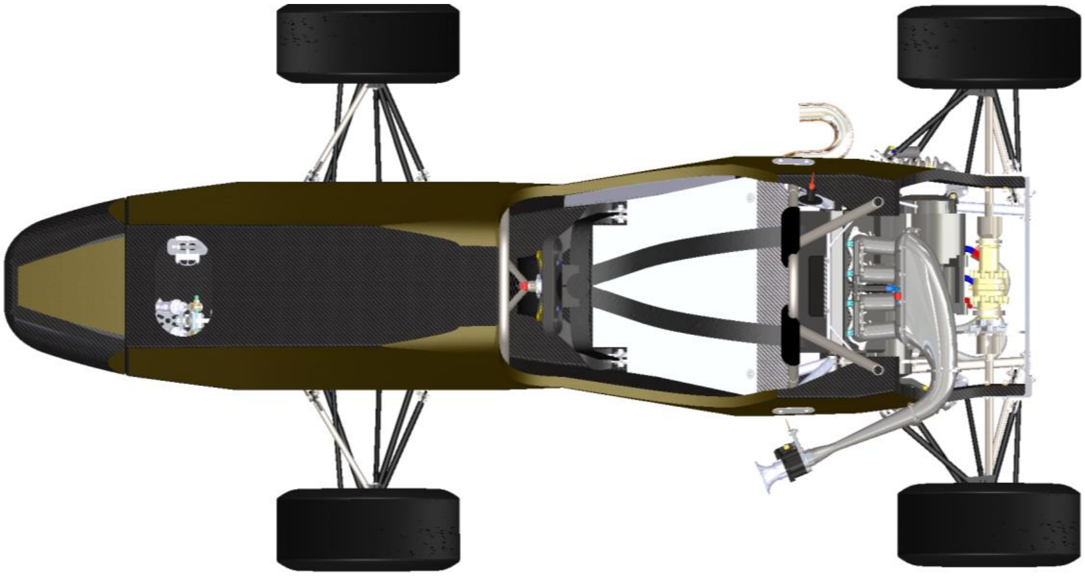


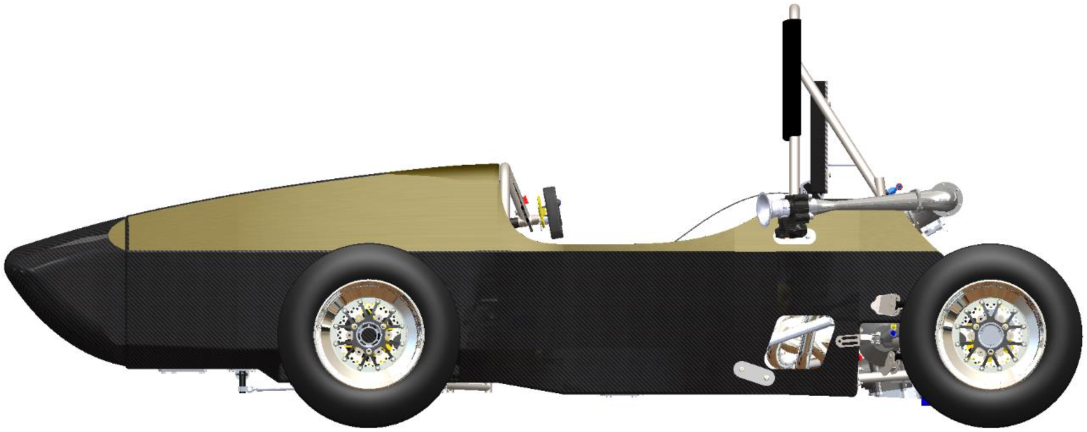


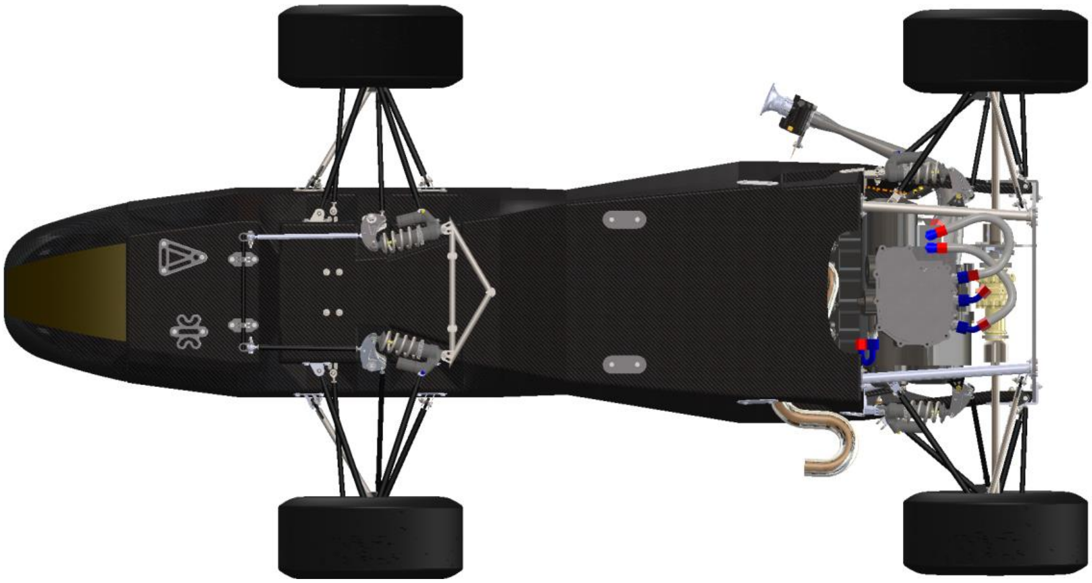


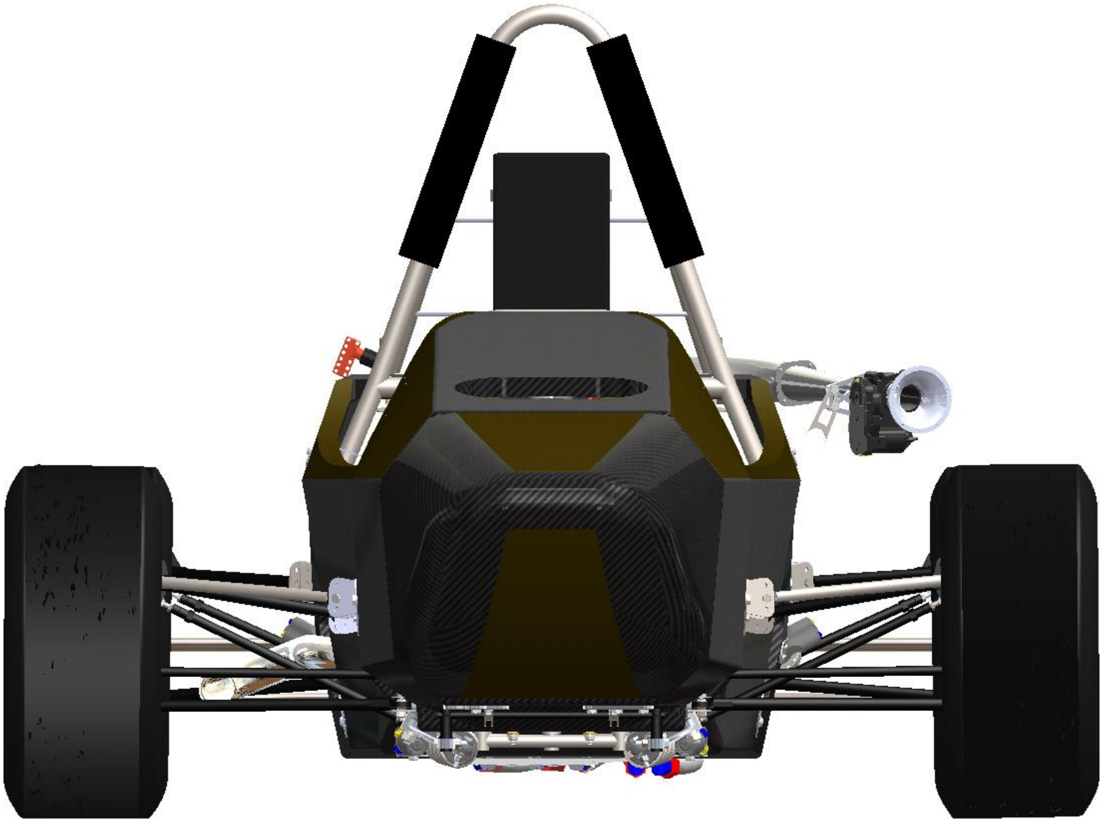


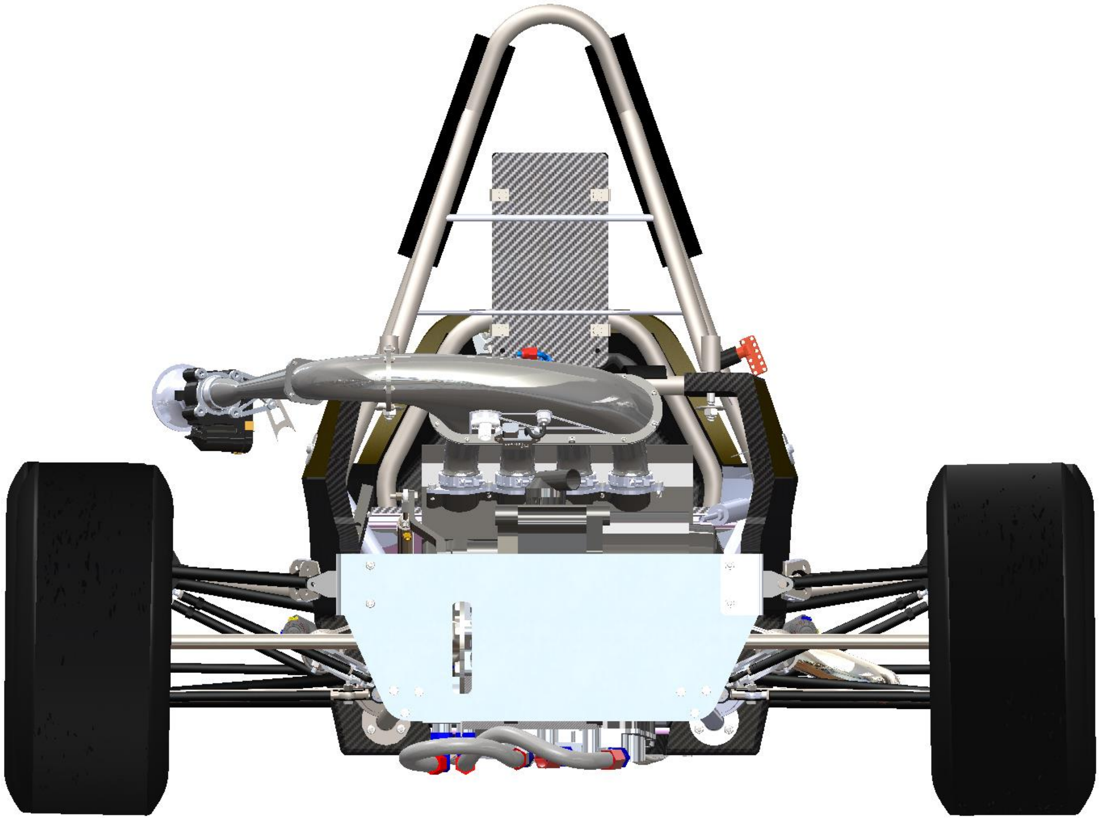
Appendix D – Vehicle Renders

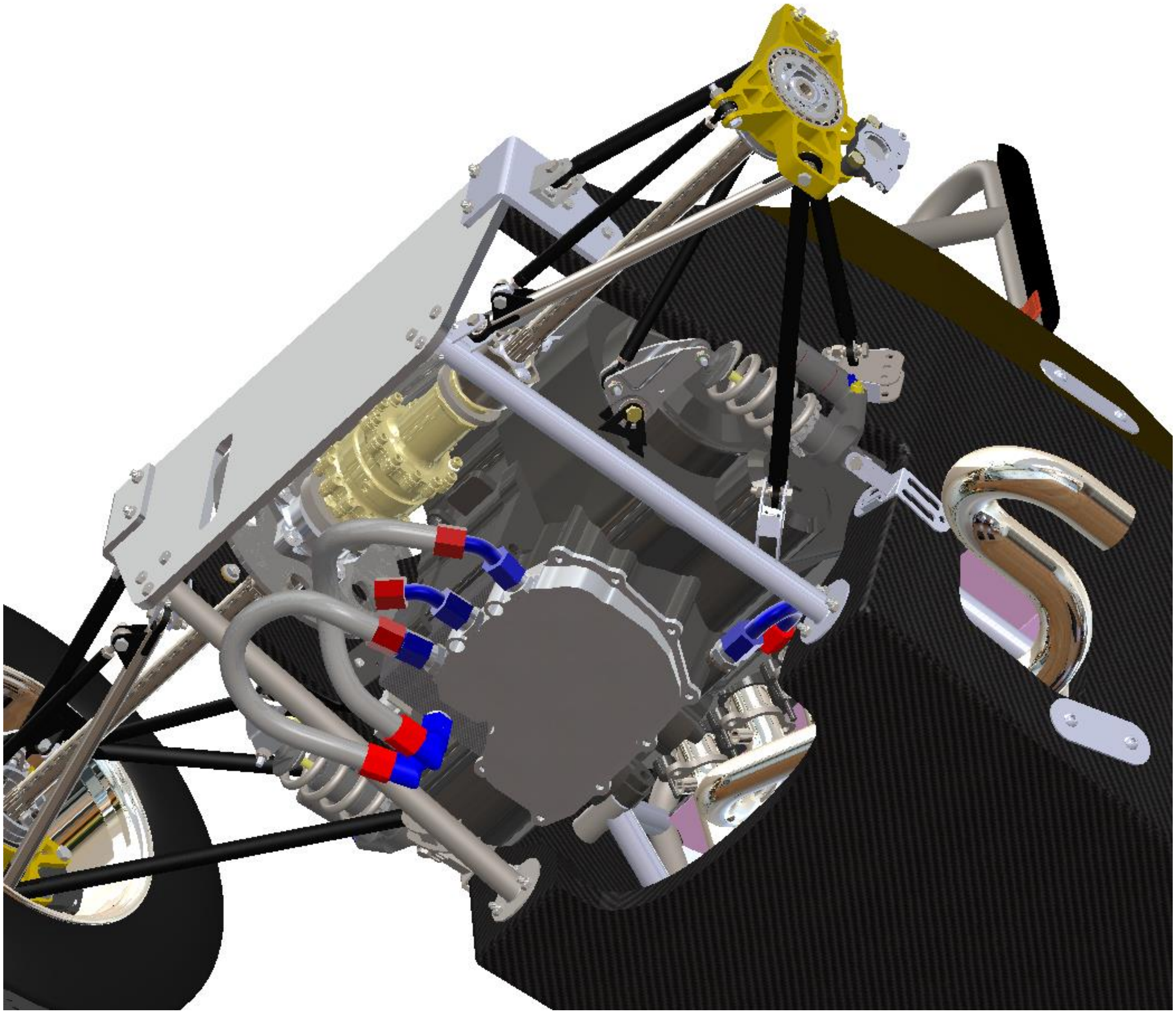


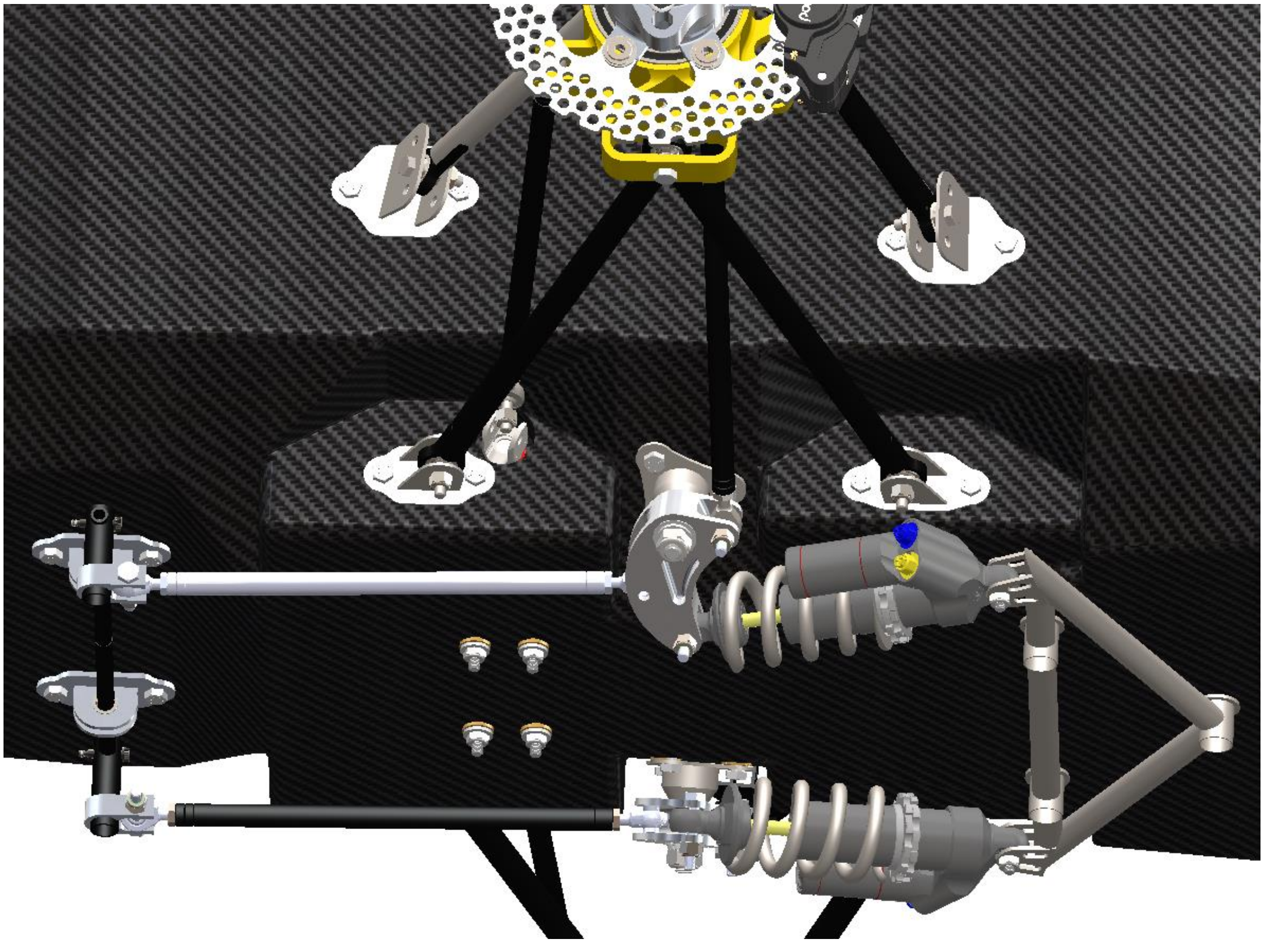


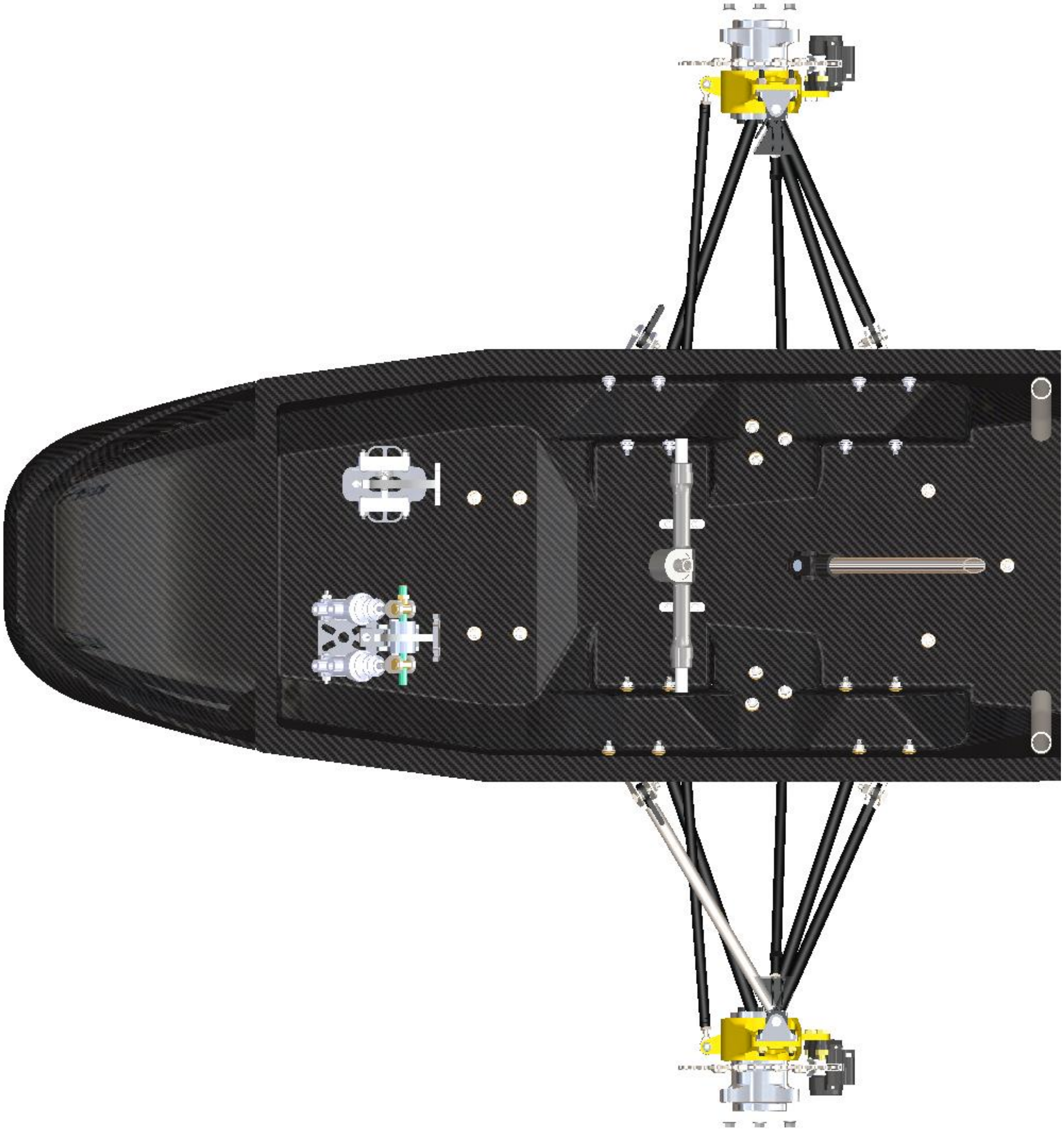






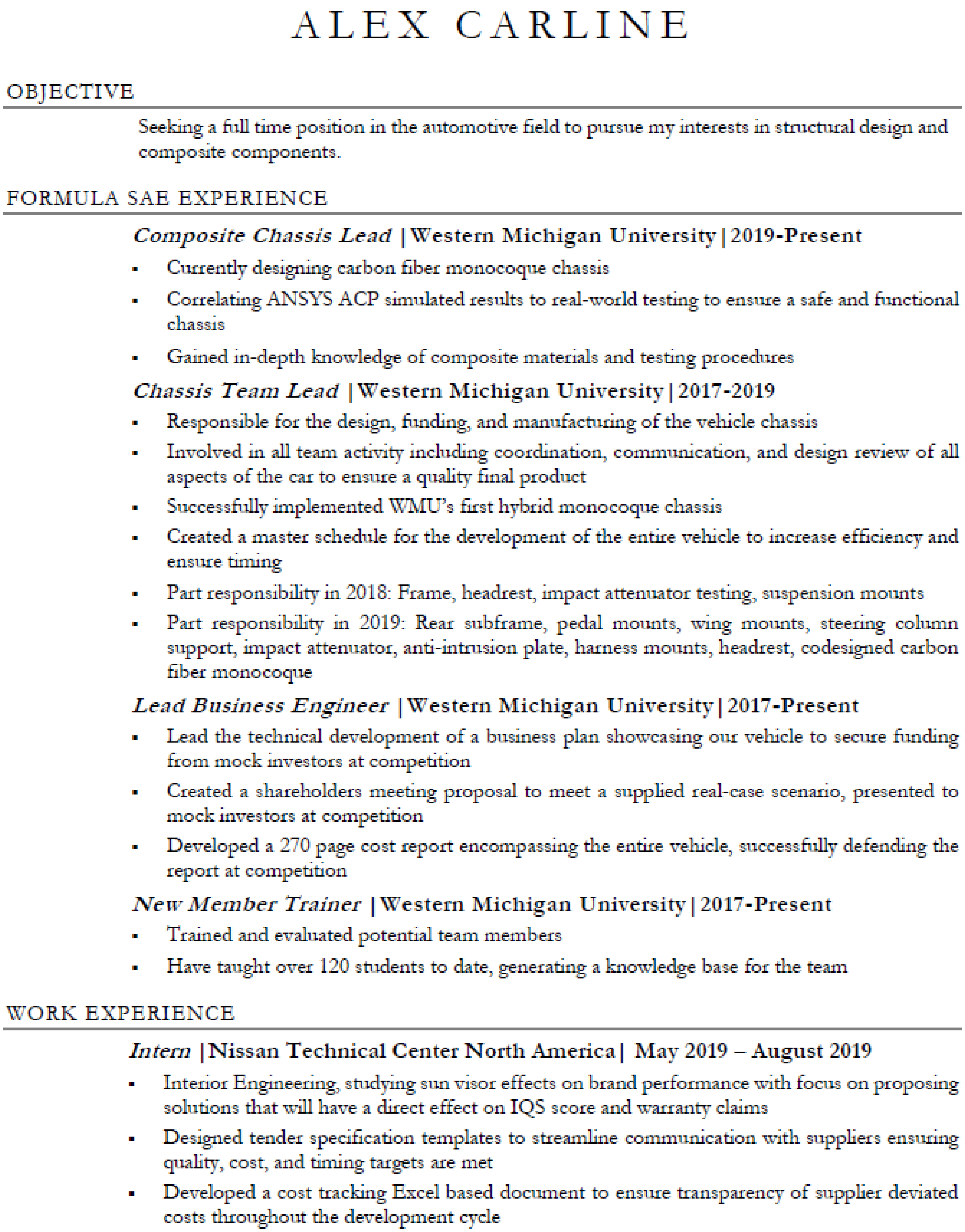






Top Section Cut Inside View

Appendix E – Resumes



ALEX CARLINE

OBJECTIVE

Seeking a full time position in the automotive field to pursue my interests in structural design and composite components.

FORMULA SAE EXPERIENCE

***Composite Chassis Lead* | Western Michigan University | 2019-Present**

- Currently designing carbon fiber monocoque chassis
- Correlating ANSYS ACP simulated results to real-world testing to ensure a safe and functional chassis
- Gained in-depth knowledge of composite materials and testing procedures

***Chassis Team Lead* | Western Michigan University | 2017-2019**

- Responsible for the design, funding, and manufacturing of the vehicle chassis
- Involved in all team activity including coordination, communication, and design review of all aspects of the car to ensure a quality final product
- Successfully implemented WMU's first hybrid monocoque chassis
- Created a master schedule for the development of the entire vehicle to increase efficiency and ensure timing
- Part responsibility in 2018: Frame, headrest, impact attenuator testing, suspension mounts
- Part responsibility in 2019: Rear subframe, pedal mounts, wing mounts, steering column support, impact attenuator, anti-intrusion plate, harness mounts, headrest, codesigned carbon fiber monocoque

***Lead Business Engineer* | Western Michigan University | 2017-Present**

- Lead the technical development of a business plan showcasing our vehicle to secure funding from mock investors at competition
- Created a shareholders meeting proposal to meet a supplied real-case scenario, presented to mock investors at competition
- Developed a 270 page cost report encompassing the entire vehicle, successfully defending the report at competition

***New Member Trainer* | Western Michigan University | 2017-Present**

- Trained and evaluated potential team members
- Have taught over 120 students to date, generating a knowledge base for the team

WORK EXPERIENCE

***Intern* | Nissan Technical Center North America | May 2019 – August 2019**

- Interior Engineering, studying sun visor effects on brand performance with focus on proposing solutions that will have a direct effect on IQS score and warranty claims
- Designed tender specification templates to streamline communication with suppliers ensuring quality, cost, and timing targets are met
- Developed a cost tracking Excel based document to ensure transparency of supplier deviated costs throughout the development cycle

***Intern* | Nissan Technical Center North America | May 2018 – August 2018**

- Vehicle Program Management Group, responsible for organizing the introduction of a halo model vehicle in a foreign market
- Required strong coordination of a large cross-functional team to meet project timing
- Used communication skills to compile high level information for executive level meetings
- Performed dynamic vehicle evaluations to benchmark competitor vehicles
- Compiled a project investment estimating tool using various existing tools and templates in Excel

***Intern* | Nissan Technical Center North America | May 2017 – August 2017**

- Worked in Engineering Strategy, Planning, and Administration, specifically in the Intellectual Property Department and Engineering Metric Systems Department
- Gained valuable resource management and multitasking skills
- Tasks ranged from researching prior art for potential inventions to troubleshooting problems affecting Nissan's engineering workflow

EDUCATION

***Student* | Western Michigan University | 2016-Present**

- Senior, May 2020 Graduation
- Major in Mechanical Engineering with Minor in Mathematics
- Lee Honors College Student
- Member of Tau Beta Pi
- 3.24 GPA

AWARDS

- Dean's Scholarship and Dean's List Award
- Kalamazoo Antique Auto Restorer's Club Scholarship
- Mechanical and Aerospace Engineering Merit Scholarships
- West Bloomfield Police Foundation Scholarship
- Research and Project Grants based off Formula SAE Experience

TECHNICAL SKILLS

- Experienced with Solidworks and ANSYS ACP
- Competent in NX, SpaceVision, and AutoCAD
- Familiar with MATLAB and Romax
- Proficient in Windows 7, Windows 10, and Microsoft Office

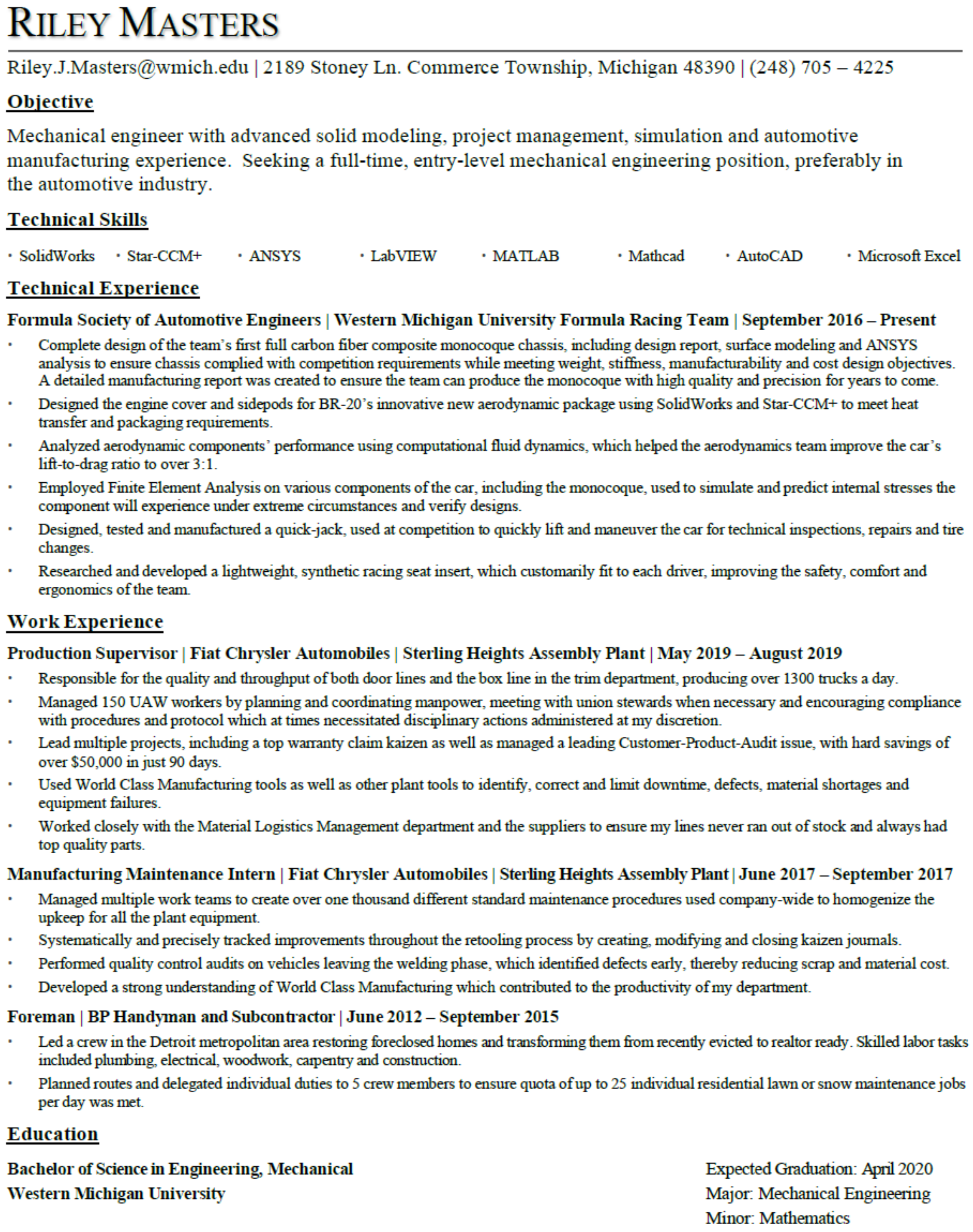
View my LinkedIn Page

HOBBIES

- Currently designing and building a custom RV from a Dodge Sprinter 3500
- Uniquely modifying my Infiniti G37x

ALEXCARLINE89@GMAIL.COM

912 WEAVER AVE • KALAMAZOO, MI 49006 • 248-520-1010



Riley Masters

Riley.J.Masters@wmich.edu | 2189 Stoney Ln. Commerce Township, Michigan 48390 | (248) 705 – 4225

Objective

Mechanical engineer with advanced solid modeling, project management, simulation and automotive manufacturing experience. Seeking a full-time, entry-level mechanical engineering position, preferably in the automotive industry.

Technical Skills

· SolidWorks · Star-CCM+ · ANSYS · LabVIEW · MATLAB · Mathcad · AutoCAD · Microsoft Excel

Technical Experience

Formula Society of Automotive Engineers | Western Michigan University Formula Racing Team | September 2016 – Present

- Complete design of the team's first full carbon fiber composite monocoque chassis, including design report, surface modeling and ANSYS analysis to ensure chassis complied with competition requirements while meeting weight, stiffness, manufacturability and cost design objectives. A detailed manufacturing report was created to ensure the team can produce the monocoque with high quality and precision for years to come.
- Designed the engine cover and sidepods for BR-20's innovative new aerodynamic package using SolidWorks and Star-CCM+ to meet heat transfer and packaging requirements.
- Analyzed aerodynamic components' performance using computational fluid dynamics, which helped the aerodynamics team improve the car's lift-to-drag ratio to over 3:1.
- Employed Finite Element Analysis on various components of the car, including the monocoque, used to simulate and predict internal stresses the component will experience under extreme circumstances and verify designs.
- Designed, tested and manufactured a quick-jack, used at competition to quickly lift and maneuver the car for technical inspections, repairs and tire changes.
- Researched and developed a lightweight, synthetic racing seat insert, which customarily fit to each driver, improving the safety, comfort and ergonomics of the team.

Work Experience

Production Supervisor | Fiat Chrysler Automobiles | Sterling Heights Assembly Plant | May 2019 – August 2019

- Responsible for the quality and throughput of both door lines and the box line in the trim department, producing over 1300 trucks a day.
- Managed 150 UAW workers by planning and coordinating manpower, meeting with union stewards when necessary and encouraging compliance with procedures and protocol which at times necessitated disciplinary actions administered at my discretion.
- Lead multiple projects, including a top warranty claim kaizen as well as managed a leading Customer-Product-Audit issue, with hard savings of over $50,000 in just 90 days.
- Used World Class Manufacturing tools as well as other plant tools to identify, correct and limit downtime, defects, material shortages and equipment failures.
- Worked closely with the Material Logistics Management department and the suppliers to ensure my lines never ran out of stock and always had top quality parts.

Manufacturing Maintenance Intern | Fiat Chrysler Automobiles | Sterling Heights Assembly Plant | June 2017 – September 2017

- Managed multiple work teams to create over one thousand different standard maintenance procedures used company-wide to homogenize the upkeep for all the plant equipment.
- Systematically and precisely tracked improvements throughout the retooling process by creating, modifying and closing kaizen journals.
- Performed quality control audits on vehicles leaving the welding phase, which identified defects early, thereby reducing scrap and material cost.
- Developed a strong understanding of World Class Manufacturing which contributed to the productivity of my department.

Foreman | BP Handyman and Subcontractor | June 2012 – September 2015

- Led a crew in the Detroit metropolitan area restoring foreclosed homes and transforming them from recently evicted to realtor ready. Skilled labor tasks included plumbing, electrical, woodwork, carpentry and construction.
- Planned routes and delegated individual duties to 5 crew members to ensure quota of up to 25 individual residential lawn or snow maintenance jobs per day was met.

Education

Bachelor of Science in Engineering, Mechanical	Expected Graduation: April 2020
Western Michigan University	Major: Mechanical Engineering
	Minor: Mathematics

Mitchell N. Hiller

7456 Westlane Ave. 616.240.9002
Jenison, MI 49428 mitchell.n.hiller@wmich.edu

EDUCATION

Bachelor of Science in Engineering Expected Graduation Date: Spring 2020
Western Michigan University – Lee Honors College Kalamazoo, MI
Major: Mechanical Engineering Current GPA: 3.64
Minor: Mathematics
Senior Design: Design of a Carbon Fiber Composite Monocoque Chassis for a Formula-Style Vehicle

WORK EXPERIENCE

Engineering Intern December 2018 – Present
Tubelite Inc. Walker, MI

- Evaluate architect or shop window drawings to recommend the storefront or curtainwall framing system that meets the customer's structural needs and design objectives.
- Answer customer's technical questions about storefront and curtainwall systems by phone and email.

Seasonal Groundskeeper May 2016 – August 2018
Eenhoorn LLC Grand Rapids, MI

- Assisted groundskeeper with tasks including daily trash run, daily plant watering, and pressure washing to ensure grounds upkeep.
- Conducted daily pool checks to test chemical levels and check pool gauges to ensure pool was operating properly.

Dining Student Employee September 2016 – April 2017
WMU Dining Services Kalamazoo, MI

- Employed time-management and multi-tasking skills to clean dishes and restock dining area in a timely manner.
- Assisted chefs with preparation of food utilizing organization skills to manage assigned area and keep area clean.

SCHOLARSHIPS, AWARDS, AND HONORS

Tau Beta Pi Engineering Honors Society	Spring 2019 – Present
Lee Honors College	Fall 2016 – Present
General Dynamics Land Systems Academic Excellence Award	Fall 2018
Mechanical and Aerospace Merit Scholarship	Fall 2017, 2018, 2019
Dean's List	Fall 2016, Fall 2017, Spring 2018, Fall 2018
College of Engineering and Applied Science Scholarship	Fall 2017
Dean's Office Scholarship	Fall 2016
CEAS Excellence Award Scholarship	Fall 2016

ACTIVITIES

WMU Formula SAE 2018 – Present

SOFTWARE PROFICIENCY

- AutoCAD
- Microsoft Office
- Windows OS
- LabVIEW
- Solidworks
- Matlab
- Maple
- Romax

Appendix F – ABET Outcomes

Outcome (2) An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

Performance Indicators:

1. Generates a detailed statement of all the specified engineering needs for the design project.
2. Identifies and lists potential public health, safety and welfare concerns for consideration in the design process.
3. Identifies and lists global, cultural, social, environmental and economic factors that are relevant to the development of the project product.
4. Produces solutions that satisfy the engineering needs, address the public concerns and consider the effects of the relevant design factors.

(If you copy and paste from the report, mention Section number or page numbers. If any question or item is not relevant to your project, write N/A)

Performance Indicator 1

Describe the engineering needs for this project.

The engineering need for this project is to design a carbon fiber composite monocoque chassis for the WMU Formula SAE Team's formula-style vehicle. This design must improve upon the performance of the previously designed monocoque to allow the team to remain competitive.

List the project goals along with performance criteria.

- Light weight design, reducing weight from previous monocoque
- Easily manufacturable through design considerations and a manufacturing plan
- Ergonomic design, improve ergonomics for driver from previous monocoque

List the project constraints.

- Budget/Cost
- Geometrical constraints from other vehicle subsystems
- Design must adhere to the Formula SAE Rules

List the methods/procedures that were implemented to ensure that the customer expectations were addressed.

- Identified improvements from previous design to be made before redesigning
- Ranked the importance of these improvements
- Throughout design process, designs were checked by whole design team to assure improvements were being
- Periodic updates of design were presented to WMU Bronco Racing Team for feedback

Performance Indicator 2

Describe potential public health, safety, and welfare concerns regarding this project and describe how they were addressed in the final design.

Public health: N/A

Public safety: Failure of the design could lead to injury of driver and observers around him, so testing and simulations were conducted to ensure safety factors are implemented into design.

Public welfare: N/A

Performance Indicator 3

List and explain all possible global, cultural, social, environmental, and economic factors relevant to the product of this project.

Global factors: N/A

Cultural factors: N/A

Social factors: N/A

Environmental factors: N/A

Economic factors: WMU Formula SAE Team, Bronco Racing, must adhere to a budget and any costs are also taken into account at competition. An economical design was taken into consideration during the design process without sacrificing performance or safety.

Performance Indicator 4

(To be addressed by the faculty adviser).

ABET student outcome 4:

An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental and societal contexts.

Performance Indicator #2: student is able to make informed judgments based on the impact of engineering solutions in global, economic, environmental and societal context.

ME4800 Assessment of PI #2

(to be completed by students and included in the ABET Appendix of the final report)

Did you adapt your project to make it useful in many countries? **N/A** If yes, explain:

Did you consider standards and regulations, either U.S. or international? **Yes** If yes, explain how they affected your project:

The design adheres to the design constraints laid out in the Formula SAE Rules. See Rules Equivalence sections for compliance with constraints.

Did you consider the effects of manufacturing in various locations? **N/A** If yes, where in the report did you address this issue?

Did you have to balance effects of costs and performance? **No** If yes, explain and refer to the report as appropriate

Did you consider effects of maintenance, failure and repair on cost, safety, etc.? **N/A** If yes, where in the report did you address them?

What were your considerations (e.g., cost, weight, manufacturing, availability, safety, recycling, etc.) in the selection of materials? List, explain and refer to the text of the report as appropriate.

- Cost
- Availability
- Strength
- Weight
- Manufacturing

Cost and availability were the main concerns in selection of material, which are dependent on sponsors available to Bronco Racing and their budget. Weight and strength were the next consideration, which were important to our design of a light and strong carbon fiber composite monocoque. Also, the ability of Bronco Racing to manufacture the monocoque using these materials were considered. Also, see the Material Selection section of the report.

Does your project impact air quality, water quality, noise levels, and other environmental aspects? **N/A** If yes, explain how and show what were your actions.

Does your project impact human health during manufacturing or normal use? **N/A** If yes, explain what you did to alleviate the risks.

Are there any other safety issues typical to your project? **Yes** If yes, explain your decisions and actions. Refer to the report as appropriate.

Failure of the design could lead to injury of driver and observers around him, so testing and simulations were conducted to ensure safety factors are implemented into design. Testing is addressed in the Testing section of the report and simulation is addressed in the Design by Region section of the report. Also, the safety factor is addressed on the Minimum Safety Factor section of the report.

Outcome (5) An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks and meet objectives

Performance Indicators:

1. Student's ability to function effectively
2. Student provides task specific leadership.
3. Student creates a collaborative and inclusive environment.
4. Group establishes goals.
5. Group plans tasks
6. Group meets objectives.

(If you copy and paste from the report, mention Section number or page numbers.)

Performance Indicators 2 & 5
List all tasks required to accomplish the goals of this project, and name the group member responsible for the completion of each task.

- Surface Modeling – Riley Masters
- ANSYS simulating – Alex Carline
- Material selection and testing – Mitchell Hiller

Performance Indicator 1
(Project's adviser will determine whether the listed tasks were completed).

Every student must answer the following question (add Student 3 & 4 if needed):

Alex Carline:
For project tasks in which I was **not** the leader, I provided the following inputs towards their completion: I would recommend solutions and methods from previous experience. For geometrical solutions, I would recommend solutions found through previous knowledge of other Formula SAE teams. I would also provide known Solidworks tricks and tips. For material data and testing, I would use previous knowledge gained from running composite testing on the Formula SAE vehicle.

Mitchell Hiller:
For project tasks in which I was **not** the leader, I provided the following inputs towards their completion: I provided help with geometrical issues based of previous knowledge from Formula SAE. I also provided help with the ANSYS simulation by providing calculations of material properties needed for the simulation.

Riley Masters:
For project tasks in which I was **not** the leader, I provided the following inputs towards their completion: I provided intuitive geometric solutions based off previous Formula SAE and monocoque manufacturing experience. I also helped support the decisions of our material lead by

providing insight to problems and suggesting alternate solutions when necessary. Finally, I created the complete surface model of the monocoque to be simulated in ANSYS.

Performance Indicator 3

For project tasks in which you **were** the leader, describe the input other group members provided towards the successful completion of these tasks.

Alex Carline: For the ANSYS design validation, the material properties came from calculations conducted by Mitchell. The actual base surface of the monocoque that was modified to be imported into ANSYS was created by Riley.

Mitchell Hiller: For material selection and testing, both Riley and Alex provided advice and solutions for the what materials were best and best testing methods.

Riley Masters: Alex and Mitch both helped provide input for the surface modeling. They would not only suggest solutions to surface modeling problems but also geometric constraints. Alex created the master CAD model as well as the roll hoops, mounts and firewall.

Performance Indicator 4

List all goals this project had to satisfy to be considered successfully completed.

- Modeling of monocoque geometry
- Simulation of monocoque in ANSYS
- Selecting of materials and testing
- Creation of manufacturing process

Performance Indicator 6

(To be addressed by the faculty adviser)

Outcome (7) An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Performance Indicators:

1. Student's ability to find information relevant to problem solution without guidance.
2. Student's ability to identify the additional knowledge needed to complete project.
3. Student's ability to acquire and apply the additional knowledge needed to complete project.

Performance Indicator 1

Describe what information you found in order to successfully complete the tasks you were assigned in the project.
Alex Carline: Information was needed regarding the suspension load case. These values were provided by the Formula SAE team. Additionally, CAD was needed of the Formula SAE vehicle. Much of this was created by me, however a large portion of items came from other people on the Formula SAE vehicle.

Mitchell Hiller: Found testing data of materials to help find material properties and discover methods for testing of materials. Also, found material properties and specs on manufacturer provided data information sheets.

Riley Masters: In order to complete the surface modeling of the full-monocoque, I first found the CAD drawing from our previous half-monocoque design as well as other schools full-monocoque designs. The helped give me an idea how to model a monocoque as well as some of the important features to pay extra attention to.

What sources did you use to find this information?
Alex Carline: WMU Formula SAE Team's information

Mitchell Hiller: Databases of research reports and material data sheets on manufacturing websites

Riley Masters: WMU Formula SAE Team's information. As well as from talking to other teams at competition.

Performance Indicator 2

Describe what additional knowledge/skills you needed to acquire or improve in order to successfully complete the tasks you were assigned in the project.
Alex Carline: Additional knowledge was needed in ANSYS Workbench. I had previous experience using this software, but the complexity of the simulations led to having to learn a few new things.

Mitchell Hiller: Applying material knowledge learned in classes to real materials. Also, learning installation processes of different materials and how they will work with our design.

Riley Masters: Additional and advanced SolidWorks surface modeling skills and techniques were needed.

Performance Indicator 3

Describe what approach/process you followed in order to acquire or improve the additional knowledge/skills you needed.
Alex Carline: I used the ANSYS Workbench online help guide as WMU does not provide an ANSYS based structural design course. Additionally, I referenced older simulations I had done on simpler designs to find shortcuts in the long setup process of ANSYS ACP Pre stage.

Mitchell Hiller: Researching information from others research and manufacturer's sites. Trial and error method and research on calculation methods to apply class information to actual materials.

Riley Masters: I started by using the SolidWorks help tutorial guide to learn as much about surface modeling as possible. I have previous experience surface modeling in SolidWorks, but this project required extra skills. To learn some of those extra skills, online resources like Reddit, YouTube and other tutorial websites were utilized as well as SolidWorks forums and tutorials.