FSAE Chassis Hardpoint Optimization

Final Design Review

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Abstract

Our team has been tasked with optimizing hardpoints for the Cal Poly Racing team. Hardpoints are the locations on the chassis of a car that are designed to carry both internal and external loads, they are the areas where the engine and suspension connect to the chassis. These points are subject to torsion, shear, bending and pull-out loads. Cal Poly Racing needs more thoroughly analyzed individualized hardpoints that are optimized for weight, strength and specific stiffness, so they can reduce the overall weight and improve the race times of the vehicle while maintaining their strength and stiffness standards. Our team has reviewed past projects, research papers, and test results to gain a strong understanding of hardpoints. Our goal was to design a hardpoint that minimizes weight while maintaining the strength and stiffness standards of Cal Poly FSAE. After changing our point of contact on the team and learning about the cancelation of a physical race car during the course of the project the design scope changed. Designing hardpoints for specified loads became less important, as the loads had become obsolete. More importance was placed on testing materials and acquiring data. Specifications were added, including designing a jig for multiple tests to be run on hardpoints and testing expired laminates to get more accurate test data, as the original datasheets aren't accurate.

We created a final hardpoint design that will need to be tested in the future. The material choices made are listed in the report, as well as testing data for laminates we obtained. Additionally, since our sponsor no longer had a suitable jig to test hardpoints inlaid into sandwich panels, we designed a new jig that would be used to test hardpoints and validate the design choices made.The jig has the ability to hold 10”x12”x1” sandwich panels at various angles and both shear and pullout tests. Our jig was designed using beam stress analysis and computer aided finite element analysis. Finally, the recommended tests and analysis for picking the final hardpoints is addressed. Shear and pullout tests at different angles must be performed to determine core puck size and insert choice. Insert and potting radius sizing will likely have to be reiterated after testing to produce the ideal final hardpoint design.

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1. Introduction

Each year, the Cal Poly Racing team participates in the Formula Society of Automotive Engineers (FSAE) collegiate design series where they design and build two race cars: one electric powered and one fuel powered. Members are split into different sub-teams, each specializing in one system within each car. The chassis team in the previous years designed a full carbon fiber reinforced polymer monocoque. This chassis consists of hardpoints that connect it to vital parts of the vehicle like the engine and suspension. Minimal research has been done to optimize these hardpoints, therefore a full scale redesign of these hardpoints has been requested by the team. This report documents our progress, testing results and findings so that the Cal Poly Racing Team can use the most effective hardpoint design found. Although the in-person portion of the competition was canceled for the 2020/21 year, we hope our hardpoint designs will be a helpful cornerstone in developing hardpoints for future competitions.

We have familiarized ourselves with hardpoints by looking through research papers, handbooks, and past Cal Poly FSAE projects to gain solid background knowledge. In our background section, we outline the different parts of a hardpoint including the laminate, core, potting material, and inserts. We discuss the different types of loads experienced by each part of the hardpoint, and various materials that may be used for each part. Applicable FSAE codes and regulations are also listed, along with common hardpoint failure modes. Finally, we review what research has already been done by the Cal Poly Racing Team in previous years regarding hardpoints.

The Objectives section of the report outlines a general scope of our project. A description of the sponsor’s wants and needs from our group as well as our established problem statement is included. A boundary diagram shows what kind of work is in the scope of our project, and the specification chart puts the sponsors wants and needs into technical terms with specific values. Our concept development section describes our ideation process from start to finish. The final design testing plan is described in the idea selection section. This section shows which materials need to be tested, and the testing parameters. Finally, the project management section describes our final quarter of work and the required testing needed to verify the designs.

2. Background

Composite sandwich panels are commonly used to provide structural support in the aerospace, marine, automobile and construction industries. Uniform structural materials like steel or concrete have excellent specific properties (tensile strength for steel, compressive strength for concrete) while severely lacking in other aspects (compressive strength for steel, tensile strength for concrete). Composite sandwich panels, on the other hand, were created to blend the ideal properties of multiple materials for the benefit of a reliable, lightweight, all around structurally sound apparatus. Sandwich panels typically consist of two thin “skin” sheets of material with a thicker core material. Typically the core material provides stiffness, rigidity, and resistance to shear for the structure, while the skins absorb compressive and tensile loads.

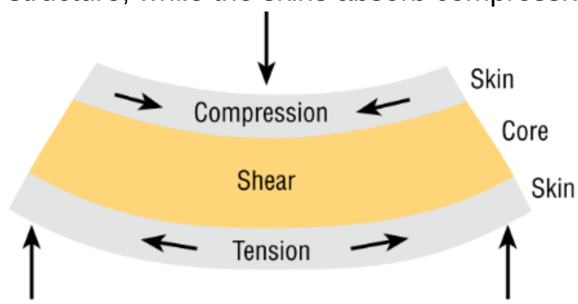


Figure 1. Diagram of different types of sandwich panel loading.

Flexural stiffness of a panel is proportional to the cube of its thickness. Some common examples of composite sandwich panel materials are carbon fiber coated in resin, skin sheets bonded with epoxy, hollow aluminum core composed of small hexagonal shaped cells, and epoxy adhesives to bind the pieces together. For the purpose of this senior project, some variation of composite materials will be used to mount particular fixtures to the chassis of the FSAE car. Examples of the various fixtures are the suspension mounting brackets, as well as engine mounting brackets/bolts. These mounting points are called hardpoints and are specific locations along the vehicle chassis that incur direct stress concentrations. The hardpoints serve as a way of attaching outside vehicle components to the chassis. Typically aluminum inserts placed within the sandwich panel allow threaded bolts to connect parts to the chassis. Aluminum inserts may go entirely through the composite sandwich panel or simply penetrate partially into the panel. Regardless the inserts must be securely held in place by potting compound (typically epoxy) . Every aspect of the composite panel serves a purpose of withstanding loads. The components of the composite panels contribute to the strength, stiffness, and durability of the panel. However, as with any design there are tradeoffs.

Table 1. Impacts of different load types on various sandwich components.

Load Type	Contribution of Sandwich Component to Inserts' Load Capability		
	Core	Facing Sheet	Core/Facing Bonding
Tension	major	medium	very little*
Compression	major	medium	little
Shear	little	major	very little*
Bending	major	medium	little
Torsion	major	little	little

Table 1 shows the qualitative load contribution to sandwich panels and the effect of inserts load capability. Table 1 is a good example of showcasing how components of the hardpoint work together. An example of information provided by Table 1 is that core material has major contributions to an inserts ability to withstand bending load. Whereas the core bonding offers little contribution to an inserts ability to withstand bending load. It is important to keep in mind that there are many commercial options for each component of the sandwich panel. The varieties offer a wide variety of characteristics. For example, some components such as the laminate material listed below in Table 2 may be able to withstand greater tensile loads, but weigh significantly more than other options.

Table 2. Material properties of common sandwich panel materials.

Material Type (MPa)	Tensile Str. (GPa)	Tensile Modulus (g/cc)	Typical Density Modulus	Specific
Carbon HS	3500	160 - 270	1.8	90 - 150
Carbon IM	5300	270 - 325	1.8	150 - 180
Carbon HM	3500	325 - 440	1.8	180 - 240
Carbon UHM	2000	440+	2.0	200+
Aramid LM	3600	60	1.45	40
Aramid HM	3100	120	1.45	80
Aramid UHM	3400	180	1.47	120
Glass - E glass	2400	69	2.5	27
Glass - S2 glass	3450	86	2.5	34
Glass - quartz	3700	69	2.2	31
Aluminium Alloy (7020)	400	1069	2.7	26
Titanium	950	110	4.5	24
Mild Steel (55 Grade)	450	205	7.8	26
Stainless Steel (A5-80)	800	196	7.8	25
HS Steel (17/4 H900)	1241	197	7.8	25

Table 2 lists some examples of tensile properties of commonly used laminate materials. The tensile strength of various materials such as carbon, aramid, fiberglass, and several metals and alloys are listed. Pros and cons of panel components must be considered to achieve a desired goal. An example of a laminate skin that would not be ideal for this project is polyester/glass woven laminate skin which undergoes micro cracking at 0.2% strain, with ultimate failure occurring at 2% strain. This laminate is only usable at 10% of the ultimate strength. However, polyester laminate is considerably cheaper than carbon laminates. Therefore polyester/glass woven laminate skins may have a practical purpose where the panel may not be under much strain. This option may serve its designed purpose while saving the manufacturer material expenses.

The goals of this project, provided by the sponsor, are to develop suitable hardpoints that can tolerate loads that the vehicle will have to endure throughout racing, maintain specified stiffnesses, and be as light as possible. Other design considerations are important such as manufacturability, durability (life expectancy), and compatibility with other design aspects such as vehicle chassis. These project considerations are to be accounted for, however, they are not as fundamentally important as the aforementioned specifications.

<u>Laminates:</u> Misalignment of fibers in the laminate causes dramatic loss of mechanical properties particularly in compression. When it comes to impact damage S-glass yard 6781 and Aramid skin sheets are more resistant to damage and are cheaper than their carbon fibre counterparts.

Hybrid Aramid/glass fibers have a lower density and higher impact resilience and come at a lower cost than strictly carbon sheets. Impact damage on laminates and hardpoints was previously ignored in other designs. Unforeseen adverse road conditions may produce impact forces which hardpoints throughout the vehicle could be subjected to.

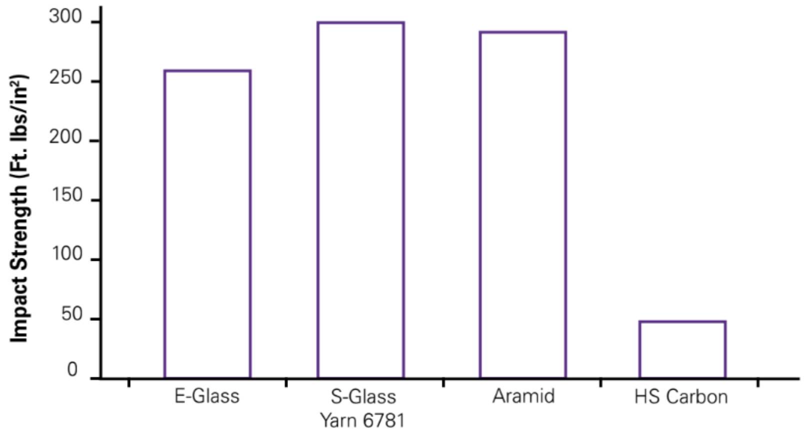


Figure 2. Laminate Impact Strength for different materials

Exposure due to heat radiation causes the composite coupons to expand significantly more than fabric coupons. Resin typically decomposes around 280 degrees celsius. Cytec BMI fabric and Cytec epoxy Fabric are not ideal under high temperature conditions because they lose more mass than other options. Bismaleimide coupons stay ignated on average two minutes longer than their epoxy counterparts but still maintain less mass loss. These heat tests were performed by using a heating plate 5.5 inches away from sample panels. The heat plate was between 800-1000 degrees celsius. Another heat test was done with a perpendicular piloted flame that was much closer to the samples. The relevance of heat tests for this project is location and temperature of hardpoints within the engine bay of the vehicle. (Sandia Report)

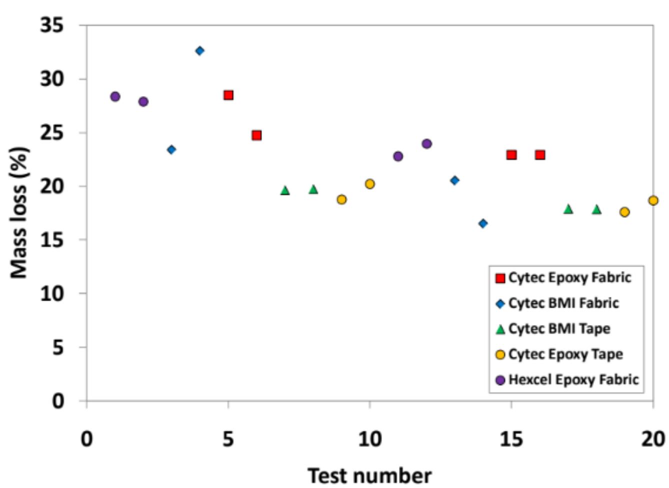


Figure 3. Mass percent loss for different test samples

Cores: A potential core material selection could be Nomex or Aluminum hexagonal shaped honeycomb. These cores tend to be less dense than other options which would reduce the overall weight of the hardpoints. Aluminium honeycomb produces one of the highest strength/weight ratios of any structural material. Nomex honeycomb is made from Nomex fiber which is based on kevlar. Nomex honeycomb is becoming increasingly used in high-performance non-aerospace components due to its high mechanical properties, low density and good long-term stability. However, as can be seen from Figure 4, it is considerably more expensive than other core materials. (GURIT). Through thorough research and understanding of FSAE material donating sponsors we have decided to investigate Hexcel aluminum core materials. Hexcel offers the current Cr3 core which is an aluminum hexagonal honeycomb core currently used by the FSAE club as a rigid core material. The current hardpoint design utilizes a circular puck of high density aluminum honeycomb core set into the low density aluminum honeycomb using a core splice. The low density aluminum honeycomb is used for the rest of the chassis to save weight and the high density core is used at the location of the hardpoints to add additional strength and stiffness at areas of high stress.

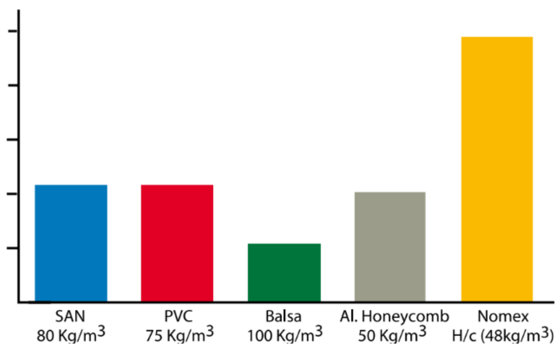


Figure 4. Comparative Core Costs For Commonly Used Materials.

Inserts: Inserts are hollow cylindrical bodies with flanged edges is the standard configuration. Inserts typically come in two varieties. A half spool, and full spool shape. Previous hardpoint designs for FSAE used the half spool shape due to ease of assembly.

Figure 5. Examples of Spool and Half Spool Inserts

Figure 5 are examples of a full spool and half spool insert. This image was used during the Chassis 2017 senior project report to illustrate the benefits of each. The 2017 team decided against the full spool design due to increased difficulty in manufacturing without significantly increasing load carrying capabilities. Inserts are “locked” into the sandwich panel with a potting compound. The flanges on the top and bottoms of the inserts prevents applied loads only being transferred by adhesion shear forces between the insert and potting material. Inserts are typically made from aluminum alloy AA 2024 but for improved strength. TiAl6v4 (titanium) may also be used. However, strength of the system is restricted by the strength of the resin/epoxy therefore choosing a more robust material may have limited influence on the effectiveness of the insert. Other insert materials may be used but have tradeoffs. For example, Carbon or stainless steel inserts have limited corrosive properties and are generally heavy. Cadmium plated aluminum inserts have great corrosion resistance properties and are lighter than their steel counterparts. However, Cadmium is a hazardous material requiring special attention to installation and disassembly. Flushed inserts are better for heat transfer than countersink inserts. The insert’s capability under tensile and compressive loading is influenced by the bending stiffness of the faceing sheets. The higher the bending stiffness of the facings compared with the shear stiffness of the core, the higher the load contribution of the facing sheets.

<u>Potting materials:</u> Potting materials can withstand far greater compressive loads than tensile loads. Typically potting materials can withstand greater compressive loads than the core material of the panel. Core fails over potting material for compression where potting material fails typically occur in tension. Insert diameter will increase tensile loads significantly. The difference between a 9mm and a 14mm insert is nearly twice as much static tensile loads before potting fails. Compressive loads increase somewhat, but not significantly. (ESA-PSS-03 Insert Design Handbook)

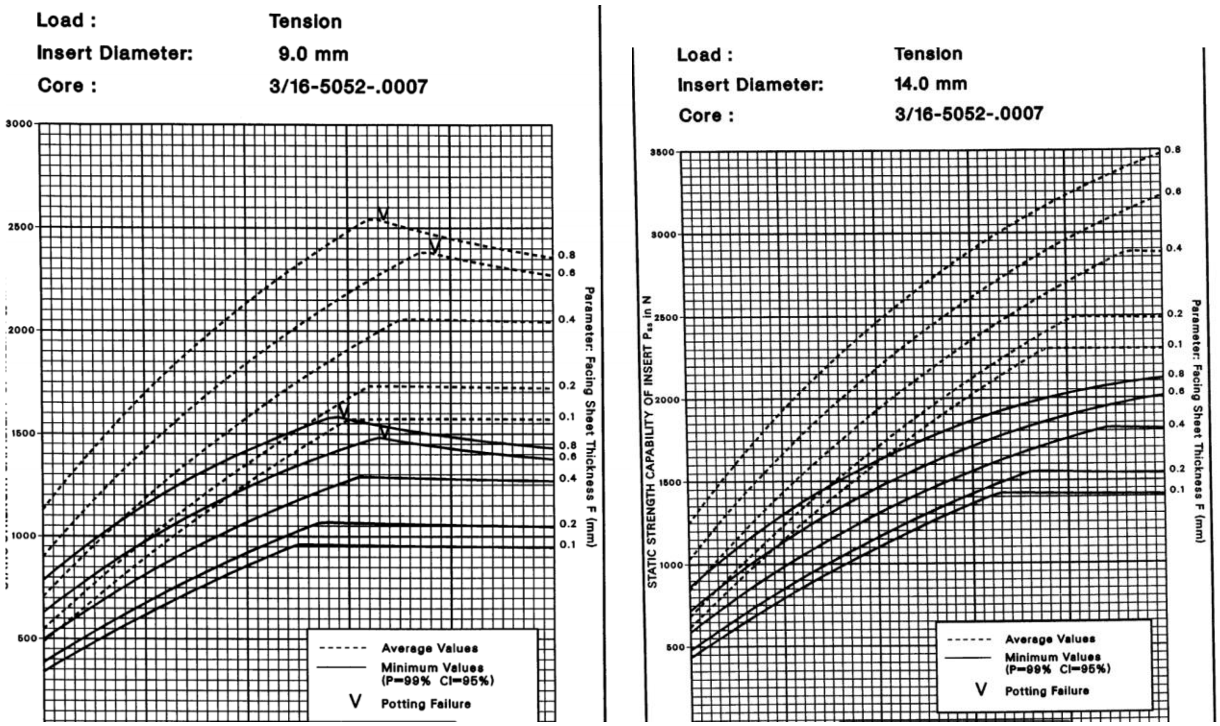


Figure 6. Charts Displaying Increasing Insert Diameter as a Result of Greater Tensile Forces.

An interesting observation as the insert diameter increases the greater tensile forces the potting material can sustain.

Facing sheets Facing sheets are used to protect the inserts from washers and mounting hardware. Facing sheets are added carbon fiber plies added to the surface of the laminate. Usually, facing sheets have no influence on the tensile or compressive load-carrying capability of the insert. Facing sheet thickness increases tensile and compressive loads that the potting material can withstand. Facing sheets are generally small and light enough to not affect the overall weight of hardpoints.

Relevant Patents

Figure 7. Sandwich Panel Schematic.

Title: Sandwich Panel

United States Patent 20070148412

Assignee: Airbus

The invention can be defined in its most general form as a building unit, namely the sandwich panel with light core from corrugated sheet material in the form of zigzag crimp, and can be used in aircraft construction, as well as in shipbuilding and construction. Making use of the claimed invention will improve the weight efficiency, the strength and the manufacturability of the panel.

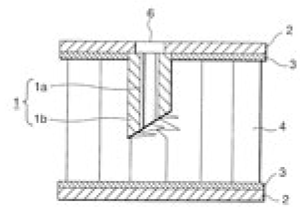


Figure 8. Sandwich Panel Manufacturing Process Schematic.

Title: Sandwich panel and method of manufacturing the sandwich panel

United States Patent 6497082

Assignee: Mitsubishi Denki Kabushiki Kaisha

A sandwich panel is manufactured-by providing: a first step (a), (b) of attaching another end portion of an insert 1 whose one end portion is made sharp to an inner side of a facing member 2 in which a hole is cut in advance.

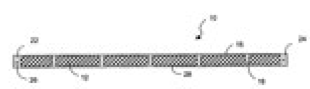


Figure 9. Fiber-Reinforced Sandwich Panel Schematic.

Title: Fiber-reinforced sandwich panel

United States Patent 20050204698

The present invention may be embodied in a sandwich panel having first and second face panels each panel having a first predetermined thickness and being formed of a fiber-reinforced cementitious material. The sandwich panel further includes a support frame for supporting the first and second face panels in a spaced apart configuration.

2017/18 FSAE Codes, Standards, and Regulations

The following FSAE codes, standards, and regulations pertain to this project because they limit/guide to some extent how the hardpoints can be designed/implemented on the FSAE cars. The following codes regard harpoint/mounting visibility, thread “stick out”, mounting point to edge proximity, material quality control, and safety precautions.

T6.1.2 All suspension mounting points must be visible at Technical Inspection, either by direct view or by removing any covers.

T11.1.3 Any bolted joint in the primary structure using either tabs or brackets, must have an edge distance ratio “e/D” of 1.5 or greater. “D” equals the hole diameter. “e” equals the distance from the edge of the hole to the nearest free edge. Tabs attaching suspension members to the primary structure are not required to meet this rule

T11.1.1 All threaded fasteners utilized in the driver’s cell structure, and the steering, braking, driver’s harness and suspension systems must meet or exceed SAE Grade 5, Metric Grade 8.8 and/or AN/MS specifications

T11.2.2 There must be a minimum of two (2) full threads projecting from any lock nut.

T11.2.1 All critical bolts, nuts, and other fasteners on the steering, braking, driver’s harness, and suspension must be secured from unintentional loosening by the use of positive locking mechanisms. Positive locking mechanisms are defined as those that: Positive locking mechanisms include: a. Correctly installed safety wiring b. Cotter pins c. Nylon lock nuts (Except in high temperature locations where nylon could fail approximately 80 degrees Celsius or above) d. Prevailing torque lock nuts 65 © 2016 SAE International. All Rights Reserved 2017-18 Formula SAE® Rules – September 2, 2016 Rev A Lock washers, bolts with nylon patches and thread locking compounds, e.g. Loctite®, DO NOT meet the positive locking requirement.

2.1 Failure Modes

As outlined in “Structurally Optimized and Additively Manufactured Inserts for Sandwich Panels of Spacecraft Structures” by Michael Ferrari, sandwich panels experience seven main failure modes. These failure modes are: failure of the insert, bonding failure of the insert, bonding failure of the sandwich, failure of the potting compound/adhesive foam, failure of the core, failure of the facesheet, and stability failure. Out of these components, the failure of the core is the most likely to occur. This failure is due to shear forces on the core material, and sometimes due to compression or tension in the out of plane direction.

Insert failure is highly unlikely because of its much higher strength compared to the core. Insert bonding failure occurs when the insert and the face sheet separate due to shear. Sandwich bonding failure is when the sandwich panel itself fails. The bonding layer delaminates as a result of facesheet rupture. Potting compound/adhesive foam failure is also very unlikely since it is usually much stronger than the adjacent core. Figure 10 shows examples of different kinds of failure modes. The left picture shows pullout failure due to an out of plane load. The middle picture shows failure due to shear perpendicular to the edge. The right picture shows failure due to shear along the edge. Failure of the facesheet occurs when the facesheet ruptures due to high shear loads or thin facesheet materials. There are a few types of stability failure. One type is when the laminate buckles inside of a single honeycomb cell. The other type is when the laminate wrinkles over a spread of cells and deforms.

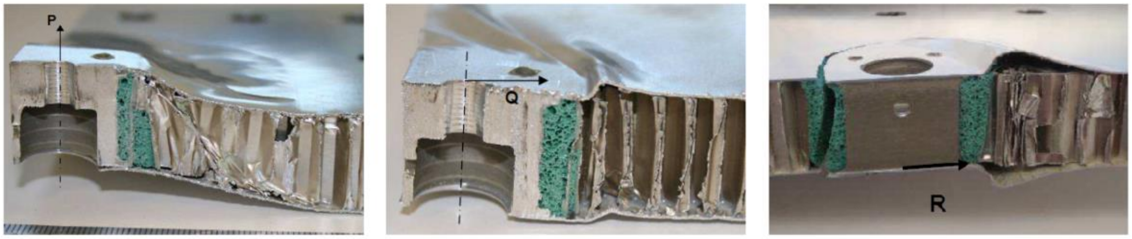


Figure 10. Different Modes of Sandwich Panel Failure.

2.2 Previous Designs

Previous hardpoint designs have been built and tested within the past few years by multiple senior project teams sponsored by Cal Poly Racing. However, these projects mainly focused on the chassis as a whole, and spent minimal time on hardpoints. Reading the previous reports and what methods were used has given us a baseline to start the current hardpoint project.

<u>Formula Monocoque Development (2015)</u>

This senior project team from Cal Poly in 2015 designed a monocoque laminate and impact attenuator to maintain specific stiffness and to reduce weight. Their hardpoint research consisted of testing both balsa wood and aluminum cores. Hardpoint locations on the chassis were unclear which resulted in an overuse of balsa wood in these areas. CLT strength code was used to determine structural integrity of the chassis. This code was part of an iterative process to solve for weight, torsional stiffness, and strength compliance of the chassis. Specifically for hardpoints, the lower suspension was subjected to a 1200 lb in-plane force for testing. The balsa reinforcements proved to excel with both in plane and out of plane loading.


Figure 11. The 2015 Chassis Senior Project Team Inserting Balsa Reinforcements Into the Chassis.

Carbon Fiber Monocoque Chassis Platform for Formula SAE and Formula SAE Electric Race Cars (2017)

The Fast and the Formula senior project team also focused on the chassis as a whole, but contributed some time into hardpoint research. They conducted testing of different core replacement materials, and were the first team to implement spool inserts. Pan downs were also tested and proved to have many disadvantages due to their weight and contribution to loss of stiffness. Use of pan downs would approximately add 2-2.5 lb of weight over the whole monocoque. Garolite reinforcements were also avoided due to weight concerns. Some significant testing with balsa wood and aluminum honeycomb proved that the honeycomb inserts were superior. Core specific compressive strength and core specific shear strength were tested between these two materials, and the honeycomb proved to be the stronger laminate material. This team also did research about half spool design, which would later be used by the next senior project.

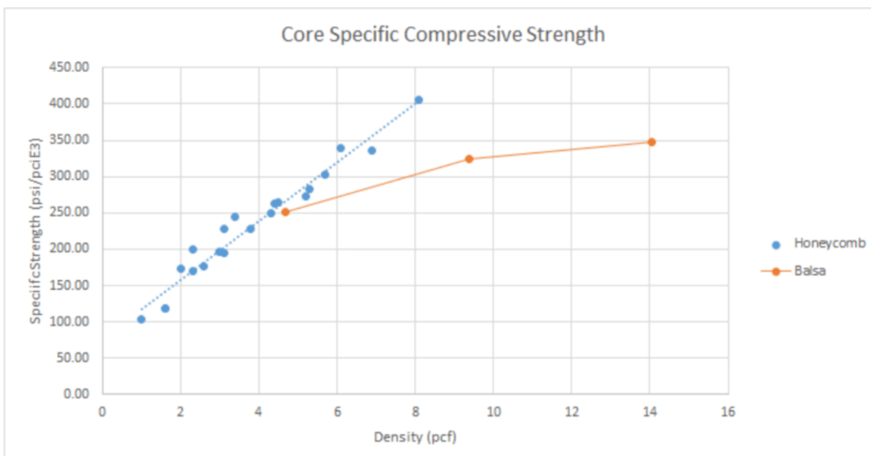


Figure 12. Specific Strength Testing Results With Honeycomb and Balsa Cores, by the 2017 Chassis Senior Project Team.

FSAE Monocoque Chassis Development (2020)

The most recent chassis based senior project aimed to redesign the previous Cal Poly Racing carbon fiber reinforced polymer monocoque chassis. A little bit of testing was done in terms of hardpoints. Half spool inserts were tested against bonded on reinforcements for carrying suspension load. The half spool inserts carried a significantly larger load. Greater density core puck sizing analysis was also conducted through ANSYS. A link load was applied to a plate representing the local laminate. Pucks of various sizes were tested to find an optimal choice. The hardpoint design chosen by this team was sufficient for the chassis, however, further testing was desired.

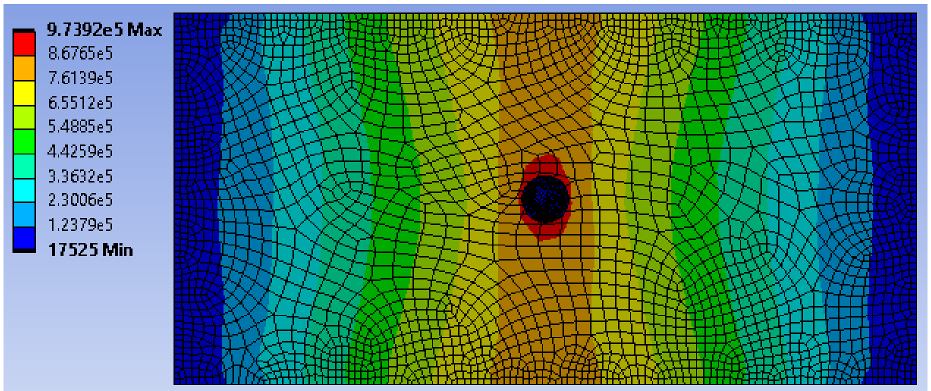


Figure 13. Local hardpoint FEM Testing For Puck Sizing, Done by 2017 Chassis Senior Project Team.

2.3 Various Mounts and Loads

Figure 14. Chassis Front Engine Mount (2019-2020 CDR)

Figure 14 shows the shape for the mount used in attaching the engine to the hardpoints, as well as the maximum stress it can accept. Evaluating the hardpoints through CAD software as well as real life testing will need to accommodate mounts such as these. This figure is important as failure of the mount is a possible failure mode if the hardpoints aren't strong or stiff enough.

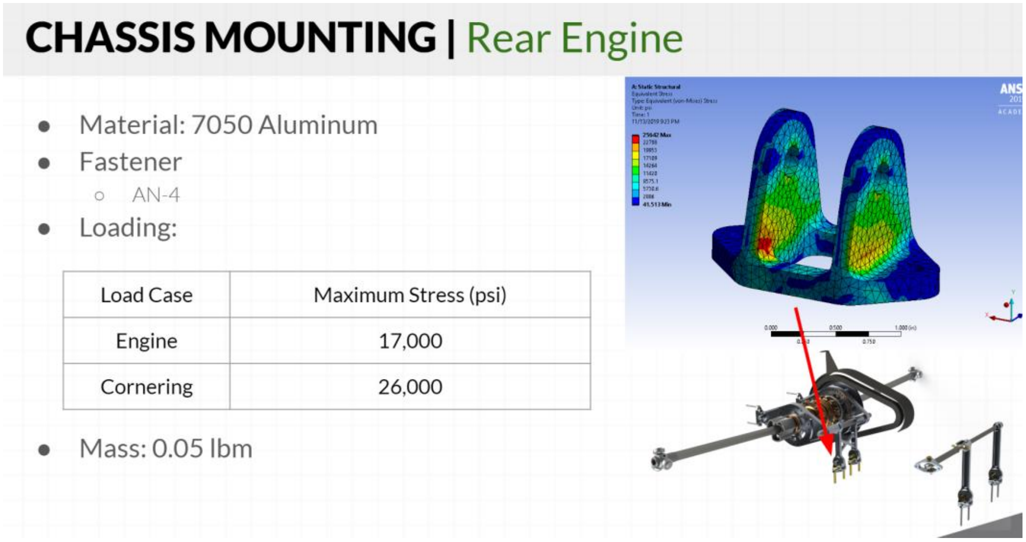


Figure 15. Chassis Rear Engine Mount (2019-2020 CDR)

Figure 15 shows the same mount as is used for the front of the engine. However, the rear mounts have an added load type associated with them that will need to be accounted for in the rear mounting hardpoints.

Table 3. Combustion Car Loads

Operating Case	Acceleration	Contact Patch Load (lb)					
		Front			Rear		
		Fx	Fy	Fz	Fx	Fy	Fz
Braking	-2.3 long	-507	0	262	-118	0	58
Acceleration	1.7 long	163	0	79	471	0	241
Cornering	2.23 lat	0	474	276	0	487	285
Combined	1.8 lat, -1.0 long	-574	514	299	-426	374	217

Table 3 provided by the 2019-2020 Chassis Senior Design Team shows the contact path loads the vehicle will be experiencing. This table also provides the worst load case scenarios the team has identified. The hardpoints will have to be designed such that these load cases may be endured over and over again. The hardpoints will need to withstand the cycling of these load cases as would be consistent with two years worth of vehicle run time (practicing, testing, racing).

Table 4. Hardpoints Loading

Max Combined loads [Max Cornering/Max Braking]				
Front	Force X [lbf]	Force Y [lbf]	Force Z [lbf]	Magnitude [lbf]
Upper a-arm	512.07	668.91	89.35	847.14
Lower a-arm	-748.24	-1662.45	-163.66	1830.41

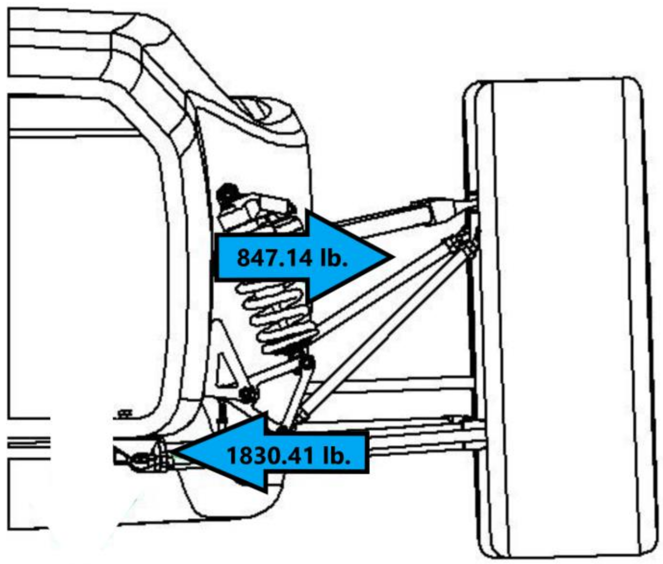


Figure 16. Upper and Lower A-arm Loads

Table 4 provides data specific to maximum loads subjected to the hardpoints. Figure 16 shows the direction and magnitude of the combined loading scenario at the upper and lower control arms. The hardpoint design will need to withstand an out of plane load of 1.6 KN, in plane load of 4.6 KN. A factor of safety of at least 1.7 will need to be achieved to reach the goal of being at least structurally equivalent to the previous hardpoint design. The calculator did not account for a bending load thus, realistic bending loads must be further investigated. While these loads were given to us at the start of the project, later on we learned that a build would not be done this year due to Covid protocols, thus our sponsor told us they were less interested in designing to fit these specific loads as they would be obsolete by the next build. They are more interested in testing data we can provide to help inform hardpoint manufacturing in the future.

2.3 Prior Manufacturing Plans and Procedures (Fall 2020)

During the Fall 2020 quarter we had determined plans and procedures for manufacturing hardpoint designs. These plans were created from the information we had at the time pertaining to materials we believed we had access to. These plans demonstrate the learning process we went through with this project. We were lacking knowledge about certain aspects of the manufacturing and designing process such as typical laminates are composed of several types of fibers. There are several differences between these plans and the ones we actually implemented. Initially we believed we had access to woven cloth fiber and epoxy resin along with prepreg. We also planned on obtaining inserts. Within these procedures we explain the wet layup process and process of potting inserts which we did not use.

Before sandwich panel assembly and manufacturing can begin, epoxy resin must be prepared, inserts and insert caps must be clean and prepared. Carbon fiber cloth prepreg as well as the core material must be cut to appropriate dimensions. Protective plastic sheets must be waxed/prepared with anti adhesive and taped onto a working surface before the manufacturing process may begin.

Cutting aluminum honeycomb cores can be done with a band saw in mustang 60 or in the hangar. This process takes about 20 minutes.

Cutting carbon fiber cloth prepreg can be done by hand with scissors. The cloth should be unraveled, dimensioned, and then cut using gloves to protect from epoxy resin. Tape can be used to firmly hold the cloth on a table ensuring accurate and clean cuts. This process usually takes about 10 minutes.

Wet hand lay-up requires a mixture of epoxy resin and hardener which can be properly measured and mixed for several minutes. This process should take roughly 10 minutes while first learning but decrease to about 5 minutes with experience. After speaking to our sponsor, wet hand lay-ups are typically not done for the FSAE project. But still may be an option depending on the laminate materials we are able to obtain.

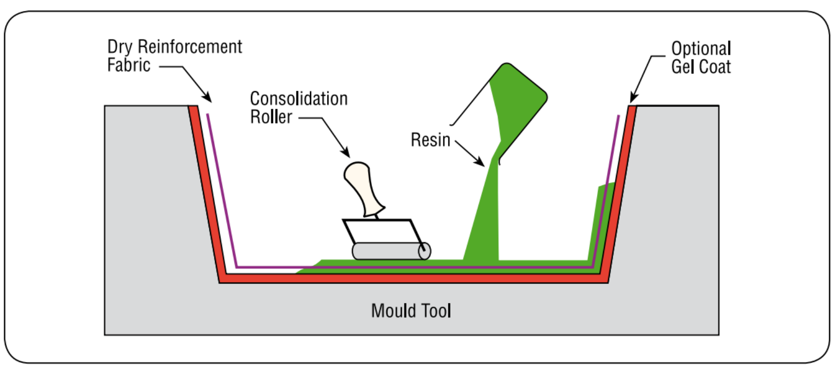


Figure 17. Wet Lay-Up Manufacturing Process

Once the epoxy is mixed the carbon fiber cloth must be laid out onto a clean flat surface a release film/wax should be laid out followed by a layer of epoxy. Next the carbon fiber cloth is laid onto the resin layer and excess air/resin bubbles must be worked out by hand or with a roller/scraper. Subsequent layers of carbon fiber cloth should be applied until the desired thickness is achieved. This process should take roughly 10 minutes.

Next the core layer is placed onto the resin infused carbon fiber. A layer of resin must then be applied to the top surface of the core. The process is then repeated for layering carbon fiber cloth ensuring there is not excess resin or air bubbles. This process should take roughly 12-15 minutes.

Another top layer of plastic sheeting with an anti adhesive coating/wax layer is then placed over the sandwich panel and sealed with tape. The entire sample and protective coating may then be placed in the oven to cure for 7 minutes.

The composite assembly must be cured at the prescribed temperature and duration of the epoxy. This typically takes 7-9 hours at 130-180 degrees celsius.

Other lay-up methods are vacuum bag molding which improves the mechanical properties of the laminate. The process is essentially the same as the hand lay-up method only it uses a vacuum seal, vacuum, and tube are used to force out trapped air and excess resin which also compresses and compacts the laminate yielding higher fiber concentrations. While using the vacuum process care and careful attention must be used to ensure the bag does not “wrinkle up” or cause any discontinuities on the laminate. Process before curing should take roughly 20 minutes. Depending on epoxy curing requirements may take over 24 hours at room temperature or 7-9 hours in the oven. As a side note all plastic/polymer/nylon bagging and sealings should be rated to handle oven conditions.

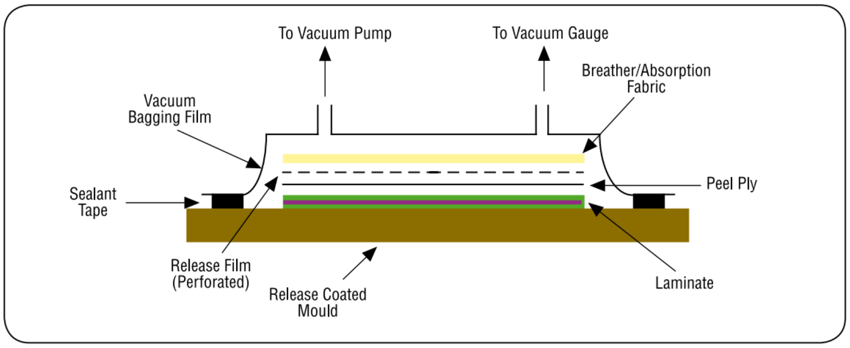


Figure 18. Vacuum Bagging Manufacturing Process

Prepreg laminates lay-ups follow the same instructions as the wet lay-up method however there is no need to use resin as it already comes imbued in the carbon fiber. Depending on the adhesives/epoxies used the prepreg sandwich panel curing times cant take up to 9 hours.

Once the sandwich panels have cured they are ready to be prepared and drilled to accept inserts. Removing the plastic sheets and excess resin seems should take roughly 5 minutes.

The panels may then be taken to mustang 60 or the hangar to drill out sections for inserts using a drill press. This process should take roughly 25 minutes.

The panels may then be brought back to the composites lab cleaned and prepared to accept the inserts. This process should take around 7 minutes.

The inserts may be placed in the drilled out holes and held in place by a potting cap that contains two holes one for potting insertion, and an excess drain hole. Next the potting is applied with a syringe like gun until excess potting seeps from the hole. Excess potting should be removed then the panel should be cleaned and prepared to go in the oven for curing per instructed time set by potting compound, roughly 2-3 hours.

As a side note, potting inserts under testing circumstances may be done at a 90 degree angle to the surface of the hardpoint on a horizontal surface. After speaking with our sponsor we learned under typical chassis construction potting inserts are done as a “finalizing step” and therefore the hardpoints are oriented in various positions and angles throughout the chassis. Some hardpoints may be horizontal in the case of the driver harness bottom mounts, some may be vertical on the suspension and otherers may be canted. As the potting cures gravity will pull and pool the compound to the core section of the inserts closest to the ground. As a result getting consistent potting with each hardpoint and insert will be a challenge under working chassis conditions. As far as our project goes, we will maintain a simpler and repeatable process with each insert. We may decide to allow the potting compound to cure at room temperature if permissible which can take up to three days.

Relevant Insert Information (Fall 2020)

The potting radius is one of the more critical design choice areas. Previous testing has determined the core size, and the insert size is currently determined by the inserts that are available. From previous testing data produced by our sponsor, the figure below was produced.

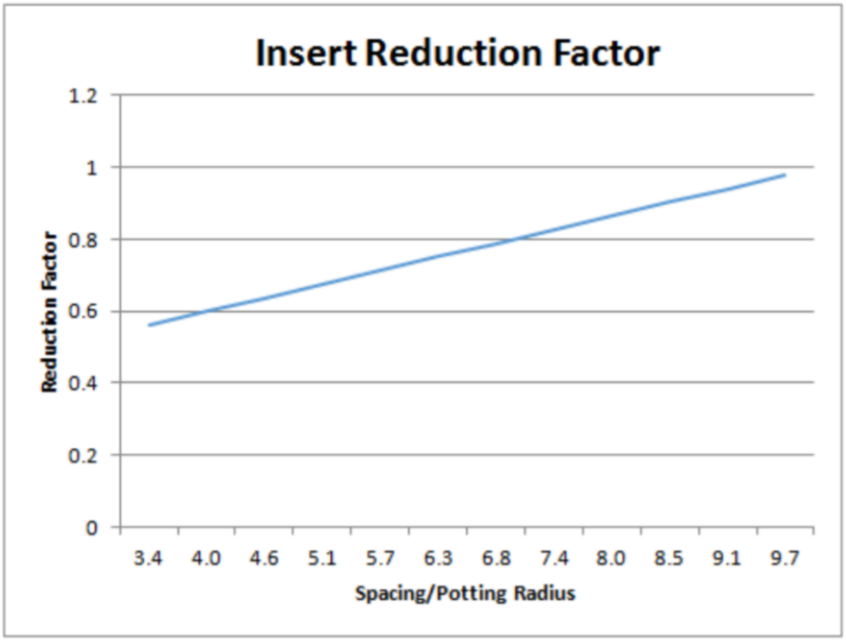


Figure 19. Insert Reduction Factor vs. Spacing Over Potting Radius

Figure 19 shows a linear relation between the spacing divided by potting radius and the Insert Reduction Factor, which is a factor that determines the reduced effectiveness of the insert. The data shows that increasing the spacing/potting radius up to 10 also increases the Insert Reduction factor, indicating that an increase in the ratio decreases the insert effectiveness. Thus, we need to be mindful of keeping this ratio low.

3. Objectives

3.1 Customer Wants and Needs

Cal Poly FSAE, our sponsor, asked for an optimized hardpoint design, their current design was chosen for convenience, rather than quality. The main concern for the hardpoints is minimizing weight while maintaining the necessary strength and specific stiffness. Additionally, the hardpoints are restricted to a set geometry to be determined by the sponsor. Cost is another determining factor in the design of the hardpoints, however since most of the required materials are donated to the sponsor, cost is not likely to be an issue. Though, if the final design requires materials that have not been donated, cost will quickly become a limiting factor. Our sponsor would like a hardpoint design working with their set geometry that minimizes weight and cost while maintaining the team's standards for strength and stiffness. Thus, the Hardpoints CP team, developed a design for the hardpoints on the Cal Poly Racing team's chassis. However, due to rapidly changing circumstances caused by the global pandemic, the wants and needs of our sponsor changed to adapt to the closure and restrictions placed on machine shops and testing facilities, Initially, our testing was to be done using a previously existing jig the team had, but since that jig was lost, our sponsor required a jig design compatible with our test panels that could also be used for multiple different testing angles. Additionally, the carbon they use as laminate for their chassis and hardpoints has expired, so the test data they have for it is no longer accurate, they needed the carbon to be tested to have accurate data that could be used in further analysis.

3.2 Problem Statement

Original Problem Statement: Cal Poly FSAE needs more thoroughly analyzed individualized hardpoints that are optimized for weight, strength, specific stiffness, and cost, so they can reduce the overall weight of the vehicle while maintaining their strength and stiffness standards. We plan to accomplish these goals through research, composite testing, and computer based analysis.

Updated Problem Statement:

Cal Poly FSAE needs more thoroughly analyzed hardpoints that are optimized for weight, strength, specific stiffness, and cost, so they can reduce the overall weight of the vehicle while maintaining their strength and stiffness standard at the worst case loading scenario located at the front suspension mounts. Additionally, they need a redesigned jig and updated laminate data. We plan to accomplish these goals through research, computer based analysis, and limited composite testing.

3.3 Boundary Diagram

The boundary diagram below shows the scope of the project undertaken, our team will receive the loads on the chassis as well as the critical locations needing hardpoints. Our team used the loads and critical locations to perform a stress analysis to choose the materials for potting, inserts, and the core, as well as determine the necessity of extra laminate. After making preliminary selections, testing will begin to determine the best combination for the final hardpoint design. This final design will be passed on to the Manufacturing and chassis subsystems to be used on the vehicle.

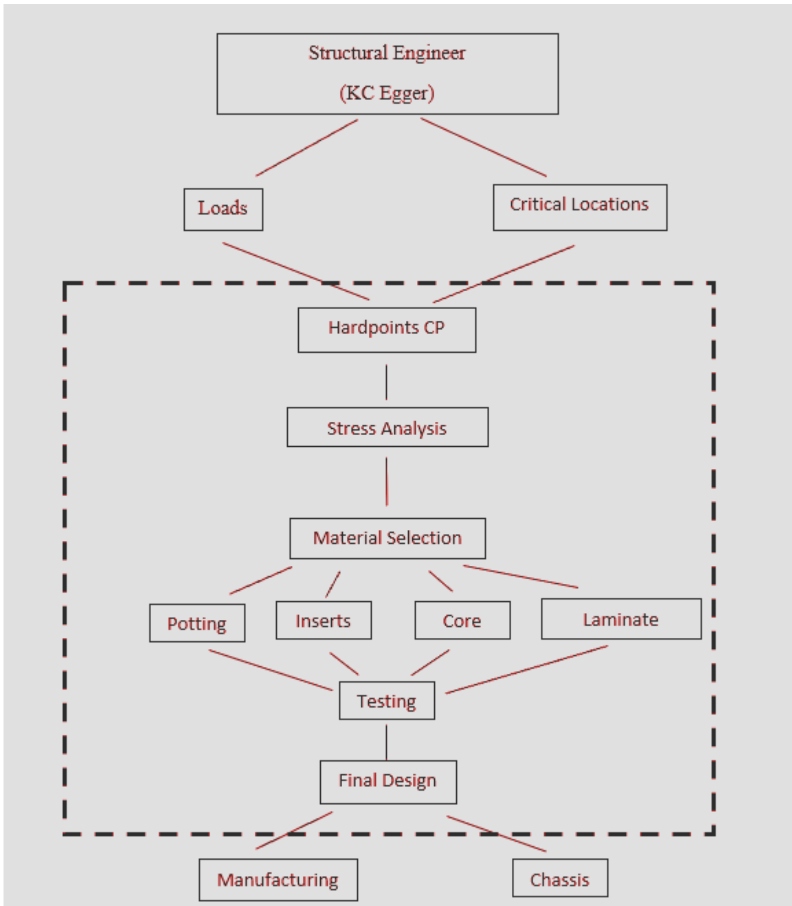


Figure 20. Boundary Diagram

To create a design, a strong knowledge of all previous and alternate designs was important. In order to better understand the utility of previous and alternate Hardpoint designs, a Quality Function Deployment or QFD was created. To develop our QFD, seen in Appendix 1, we consulted our sponsor, and made sure that their needs and wants were clear to us. Using the information from our sponsor, as well as research into hardpoints, we created specifications that would be useful in determining the best final design. Looking back at previous designs used by the Cal Poly FSAE team, a myriad of alternative designs were identified. Previous senior projects were consulted to better understand testing and specifications important to the success of hardpoints. Using the specifications, a weighting system ranking their importance was decided upon based on the needs and wants given by our sponsor.

3.4 Specification Chart

Table 5: Specifications Table

Spec #	Specification Description	Requirement or Target	Tolerance	Risk	Compliance
1	Specific Stiffness	30000 lbft/deg	Max	High	A,T
2	Strength	7397.9 N (Out of Plane)	Max	High	A,T
		3408.39 N (In Plane)			
3	Weight	TBD	Max	High	A,T
4	Time to Manufacture	1 week	± 0.5 Day	Low	T,I
5	Life expectancy	2 years	± 2 months	Medium	A,T
6	Cost (If using non donated material)	(unknown as of now)	Unknown	Low	I,A
7	Sizing	(unknown as of now)	Max	Low	I,A

The specifications chosen are all critical to choosing a final design with regards to the requirements that our sponsor requires. Specific Stiffness is the max load over the max deflection for the whole chassis. We want a light material that is resistant to deformation due to in plane, out of plane, and the overall torsional loads on the chassis. Specific Stiffness will be measured on individual hardpoints during testing. Using the Instron machine, the max load and the deformation at that load on the individual hardpoint will be found. Next, we used an FEA of the whole chassis to verify that the overall stiffness is maintained to standards the team requires. Future testinging will need to be done to verify our findings.

Strength is the maximum load a material can withstand before yielding. There are different strengths taken into account based on the different modes of failure observed during testing. Strength was analyzed by meeting the required load to an appropriate safety factor as determined by the likelihood of failure at the particular location on the chassis. This needs to be tested using the Instron machine

Reducing weight is one of the most important specifications we're designing for. The hardpoints have to be weighed individually, since hardpoints in different locations will have different weights based on different load conditions.

Time to Manufacturing is also very important to the sponsor. It currently takes one week for the team to complete the chassis layup process, which includes all of the hardpoints, we hope to maintain this time frame as best as we can. We have a tolerance of +/- 6 hours, meaning the total time to layup the chassis with the new hardpoints design should be within 6 hours of the previous chassis process. This should be an adequate tolerance as the hardpoint manufacturing and installation process will be mostly the same as the previous year. The only difference is in regards to the installation process. In previous years, all hardpoints on the chassis had the same design, thus the installation process will be slightly longer as there will be varied designs for localized hardpoints. However, this should not add a significant amount of time to the installation process as it simply requires a change in materials or sizing which won't take too long. Time to manufacture must be verified during testing by seeing how long it takes to manufacture and install the hardpoints into sandwich panels.

The life expectancy of the part is important, but not one of the more important factors to take into account as the part will likely meet the short life required by our sponsor of two years. This will be verified largely through analysis to determine the life of the part.

Cost is a specification that was very limiting. There is no set budget for hardpoints and the majority of parts are typically donated. This year is an anomaly, as the team will not be building a vehicle due to Covid-19 restrictions. Thus, donations may be hard to come by. The majority of parts required will likely be too expensive for purchase, so cost is a very limiting restriction. Most of the parts used will be of what is already on hand.

Added Specifications to our initial scope include designing a jig for multiple tests needed for hardpoint design. The jig needs to hold a sandwich panel with a suspension mount attached to a hardpoint. The jig needs to fit in the Instron machine and needs to have a place for the bottom jaw of the machine to clamp onto. The tests needed are a pullout test and a shear test. Additionally, the jig needs to be able to be adjusted to position the sandwich panel at different angles to help test different load cases.

Another specification is to retest the laminates the club has on hand. We must retest their carbon as it has expired a few years ago, thus the datasheets are no longer accurate. So, by producing updated data through tensile testing, hardpoint analysis will be more accurate. The laminates that need to be tested are HTS 40, in both the 0 degree and 45 degree orientations, and the unidirectional T700. These laminates need to be laid up and cured before cutting them into samples following ASTM testing standards. Then, the samples must be tensile tested in order to find ultimate tensile strength, ultimate tensile strain, and modulus of elasticity.

4. Concept Development

To create an optimized Hardpoint design that would better suit the needs and wants of FSAE, we decided to separate the hardpoint into individual components. The components of the hardpoints that require optimization are the laminate, core, potting compound, insert, and hardpoint geometry. For the laminate, core, potting compound, and insert, much of the optimization lies in making engineering decisions based on calculations and material property data as well as sizing. The hardpoint geometry is an area where we believed there would be more freedom to design the shape and size of the hardpoints. However, from our ideation process outlined below, we found there are many limitations in terms of designing the hardpoint geometry as well.

4.1 Hardpoint Geometry

Our design process began with multiple brainstorming sessions. We compiled a list of 6 ideas, which we narrowed down based on feasibility. Some designs were not practical or easy to manufacture, so they were discarded. We then took our designs to our sponsor to better gauge their wants as well as to seek their advice on certain designs. After this meeting, we were able to finalize which designs we wanted to proceed to testing and which designs would not be feasible due to manufacturing limitations.

4.2 Alternate Designs

Design 1

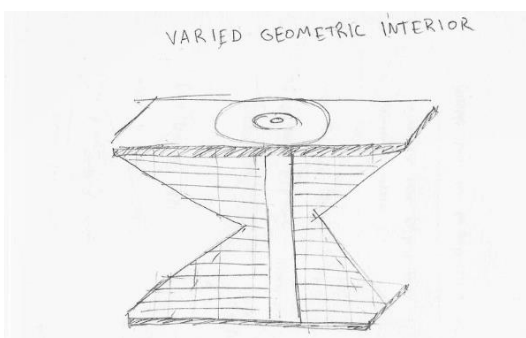


Figure 21. Square Hardpoint With Varied Geometric Interior

The first design we considered involved two square sections of laminate skin, with a core that has a varied geometric interior, designed specifically to save weight. However, after consulting, this design turned out to not be feasible due to the complex manufacturing that would be required. Thus, we decided to no longer pursue this idea.

Design 2

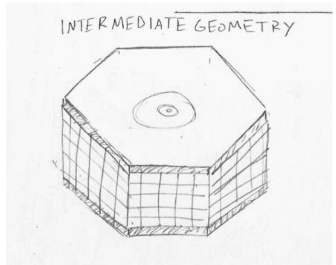


Figure 22. Hexagonal Hardpoint

This second design, using a hexagonal shape, was intended to provide higher strength and stiffness than the circular design. However, it was quickly realized that this design would not provide much advantage in terms of weight saving, so we scrapped this design.

Design 3

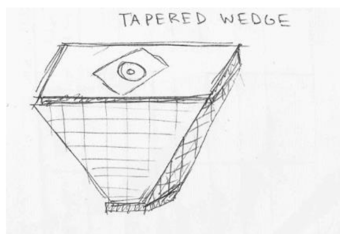


Figure 23. Tapered Square Hardpoint

The third design involves a square hardpoint geometry, that is tapered down to save weight. The goal behind this design would be to negate material limits with geometric limits. For example a large area cannot easily be pushed through a small hole. Therefore this design had potential at increasing one applied load tensile or compressive. This design seemed to provide a combination of things that our sponsor was interested in, so we were interested in pursuing this design. However, after speaking to our sponsor, it became evident this design would not be easily integrated into the manufacturing process, so it was decided the design would not be worth pursuing.

None of the above designs were chosen as they did not fit into the needs of the sponsor, the designs selected below are the ones we hope to pursue. For future projects we expect analysis and testing these designs in order to best optimize the hardpoint design.

5. Idea Selection

5.1 Initial Hardpoint Geometry Designs

Design 1

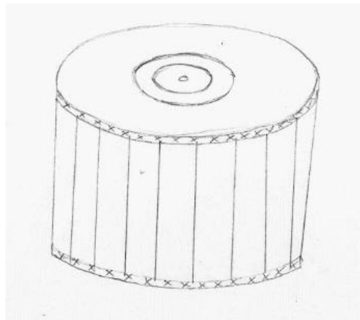


Figure 24. Circular Hardpoint

The circular hardpoint design is the design that was agreed upon for evaluating and testing by our team and our sponsor. This design is the classic hardpoint design, involving a half spool insert, and circular geometry. This design has good strength and stiffness, but has a higher weight than other designs. This design is what is currently used, and has been used in past designs, so it is the standard. This design is proven to work but that doesn't necessarily mean it is the best design. However with the limitations we have experienced, optimizing this design will be a success for this project.

Design 2

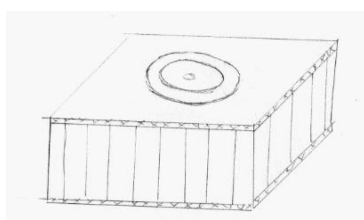


Figure 25. Square Hardpoint

This design was not chosen due to its deviation from the norm. Our new sponsor felt that narrowing down the scope of the project to one critical variable i.e. core diameter size would yield valuable data. Although this design was not chosen it has favorable qualities that may be investigated in the future. This design uses a square geometry, which we believe may offer some advantages to the traditional design. This design may be more seamless to manufacture and should provide good strength and stiffness as well.

Design 3

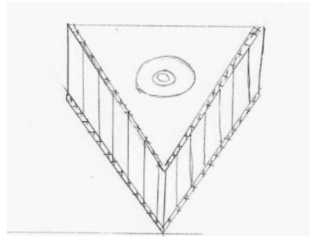


Figure 26. Triangular Hardpoint

Similar to the previous design, this design was not chosen due to its deviation from the standard. However, in the future this design may be investigated for having some mechanical advantage such as additional in-plane strength. The in-plane loads are the largest, thus this design may be able to provide the necessary strength and stiffness at a size smaller than the other geometries. As a result it may be able to save weight. There is no information on hardpoints of this shape available.

5.2 Final Hardpoint Geometry Designs

Since our PDR, and collaborating more with our new sponsor, we decided to move forward with the Circular Hardpoint Geometry as it is the best for meeting our sponsors needs in terms of optimizing a hardpoint for weight. The other geometries are dramatically different from what is traditionally used and investigating those designs may prove to be futile. At least with the standard design subsections of the hardpoint can be optimized with time and testing.

5.3 Initial Material Selection

Core

The pugh matrix below shows our design process for the core material of the hardpoints. The parameters we considered are Specific Stiffness, Compressive Strength, Density, Tensile Strength, Shear Strength, and Cost. Multipliers were added for the parameters we prioritized higher, namely density, compressive strength, and specific stiffness. Density was given an added multiplier as reduced weight is the primary objective. From datasheets we are able to ascertain the values for these properties for different core material we are considering. From the pugh matrix we can determine the hex web and Aluminum Flex Core are the most viable options. Upon project progression, cost, as well as all other core materials aside from the aluminum hexweb were eliminated as prospects for evaluation.

Table 6: Core Pugh Matrix

Core Material	Current (1/8 hex web cr3)	Aluminum Flex Core	G10/FR4 puck	Balsa Puck	Corecell A1200	Multiplier
Specific stiffness(E/rho)	0	1	-1	1	-1	2
Compressive Strength	0	-1	2	-1	-1	2
Density/weight	0	1	-2	-1	-5	3
Tensile Strength	0	0	2	-2	0	1
Shear Strength	0	-1	2	-2	-1	1
Cost	0	0	-2	-1	-1	1
Total	0	2	-2	-8	-20	N/A

Potting Compound

Table 7 compares several potential potting compounds. Important traits being investigated for the potting compound are shear modulus, tensile strength, and cure time. The table shows that Hysol EA 9396, Loctite 9313, Loctite 9360, Loctite 9390 are all superior options that the current potting compound being used by FSAE. We have determined Loctite 9390 offers the best characteristics for a potting compound. The total points at the bottom of the table demonstrate the best options are those with the highest total points.

Table 7: Potting Compound Pugh Matrix

Potting Compound	LOCTITE EA 9309NA AERO	Hysol® EA 9396	LOCTITE 9313	LOCTITE 9360	LOCTITE 9390	Multiplier
Shear Modulus	0	0	0	0	1	2
Time to Cure	0	-1	-1	-1	1	1
Tensile Strength	0	2	1	1	2	2
Compressive Strength	0	0	3	2	0	0.25
Total	0	3	4.75	1.5	7	N/A

Laminate

Table 8 shows a pugh matrix for laminates to be used for the skins of the hardpoints. The current 2019-2020 CDR claims HTS40 fabric and Toray T700 laminate are the choices for the overall laminate for the monocoque chassis. Some promising laminate considerations are listed in this table with the best being Toray-cetex TC1100 as it offers superior tensile strength, shear strength, and lower density than the current laminate. Toray-1100 series laminates have been hard for FSAE to acquire in the past. However, obtaining either the TC1100 or T1100G would be beneficial to the hardpoints overall tensile load carrying capabilities as well as reducing the overall weight of the hardpoints.

Table 8: Laminate Pugh Matrix

Laminant	Tencate TC275	HTS 40 (current)	Toray T700 (current)	Toray-cetex TC1100	T1100G	Multiplier
Tensile Strength	0	0	0	2	1	2
Impact Strength	0	0	0	0	0	1
Resistance to Heat	0	0	0	0	-1	1
Specific Stiffness (E/rho)	1	0	0	1	1	2
Cost	0	0	0	0	0	1
Shear Strength	0	0	0	1	1	2
Density	2	0	0	1	1	2
Total	5	0	0	14	7	N/A

Insert

Insert material selection can be seen in Table 9. Previous hardpoint designs have determined the half spool design is optimal for hardpoints as it is significantly easier to manufacture than the full spool design. However, the difference in compressive strength and pullout/shear failure due to the type of insert is practically negligible. Deciding on which material is best was left up to the criterion presented in the pugh matrix. Through investigation of material properties, it is apparent that aluminum offers the best overall properties for an insert. Aluminum maintains high compressive strength and tensile strength at a relatively light weight. The next best insert choice is polymer/ultem followed by steel and titanium.

Table 9: Insert Material Pugh Matrix

Insert Material	**Current (Aluminum)**	**Titanium**	**Polymer**	**Steel**	**Multiplier**
Compressive Strength	0	1	-2	1	1
Tensile Strength	0	1	-2	1	1
Density/Weight	0	-1	1	-2	2
Cost	0	-2	1	-1	1
Total	0	-2	-1	-2	N/A

6. Final Design

6.1 Final Design Schematics

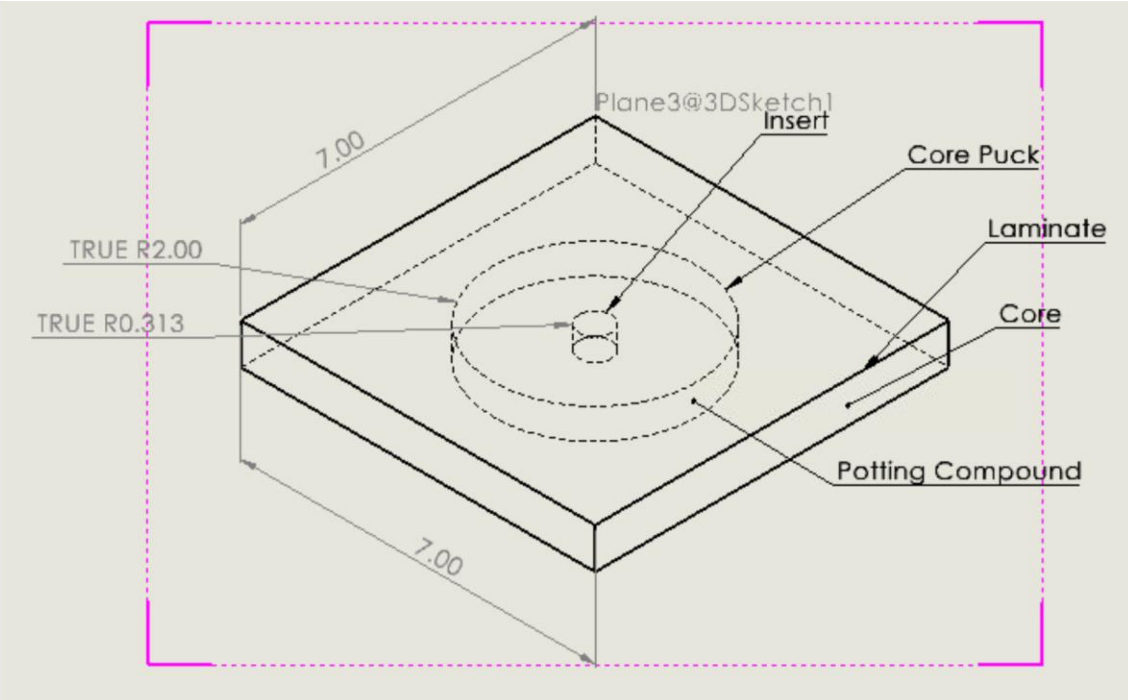


Figure 27. Previous Final Design Isometric

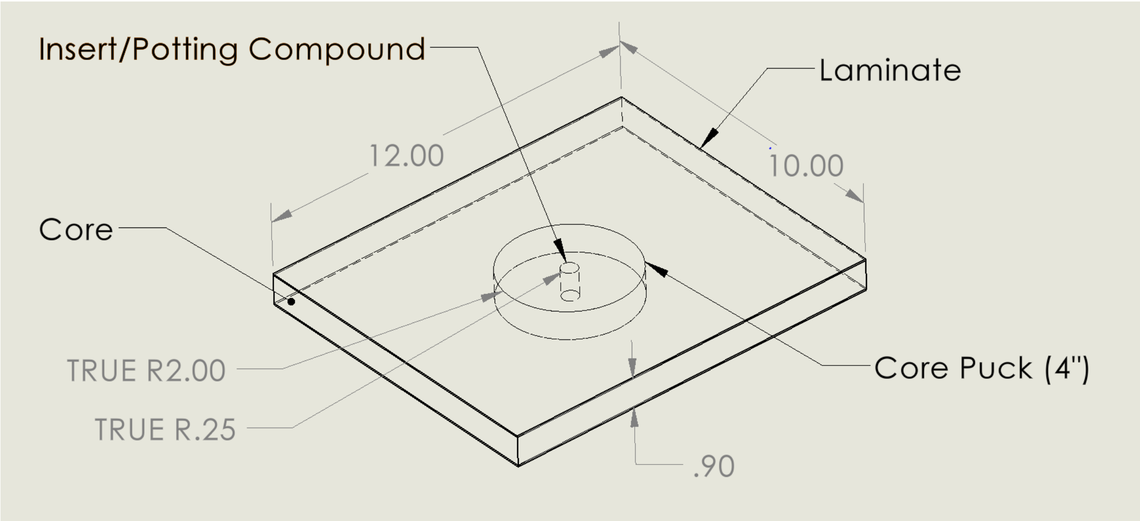


Figure 28. Final Design Isometric

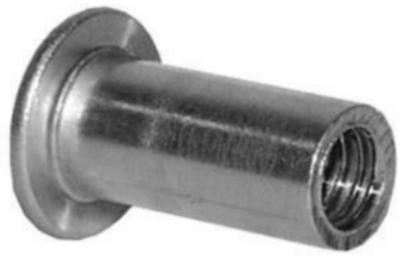


Figure 29: Final Insert Choice

Shown above is our Final Hardpoint Design, the core puck, inserts, and potting radius have been predetermined by our sponsor. These dimensions were determined by FSAE club members and previous senior projects to meet the demands of the worst case load scenario. Along with the dimensions, the materials have also been chosen to meet the demands of these loads. The insert chosen is an aluminum half spool insert, which comes in a standard size. Future testing will be able to determine the prevalent failure modes and reiterate the sizing to meet these loads.

When we started this project we had intentions to blend a variety of materials and geometric shapes to optimize hardpoints for the FSAE electric and combustion cars. As tentative plans and schedules have been updated accordingly to Covid-19, we learned about the cancelation of production testing and racing of FSAE cars for the 2020/21 year. We have also experienced a change in sponsor thus resulting in an adjusted project scope. Our sponsor wanted us to test tensile samples made of the three fibers that would compose the hardpoint laminate to help us familiarize ourselves with the panel manufacturing process. This tensile data is also invaluable to the FSAE team as it pertains to the shell of the vehicle monocoque, and provides more accurate data for improving hardpoint design and analysis. We were able to provide some tensile testing for the HTS40 and T700 carbon fiber laminate, which will be shown later in the report. Additionally, we compared two hardpoint designs, a four inch diameter core puck vs a three inch diameter puck. Testing will still need to be conducted to determine which sizing choice is better. All material choices excluding inserts have been decided, as we had no inserts available during the manufacturing portion of our project to use for testing.

Our sponsor guided us to design hardpoints based on the currently used hardpoint geometries and models while only adjusting core diameter size to see if the smaller size will be sufficient for withstanding dynamic suspension loading. We suggest the future direction of this project aims to adjust one hardpoint variable at a time such as core material, potting material, laminate configuration, and insert materials to see how the material choice affects the hardpoint capability.

6.2 Final Design Choices

Due to the unforeseen circumstances regarding Covid-19 our material evaluation and selection has been greatly reduced. We only had access to HTS40 multidirectional prepreg laminate as well as T700 unidirectional prepreg cloth. We used 5052 aluminum honeycomb cores available in two densities (4.4 lbm/ft^3 and 3.1 lbm/ft^3). Loctite 9309 was the only available potting compound. Due to lack of available resources we were unable to obtain inserts. For the future of this project we recommend using corrosion resistant aluminum alloy inserts based on the material properties such as high tensile strength coupled with low density. If aluminum inserts are not feasible, we recommend testing with polycarbonate or polylactic acid filament inserts as they can be manufactured on campus. In terms of mounting and physically testing hardpoints, we have developed a jig that allows for insert pull-out tests. These pull-out tests can be done for a variety of angles which will simulate the stresses and loading the vehicle would exert on the hardpoints as it drives around the track. We also have a variety of suspension mounts that vary in condition and have been accumulated by FSAE over several years. Data sheets pertaining to the laminates provide some insights as to the ultimate loads these materials can withstand. It should be noted that based on the design criteria many of these ultimate loads will never be realized during our physical testing. The following data sheets are critical for our material selection and recommendations for the project going forward.

Laminates

T700S	C	12,000	5	0	C
Fiber Type	Twist*	Filament Count	Sizing Type	Surface Treatment	Sizing Amount

** C: Never Twisted*

FIBER PROPERTIES

PROPERTY	ENGLISH	METRIC	METHOD
Tensile Strength	711 ksi	4,900 MPa	TY-030B-01
Tensile Modulus	33.4 Msi	230 GPa	TY-030B-01
Strain at Failure		2.1%	TY-030B-01
Density		1.80 g/cm3	TY-030B-02

RESIN SYSTEM COMPATIBILITY

SIZING TYPE & AMOUNT	RESIN SYSTEM COMPATIBILITY	METHOD
50C (1.0 %)	Epoxy, phenolic, polyester, vinyl ester	TY-030B-05
60E (0.3 %)	Epoxy	TY-030B-05
F0E (0.7 %)	Vinyl ester, compatible with epoxy	TY-030B-05

COMPOSITE PROPERTIES

PROPERTY	ENGLISH	METRIC	METHOD
Tensile Strength*	415 ksi	2,860 MPa	ASTM D-3039
Tensile Modulus*	19 Msi	134 GPa	ASTM D-3039
Tensile Strain		2.02%	ASTM D-3039
Compressive Strength*	210 ksi	1,450 MPa	SACMASRM1R-94
Flexural Strength*	245 ksi	1,690 MPa	ASTM D-790
Flexural Modulus*	17 Msi	120 GPa	ASTM D-790
ILSS	13 ksi	86.9 MPa	SACMASRM1R-94
In Plain Shear Strength	20 ksi	136 MPa	ASTM D-3518
90° Tensile Strength	12 ksi	81 MPa	ASTM D-3039

*Normalized to 60% fiber volume. Cured with #2592 epoxy at 130 °C.

Figure 30. T700 Laminate Datasheet

The datasheet above pertains to T700 unidirectional prepreg. Some important information gathered from this data sheet is the tensile strength, shear strength, flexural strength, compressive strength and compatible epoxies. The composite properties are more important to us than the fiber properties because our laminate will be composed of both the T700 cloth combined with a stiffening epoxy. Fortunately this fiber is compatible with epoxy resin sheets which we have onhand. This laminate also comes in pre impregnated resin sheets which were available to us. The values for the various loads are as follows: Tensile strength 415 ksi, Flexural strength 245 ksi, in plane Shear strength 20 ksi, 90° tensile strength 12 ksi, Compressive strength 210 ksi. As mentioned earlier in the report the laminates will experience all of the loads mentioned above. The “weakest” load the laminate can withstand before failure is the 90° out of plane tensile strength which will come from bending moments caused by forces applied at the inserts. The reason these 90° loads are weakest is the only thing keeping the fibers from separating is the epoxy resin. The benefit of this fiber is to experience tensile loads acting parallel to the fiber strands, not perpendicular. An important note to understand the testing conditions this data was acquired from. In this case the composite laminate was made with a 60% fiber to 40% #2592 resin per volume. The data provided is from a cure at 130° C likely following the recommended time per the epoxy.

PRODUCT DESIGNATION

T1100G	C	12,000	7	1	E
Fiber Type	Twist*	Filament Count	Sizing Type	Surface Treatment	Sizing Amount

**C: Never Twisted*

FIBER PROPERTIES

PROPERTY	ENGLISH	METRIC	METHOD
Tensile Strength	1,017 kpsi	7,000 MPa	TY-030B-01
Tensile Modulus	47.0 Mpsi	324 GPa	TY-030B-01
Strain at Failure		2.0%	TY-030B-01
Density		1.79 g/cm^3	TY-030B-02

RESIN SYSTEM COMPATIBILITY

SIZING TYPE & AMOUNT	RESIN SYSTEM COMPATIBILITY	METHOD
71E (0.6%)	Epoxy, phenolic, polyester, vinyl ester	TY-030B-05

COMPOSITE PROPERTIES

PROPERTY	ENGLISH	METRIC	METHOD
Tensile Strength*	502 Ksi	3,460 MPa	ASTM D-3039
Tensile Modulus*	27 Msi	185 GPa	ASTM D-3039
Tensile Strain		1.82%	ASTM D-3039
Compressive Strength*	271 Ksi	1,870 MPa	SACMASRM1R-94
Flexural Strength*	278 Ksi	1,920 MPa	ASTM D-790
Flexural Modulus*	23 Msi	159 GPa	ASTM D-790
ILSS	15 Ksi	104.5 MPa	SACMASRM1R-94
In Plain Shear Strength	23 Ksi	160 MPa	ASTM D-3518
90° Tensile Strength	12 Ksi	80 MPa	ASTM D-3039

*Normalized to 60% fiber volume. Cured with #2574 epoxy at 130 °C.

Figure 31. T1100G Laminate Datasheet

Similar to the T700 prepreg, we have a data sheet for Toray T1100G carbon fiber cloth. We were unable to acquire this material for testing, however according to the datasheets this fiber looks promising due to its ability to withstand greater tensile loads and is less dense than the T700. Some of the datasheet information to take note of are as follows: Tensile strength 502 ksi, Compressive strength 271 Ksi, Flexural strength 278 ksi, In plane Shear Strength 23 ksi, and 90 degree Tensile strength 12 ksi. The “weakest” link for T1100G is the 90 degree Tensile strength consistent with insert pullout at the same value as the T700 of 12 ksi. However, one other important factor contributing to material selection is reducing hardpoint weight. T1100G has a density of 1.79 g/cm^3 compared to 1.8 g/cm^3 for the T700. Although the difference of .01g/cm^3 seems insignificant some calculations regarding surface area will prove the weight saving benefit of going with this lighter material as an option not only for the hardpoints but perhaps then entire chassis monocoque in future designs. An example for our purposes would be 24 suspension hardpoint mounts with a volume of roughly 97 cubic centimeters saves nearly 6 grams of weight. Not only does the T1100G save weight and maintain mechanical properties which are consistent with our scope of work. It also has a higher ultimate load capacity for every other type of force than the T700. To reiterate however, the out of plane tensile strength is the least capable load, that does not necessitate that the hardpoint laminate will not fail due to other loading configurations.

Typical Fiber Properties		**Inch-Pound**		**SI**
Tensile strength	3K E13 (EP03)	610 ksi		4205 MPa
	6K E13	630 ksi		4345 MPa
	12K E13	620 ksi		4275 MPa
	12K/24K F13 (F301)	670 ksi		4620 MPa
Tensile modulus*	3K/6K/12K E13 [(1)]	34.3 Msi		237 GPa
	12K/24K F13 [(2)]	34.7 Msi		239 GPa
Elongation*	3K E13 [(1)]		1.78%	
	6K E13 [(1)]		1.82%	
	12K E13 [(1)]		1.80%	
	12K/24K F13 [(2)]		1.80%	
Density		0.064 lb/in^3		1.76 g/cc

Figure 32. HTS40 Datasheet

The datasheet above shows the tensile strength and density of various Tenjin HTS40 carbon fibers. Unfortunately the Tenjin datasheets are not as insightful about composite properties as TORAY. If we compare the fiber properties from the HTS40 to the T1100G and T700 we will see that all of the HTS40 variants have the lowest ultimate tensile strength. We can infer that the HTS40 composite will likely be inferior to the T1100G and T700 at least in terms of tensile strength acting in one direction across the fibers. The HTS40 does have some valuable qualities however. The samples we have to work with are prepreg meaning they already have resin infused in the fibers and simply need to be set and cured to make a testing sandwich panel. Likewise, the HTS40 is the least dense of the three laminates we are evaluating which contributes to our project scope of reducing hardpoint weight. HTS40 has the added benefit of being “woven” fibre which unlike the T700. Woven fibers allow load distribution in multiple directions. The woven pattern resembles a wooden lattice in that each weave alternates 90 degrees. In making our hardpoint samples we used HTS40 prepreg in 45/-45° and 0/90° patterns.

Potting Compound

Bond Strength Performance
Tensile Lap Shear Strength - tested per ASTM D1002. Adherends are aluminum as referenced and treated with Phosphoric Acid Anodizing (PAA) per ASTM D3933.

	Typical Results			
	7075-T3 Alclad / PAA 3 days @ 77°F/25°C		2024-T3 Alclad / PAA 1 hour @ 180°F/82°C	
Test Temperature, °F/°C	**psi**	**MPa**	**psi**	**MPa**
-67/-55	4,000	27.6	6700	46.2
77/25	5,000	34.5	6100	42.1
180/82	600	4.1	1300	9.0
77/25 (Hot/Wet) 750 hours @ 160°F/71°C & 85% RH	-	-	5700	39.3

Figure 33. LOCTITE 9309 Datasheet

Curing - This adhesive may be cured for 3 - 5 days @ 77°F/25°C to achieve normal performance. Accelerated cures up to 200°F/93°C (for small masses only) may be used as an alternative. For example, 1 hour @ 180°F/82°C will give complete cure.

The datasheet above shows the curing temperatures and time duration as well as tensile lap shear strength for the LOCTITE 9309 potting compound we have used in tests. The important data for our manufacturing and testing purposes is a 1 hour cure time at 180℃ yielding a complete cure. Likewise the test temperature of 77℉ yielded an ultimate tensile lap shear strength of 6.1 ksi. Lap shear strength testing measures a material's ability to withstand in plane stresses where the exerted force moves two test pieces in opposite directions. This sort of shear testing is especially valuable to gain an understanding of the loads that will cause the inserts to either be “pulled” or “pushed” out of the composite sandwich panel. Our experience with LOCTITE 9309 was limited as we were only able to use it to adhere steel tabs to our carbon fiber laminate tensile testing samples. We did not use an oven to cure the epoxy, rather we allowed the epoxy to cure at room temperature for three days. In retrospect the three days of cure was insufficient because a constant temperature of 77℉ was not met due to day and night temperature fluctuation. Therefore during tensile testing we experienced some separation issues with several samples.

Curing - This adhesive may be cured:
220 minutes @ 200°F/93°C
150 minutes @ 250°F/121°C
130 minutes @ 300°F/149°C

Cleanup - It is important to remove excess adhesive from the work area and application equipment before it hardens. Denatured alcohol and many common industrial solvents are suitable for removing uncured adhesive. Consult your supplier's information pertaining to the safe and proper use of solvents.

Bond Strength Performance
Tensile Lap Shear Strength
Tensile lap shear strength tested per ASTM D1002 after curing 1 hour @ 250°F/121°C. Adherends are 2024-T3 bare aluminum with phosphoric acid anodized per ASTM D3933.

	Typical Results	
Test Temperature, °F/°C	**psi**	**MPa**
-67/-55	2,200	15.2
77/25	2,600	17.9
180/82	3,000	20.7
250/121	3,600	24.8
300/149	2,700	18.6
350/177	1,700	11.7

Figure 34. LOCTITE 9390 Datasheet

Datasheets for LOCTITE 9390 are seen above. We believe LOCTITE 9390 would be an interesting potting choice because although the shear lap strength is significantly lower than the 9309 we have available, the bulk resin properties are very promising. Of roughly six options of epoxy potting compounds LOCTITE 9390 could withstand the highest loads for bulk resin properties while the LOCTITE 9309 had the highest tensile shear lap test results. For the sake of experimentation we would recommend testing both compounds to see which works best for hardpoint designs.

Cores

PAMG-XR1 5052 Mechanical Properties

CELL SIZE		NOMINAL DENSITY		BARE COMPRESSIVE STRENGTH				PLATE SHEAR STRENGTH "L" DIRECTION				PLATE SHEAR MODULUS "L" DIRECTION		PLATE SHEAR STRENGTH "W" DIRECTION				PLATE SHEAR MODULUS "W" DIRECTION	
				Typical		Minimum		Typical		Minimum		Typical		Typical		Minimum		Typical	
in	mm	lb/Ft^3	Kg/m^3	psi	Mpa	psi	Mpa	psi	Mpa	psi	Mpa	ksi	Gpa	psi	Mpa	psi	Mpa	ksi	Gpa
1/8	3.2	3.1	50	310	2.14	215	1.48	225	1.55	155	1.07	50	0.34	123	0.85	90	0.62	26	0.18
1/8	3.2	4.5	72	600	4.14	405	2.79	372	2.56	285	1.96	70	0.48	229	1.58	168	1.16	30	0.21
1/8	3.2	6.1	98	935	6.45	680	4.69	539	3.72	455	3.14	117	0.81	340	2.34	272	1.88	45	0.31
1/8	3.2	8.1	130	1445	9.96	1100	7.58	800	5.52	670	4.62	135	0.93	445	3.07	400	2.76	57	0.39
1/8	3.2	10.0	160	1900	13.10	1500	10.34	1000	6.89	860	5.93	175	1.21	455	3.14	490	3.38	65	0.45
1/8	3.2	12.0	192	2400	16.55	1910	13.17	1920	13.24	1250	8.62	-	-	1000	6.89	750	5.17	-	-
3/16	4.8	2.0	32	187	1.29	80	0.55	150	1.03	80	0.55	34	0.23	80	0.55	46	0.32	20	0.14
3/16	4.8	3.1	50	346	2.39	155	1.07	218	1.50	155	1.07	51	0.35	127	0.88	90	0.62	27	0.19
3/16	4.8	4.4	70	580	4.00	280	1.93	320	2.21	280	1.93	72	0.50	240	1.65	160	1.10	36	0.25

Figure 35. 5052 Aluminum Honeycomb Datasheet

The datasheet above shows the mechanical properties for 5052 aluminum honeycomb which was available for us to use during the manufacturing phase of our project. The highlighted sections show the properties for the less dense chassis core material and the more dense hardpoint core material. The valuable information from this datasheet are as follows: Bare compressive strength .580 ksi, Shear strength L direction .320 ksi, and Shear strength W direction .240 ksi. The limiting factor is the cores ability to withstand shear loads in the W direction. Although the ultimate loads appear to be much smaller than the other materials investigated so far, it should be noted that the core area is much larger than the potting area around the inserts for example. regardless these ultimate loading values will be instrumental in running FEA.

Aluminum Flex-Core®
Formable Aluminum Honeycomb

TORAY
Toray Advanced Composites

PRODUCT DATA SHEET

MECHANICAL PROPERTIES

	Material/ Cell Count – Gauge in in.	Nominal Density pcf (lb/ft³)	Compressive Strength					Crush Strength psi	Beam Shear Strength					
			Bare		Stabilized				"L Direction"			"W Direction"		
			Strength (psi)		Strength (psi)		Modulus (ksi)		Strength (psi)		Modulus (ksi)	Strength (psi)		Modulus (ksi)
		Typ.	Typ.	Min.	Typ.	Min.	Typ.	Typ.	Typ.	Min.	Typ.	Typ.	Min.	Typ.
5052	F80-.0013	4.3	524	402	542	455	195	–	300	196	45.0	190	120	20.0
	F80-.0025	8.0	1600	1100	1750	1120	400	–	650	434	98.0	455	260	31.0
5056	F80-.0014	4.3	780	475	860	518	195	–	375	235	47.0	240	138	20.0

Figure 36. Aluminum Flex-Core Datasheet

The above datasheet pertains to TORAY Aluminum Flex Core. Like the 5052 aluminum honeycomb core the same loading configurations apply to the Flex Core. The Flex core shows an ability to withstand higher loads than the 5052 in almost every aspect. The compressive stabilized strength is a whopping .860 ksi for the 5056. The shear strength for the L direction is .375 ksi for the 5056. The shear strength in the W direction is .240 ksi for the 5056. Like the other materials we have evaluated so far the limiting factor matches the material on hand, however we see that the Flex Core offers an added benefit of being lighter and better for taking loads in almost every other configuration. Because the shear strength is the weakest in the W direction does not necessitate the hardpoint will always fail in that particular mode. Consultation with our sponsor eliminated Flex Core as a possible option in order to minimize project complexity, scope creep, consumption of resources, and time and effort spent on the project.

Insert

Unfortunately, we were unable to obtain inserts. Initially we considered three types of inserts that were expected to be available. The three inserts were as follows, outsourced Ultem inserts, polycarbonate inserts, and aluminum inserts. All of our material selection has been based on online research and datasheets, or what was provided by our sponsor. Finding reliable datasheets and information about inserts is nearly impossible as we do not know the material composition of the Ultem, aluminum, and polycarbonate inserts previously used by FSAE. From a materials properties research standpoint we found that aluminum alloys tend to be a stronger material option in terms of tensile strength, compressive strength, and shear strength than polycarbonates or other plastics. After speaking with our sponsor we learned about a potential for corrosion if an aluminum insert is used with a carbon fiber laminate. Likewise, aluminum tends to be heavier than polymers which may have sufficient mechanical properties to be used as hardpoint inserts. For the future continuation of this project it is expected that a PLA filament will be used to produce inserts.

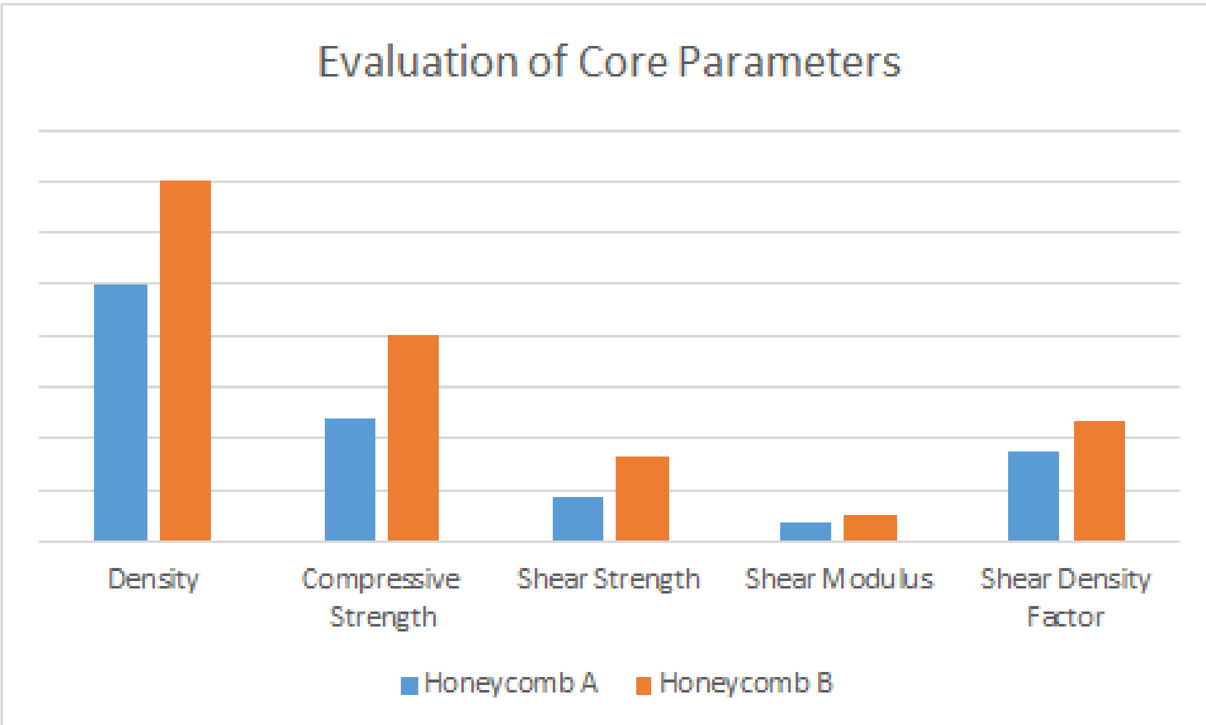


Figure 37. Evaluation of Core Parameters Chart

The chart above gives a visual representation comparing the two 5052 aluminum honeycomb cores we have. The chart was made to normalize strength over density. Although honeycomb B, the high density honeycomb (4.4g/cm^3), is heavier than honeycomb A (3.1g/cm^3), the normalized compressive, and shear strength confirm that the 4.4g/cm^3 is the best on hand choice for manufacturing and testing hardpoints. This core material will better prevent failure modes that the hardpoints are likely to see. The stronger core will help meet the stiffness and strength requirements needed by our sponsors.

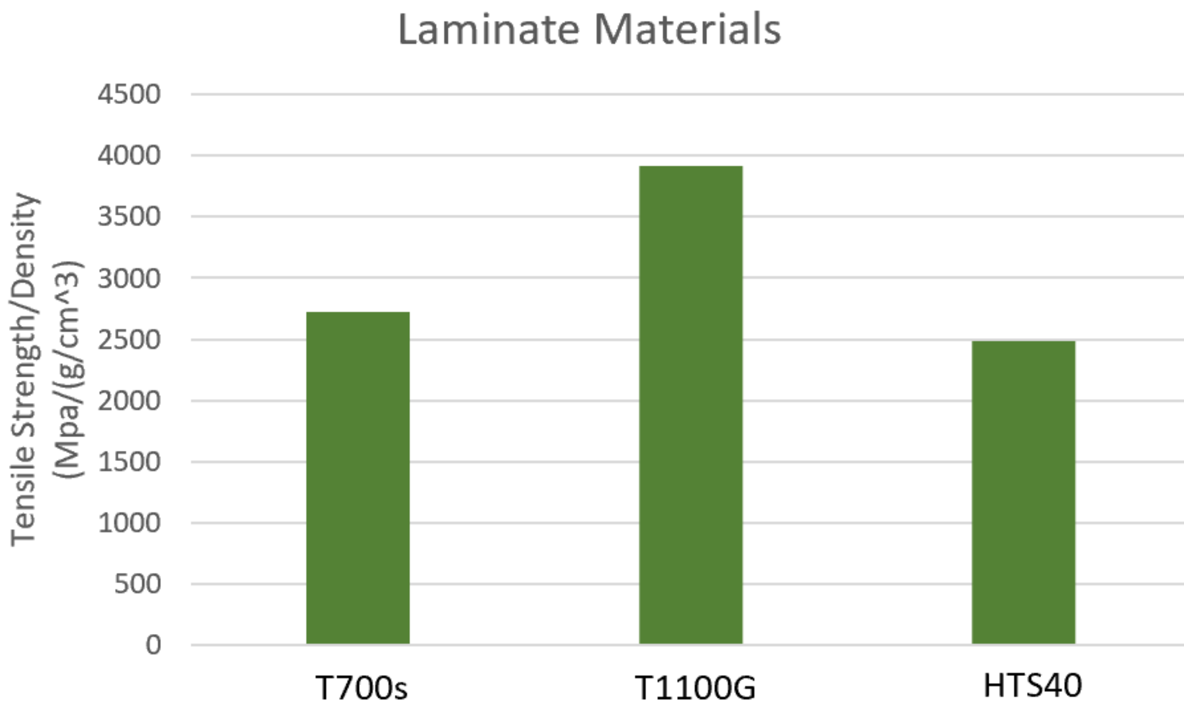


Figure 38. Laminate Materials Chart

Similar to the core chart, the laminate chart normalizes tensile strength to density for three choices. The T700 and the HTS40 we have used and tested. available to test and rank similarly on this chart with the T700 having a slight edge over the HTS40. According to this graph the T1100G would be the ideal laminate as far as testing for tensile strength.

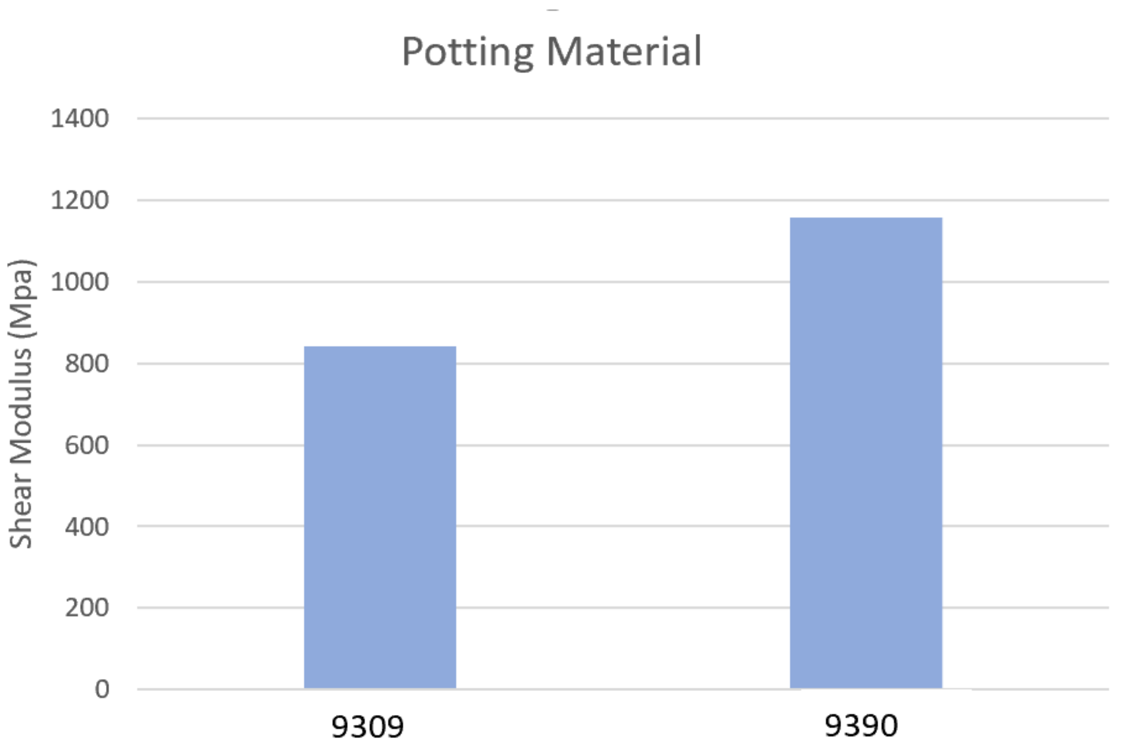


Figure 39. Potting Materials Chart

The chart above gives a quick visual representation of the shear modulus for two potting compounds. This chart simply evaluates the raw data of the bulk resin properties provided by the datasheets and does not necessarily correlate with effectiveness in a hardpoint. Currently 9309 is the available compound we have on hand to use to pot the inserts. However, figure 34 can be used as a justification for acquiring 9390 for future projects.

The following equation was used to determine the potting radius:

$$(1.002064*A) + (0.940375*B) - 0.7113 = C$$

C is the potting radius, A is the Insert radius, and B is the Core cell size. So using this relationship found in the ESA Insert Design Handbook, the potting radius was determined as shown in Table 10 below. The insert radius used was from the aluminum inserts we recommended to the team, these inserts come in a standard size, the size can be changed through manufacturing, but this adds a lot of time to the overall manufacturing process that the team may not want to spend. Thus reiterating the size of the potting radius will be recommended after testing as the sizing of this radius is a lot easier to control and does not affect the overall manufacturing process time. However, since the team has expressed interest in manufacturing their own inserts, it might be possible to change the sizing of the inserts in the future to better serve the needs of the hardpoint.

Core Splice

LOCTITE EF 9899 AERO was used to adhere the two core densities together. As there is some discontinuity associated with mating the two honeycomb cores, a core splice is used to fuse the gaps between cells. Loctite EF 9899 expands during the curing process closing cell gaps, providing a completely homogenous cell structure. The curing temperature and time for Loctite EF 9899 is 250 degrees Fahrenheit for one hour. Loctite EF 9899 has an expansion capability of 650%. The magnitude of expansion is controlled by the volume parameters of the mold as well as cure pressure administered via a vacuum bag. Typical cured density for loctite EF 9899 is 7.5 to 25 lbs/ft^3, much less dense and structurally weaker than the density of either aluminum honeycomb core. Thus mitigating excessive gaps or crude cuts when fitting cores together is crucial.

Going forward, there are a few issues that we are aware of. It is likely, we will have to reiterate the design multiple times in order to reduce the risk of failures that we observe during testing. Finally, adjusting one component will likely have adverse effects on the other components. Thus, the sizing will have to be adjusted and reiterative testing measures used to find the optimized hardpoint design. Table 10 below shows the final design components choices we had made by the end of Fall 2020.

Table 10: Final Design Choices

Parameters	**Design Decision**	**Initial Sizing**
Hardpoint geometry	Circular	-----
panel Geometry	Rectangular	10"x12"
Potting Compound	Loctite 9309	0.75" radius
Laminate	HTS 40 @ 45° and 0°, T700	45c/02/0c2/Core/0c/45c
Insert	Aluminum Half Spool Inserts	0.33" Diameter w/ 0.625" diameter spool
Core	5052 Aluminum honeycomb B	4" and 3" Diameters

6.3 Safety

We will be frequently working with hazardous materials therefore safety precautions will be used to limit exposure and likelihood of injury. While working in the composites lab/shed we will be wearing safety glasses/goggles at all times. When working with epoxy resins, latex or some form of silicon gloves will be worn at all times. If at all possible respirators or vapour shields will be used to mitigate inhalation of harmful chemicals. Protective gloves will be worn while working with tools such as drills, putty knives, razors, and screwdrivers. One of our biggest concerns is the dangers associated with the instron testing machine. A protective shield will be used as a barrier between us and the workpiece when the machine is under load. One person will load the machine while another person will operate the machine. There will be a lab supervisor on site whenever we are working in the lab. We will use protective gloves whenever maneuvering test samples in or out of the oven to cure.

6.4 Bill of Materials

Below is our finalized bill of materials. This list is a mix of what is currently available in the hangar through CPFSAE, and a few materials we recommend for future testing. We considered individually purchasing components to test, like the Loctite 9390 potting compound, however, the price was out of our budget. We are only allowed to receive materials through CPFSAE's sponsor companies. Thus, all the materials used were on hand or donated.

Table 11. Finalized Bill of Materials (Winter 2021)

Material	Supplier	Cost
HTS Multidirectional Prepeg (skin)	FSAE	$0.00
T700 Unidirectional Cloth (skin)	FSAE	$0.00
Toray-cetex TC1100 (skin)	Toray/Donation	$0.00
5052 Aluminum Honeycomb 3.1 lbm/ft^3 (Core)	FSAE	$0.00
5052 Aluminum Honeycomb 4.4 lbm/ft^3 (Core)	FSAE	$0.00
Aluminum Flex Core	Donation	$0.00
Loctite 9309 (Potting Compound)	FSAE	$0.00
Loctite 9390 (Potting Compound)	Pilot's HQ/Donation	$0.00
Polycarbonate (insert)	FSAE	$0.00
Ultem (insert)	FSAE	$0.00
Aluminum (insert)	FSAE	$0.00
Redux 312UL Adhesive Film	Donation	$0.00
Total		$0.00

6.5 Testing Parameters

According to our sponsor, hardpoint test panels should be 24"x12" to mitigate artificial panel stiffness imposed by the jig. However, we have decided on standardizing panel size to 10"x12". With the size of the core pieces available to us in the composites shed, this panel size was the maximum size we could make. The thickness of each panel is 0.91 inches and contains a circular higher density core. We have opted for 3" and 4" diameters to test. Our sponsor has determined through previous projects that a 4" diameter core is sufficient to meet the load specifications of the hardpoints. We have decided to test 3" diameter cores as well to see if they are a viable option that will reduce overall weight. Polycarbonate inserts will likely be one option used for future project testing due to their relative ease of access as they can be printed at school or by the sponsor. Aluminum inserts are also available and provide better strength, which is why we recommended them. However, it will be valuable to test other insert materials as the team is interested to see if a lower density insert will be able to prevent failure while saving weight. Loctite 9309 will be used as a potting compound due to its onhand availability. HTS40 in a 45° configuration followed by two T700 sheets, followed by two HTS40 aligned at 0° have been used to create the top facing sheet. HTS40 0° followed by HTS40 at 45° was used for the bottom sheet of each panel.

For future testing, we suggest finding the best material or shape combination for each function: geometry, potting compound, core and laminate. Finding the best geometry according to our project scope maintaining constant materials and dimensions with the exception of hardpoint core diameter is pivotal. For finding the best materials, we suggest keeping the geometry constant. A list of suggested materials for each function is shown in Table 12 below.

Table 12. Planned testing choices for each function.

Parameters	**Design Decision**	**Initial Sizing**
Hardpoint geometry	Circular	-----
panel Geometry	Rectangular	10"x12"
Potting Compound	Loctite 9309	0.75" radius (Requires Iterartion)
Laminate	HTS 40 @ 45° and 0°, T700	45c/02/0c2/Core/0c/45c
Insert	Aluminum Half Spool and PLA Inserts	0.33" Diameter w/ 0.625" diameter spool
Core	5052 Aluminum honeycomb B	4" and 3" Diameters

The hardpoint combinations were planned to be tested on campus in the composites materials lab using the Instron Tensile and Compressive Tester. The form of testing to be used is 90 degree pull-out tests. The pull-out test is executed by mounting the hardpoint parallel to the ground and attaching a fixture to the insert of the hardpoint. The hardpoint is subjected to an increasing tensile load on one side of the skin, compressive load on the other, and shear load in the core until ultimate failure. Under this type of load, the hardpoints are most likely to experience core failure as stated in the failure modes section of this report. An example testing set up and schematic of the pull-out test is shown in Figures 40 and 41.

Figure 40. Testing Setup of a Hardpoint Pull-Out Test

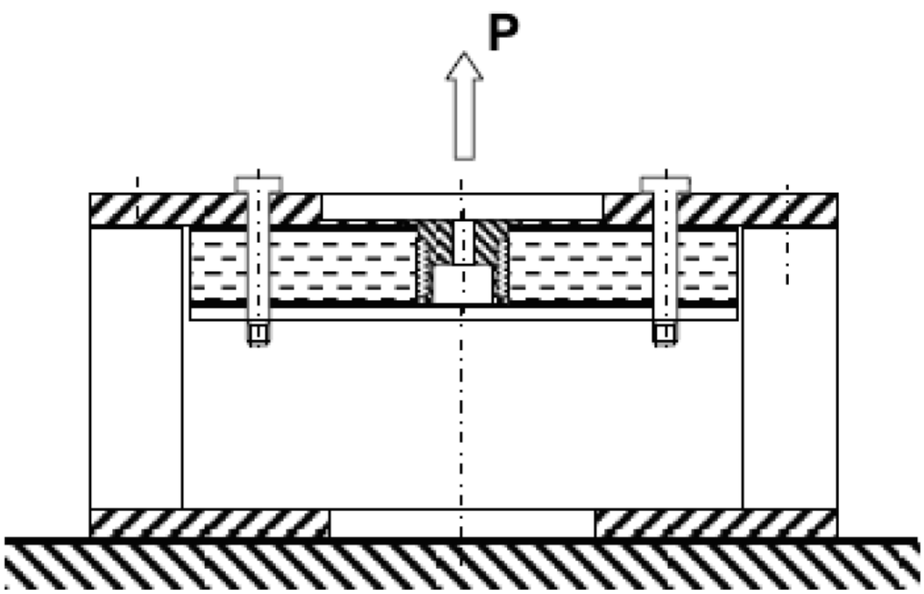


Figure 41. Schematic of a Hardpoint Pull-Out Test

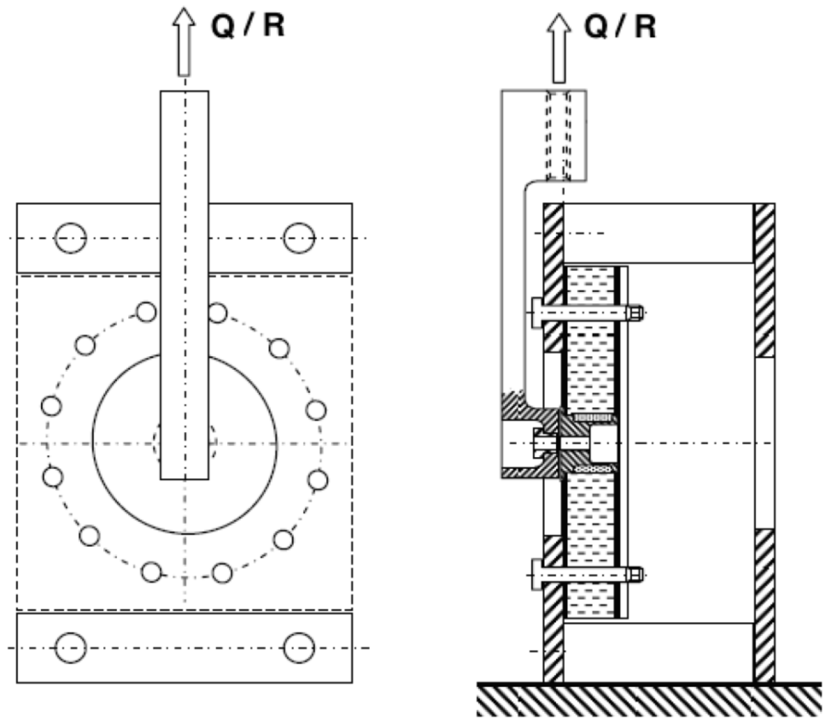


Figure 42. Schematic of a Hardpoint Shear Test

Due to the nature of individualized hardpoints, individualized testing will be required. Hardpoints located in the engine bay typically experience more out of plane loading where three point testing for tensile and compressive failures will provide useful information. Other hardpoints such as those pertaining to the suspension my experience torsional and bending loads. Using the Instron testing equipment bending and torsional tests can be achieved. Further investigation of how to administer these tests is required from our team. Our next step is to contact Dr. Elghandour and experienced members of the FSAE team in order to learn ways to create niche testing scenarios such as bending and torsion.

7. Manufacturing/Testing

7.1 Material Procurement

Our project is sponsored by Cal Poly Racing, so all of our materials must be procured through them. Cal Poly Racing receives these materials as donations from various companies, so the materials we have available are somewhat limited. Some materials were left over from previous years, so our tests will be conducted using these materials. A list of available materials is shown in Table 13 below. These materials were available to us in the composites shed on campus, as well as in the Formula team cage in the hangar.

Table 13. List of Materials currently available for testing.

Material	Component
HTS MultiDirectional Prepreg	Skin
T700 Unidirectional Cloth	Skin
5052 Aluminum Honeycomb 3.1 lb/ft^3	Core
5052 Aluminum Honeycomb 4.4 lb/ft^3	Core
Loctite 9309	Potting Compound

7.2 Manufacturing and Assembly Steps

During Winter 2021, we worked with the materials available to us in the composites shed. Our contact from the formula team, Al, assisted us in all of our construction processes. The quarter started out with testing samples of HTS 40 directional prepreg and 0° unidirectional T700 prepreg. We tested two configurations of the HTS 40 material cut at 0° and 45°. The goal of these tests was to gain a better understanding of the laminate material we would be using while collecting valuable data for the Formula team. Additionally, the preparation of these panels The sponsor tasked us with testing fibre tensile coupons because the materials on hand had been sitting in the freezer for a couple of years, and the team was curious to see how the material properties of the laminates had changed over time.

The HTS 40 samples were prepared in the composites lab located in building 192. We used a 10 ply lay up, and made enough for 5 samples of each orientation. The lay up was done in a large sheet that was 11’’x11’’, then placed in the oven to cure. Each layer of the HTS 40 had a protective plastic layer covering the adhesive side. We peeled each of these protective layers off, and placed the layers on top of each other. The curing process was done using the TC275 oven preset. The oven cure preset was as follows, (2°F)/min to (225°F) and held for 1 hour, then (1°F)/min to (275°F) for 3 hours, followed by freestanding post cure for 2 hours at (350°F). The total cure time was 10.5 hours.

To prepare for the cure, we first wiped down a steel sheet with acetone to clean off any residue. This was our curing surface that the lay up would be placed on. After the acetone dried, we wiped the curing surface with release wipes, which allowed the sample to be removed from the steel sheet easily after curing. After the release wipe dried, we began constructing our vacuum bag setup. We put tacky tape along the edges of the sheet to create an airtight seal for the vacuum bag. For our vacuum valve, we used an airtech valve supplied by the formula team. The vacuum bag goes in between the two pieces of the vacuum valve. This is where the air is sucked out of the setup. We also placed a piece of breather cloth underneath the vacuum valve to allow a path for air to escape throughout the setup.

Figure 43. Sandwich Panel Prepared for Curing in a Vacuum Bag

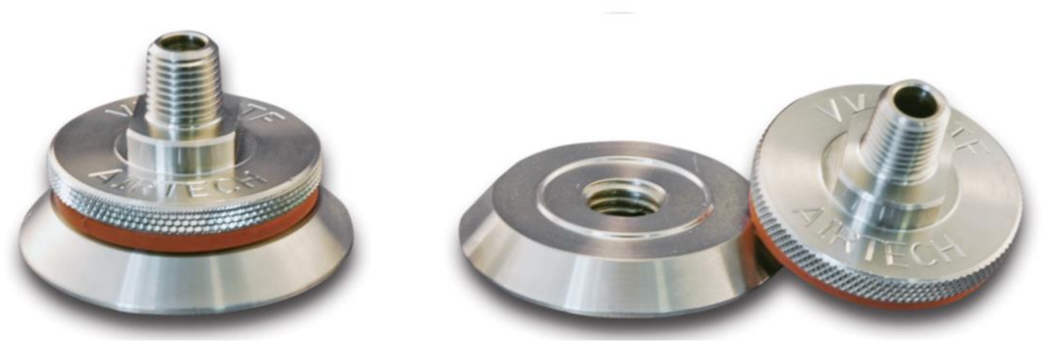


Figure 44. Vacuum Breathing Valves

After the curing process was complete we took the hardened 11”x11” carbon sheets to Mustang 60 to prepare tensile testing coupon samples according to the dimensions listed in ASTM D3039. We used a tile saw to cut all of our HTS40 samples cut to 1”x10”. The same tile saw was used to cut the T700 unidirectional coupons to measurements of 0.5”x10”. The saw had a tendency to split the T700 because we were cutting parallel to the fibre layout. As a result of sample splitting, the T700 coupons ranged in thickness from 0.8 to 1.2 inches. The disparity in size variation can be neglected as long as a sufficient sample size is used to gather data.

To prepare each carbon fiber laminate coupons for testing in the instron machine, steel tabs had to be manufactured. The steel tabs acted as a barrier between the test samples and the jaws of the instron machine. The tabs reduced the likelihood of the instron machine damaging the samples and interfering with the failure mode data. The steel tabs were cut from a 24”x24” sheet of 0.06” steel using a shear. The tabs were cut to 1”x2” for the HTS40 and 0.5”x2” for the T700 coupons. Each tensile coupon required four tabs to be custom cut for fitting. Due to minor inconsistencies in sizing the tensile bars, we wanted to ensure each tab fit flush with the edges of the samples. The tabs were then sanded using 240 and 400 grit sandpaper to remove any coatings or surface inconsistencies. Likewise, the sanding process aided by roughing up the surface of the steel allowing for better bonding to the tensile bars. Next Loctite 9309 was prepared by mixing the directed proportions together, a mass ratio of 23:100 for components A and B. The epoxy was liberally coated onto one side of each tab and then placed on either end of the tensile bars and allowed to cure for three days.

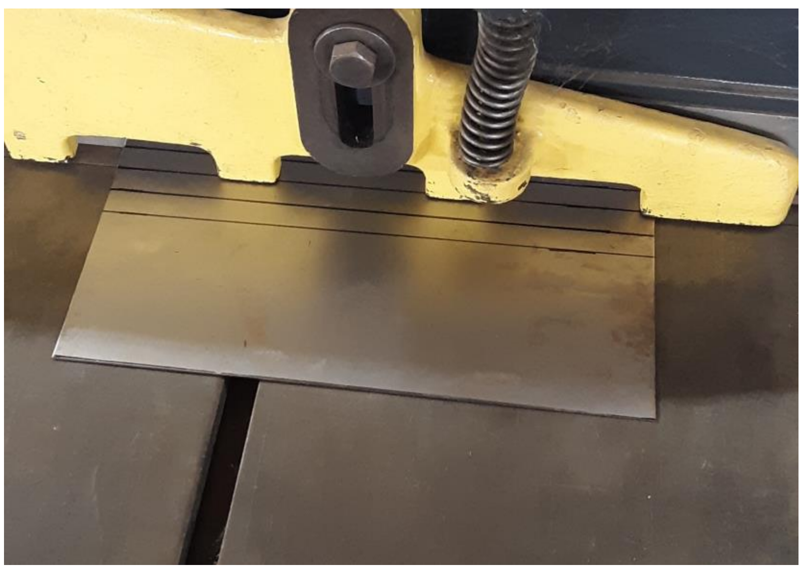


Figure 45. 0.06 Inch Steel Tabs Being Cut with Shear

Table 14. Chassis Carbon Fiber Lay-up Arrangement

	Laminate	Core	Core Thickness
FBHS	[45c/02/0c2/Core/0c/45c]	3/16 3.1 pcf Aluminum	0.7
Front Bulkhead	[(45c/0/0c)*5/Core/(0c/0/45c)*4/0c/45c]	3/16 3.1 pcf Nomex	0.5
SIS	[45c/03/0c3/Core/0c2/0/45c]	1/8 4.4 pcf Aluminum	0.7
Upper Harness	[(45c/0c)4/Core]s	3/16 3.1 pcf Fiberglass	0.5
Rear/General	[45c/0/0c/Core/0c/45c]	3/16 3.1 pcf Aluminum	0.5

The next segment of our project consisted of constructing the panels that would be used to test our hardpoint configurations. The first panel we made was a tester panel to help us familiarize ourselves with the panel construction process. This panel was 8”x8” in size.

For the rest of the panels we made, we varied the diameter of the core puck. The current standard that CPFSAE uses for their core puck is a 4” diameter. Half of the panels we made consisted of the standard 4” core puck, and the other half of the panels consisted of a 3” core puck. Due to having a limited supply of honeycomb core available on hand the panel size was limited to 10”x12” to ensure uniform sizing for all panels. The reduced size risks introducing artificial stiffness from the clamped edges. We made 6 panels in total. The vacuum bagging process and the curing process was exactly the same as described for the tensile bar samples. Preparing the panels started with the cutting of HTS 40, in both the 0 and 45 directions, T700 Unidirectional prepreg, and the honeycomb core. This was done using a box cutter and scissors. The panel construction varied in the lay up order of carbon sheets and cloth, as well as the use of core splice and adhesive film. The lay up order of the panels is shown in Table 14. Our panels are laid up according to the FBHS, or Front bulkhead support. So, we began with a 45 degree sheet of HTS 40 placed face down followed by two sheets of T700. Next, a 0 degree sheet of HTS 40 was placed down followed by the film adhesive, then the core, then another layer of film adhesive. Finally, one sheet of 0 degree HTS 40 is placed on the film adhesive, then the final 45 degree HTS 40 is placed on that. Once the last sheet of plastic is removed from the 45 degree HTS 40, the entire panel is flipped onto a cleaned steel sheet. The panels are made of an outer Aluminum honeycomb core that has a density of 3.1 lbm/ft^3, along with a circular section of higher density core of 4.4 lbm/ft^3. This area is also known as the core puck. We then cut the main core material and core puck from sheets of aluminum honeycomb located in the FSAE shed using box cutters. Careful cutting practices had to be used to minimize cell distortion and crushing. We then merged the main core, and core put together using core splice (Loctite EF 9899). The core splice was a putty-like substance that was molded in between the high density and low density cores. Next, we layed up the carbon sheets in the order shown as described above. Once the panels were assembled, we prepared them for curing in the oven. The curing procedure was the same as that used for creating the tensile test coupons. Likewise, the same curing conditions were used, the TC275 preset on the oven for 10.5 hours. When curing panels however, we placed a cotton layer on top of the test sample in between the bag and the sample. This prevented sharp corners or aluminum shavings from penetrating the vacuum bag during the cure. Through future testing, we hope that tests show if a smaller core puck can be used to reduce overall weight in the chassis while maintaining sufficient mechanical properties.

Figure 46: Cleaning the Vacuum Lay-up sheet and Removing Adhesive Lining

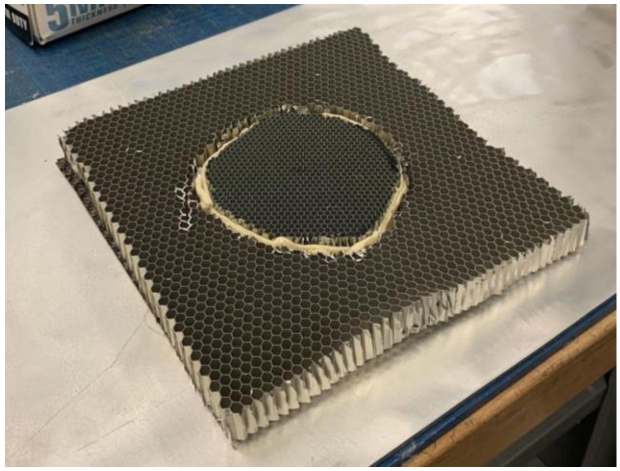


Figure 47: Hardpoint Panel With 4” Core Puck and Core Splice

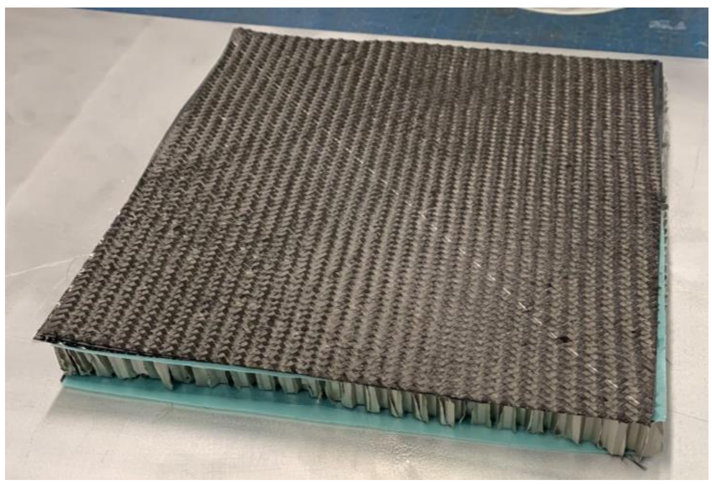


Figure 48: Hardpoint Panel Before Curing

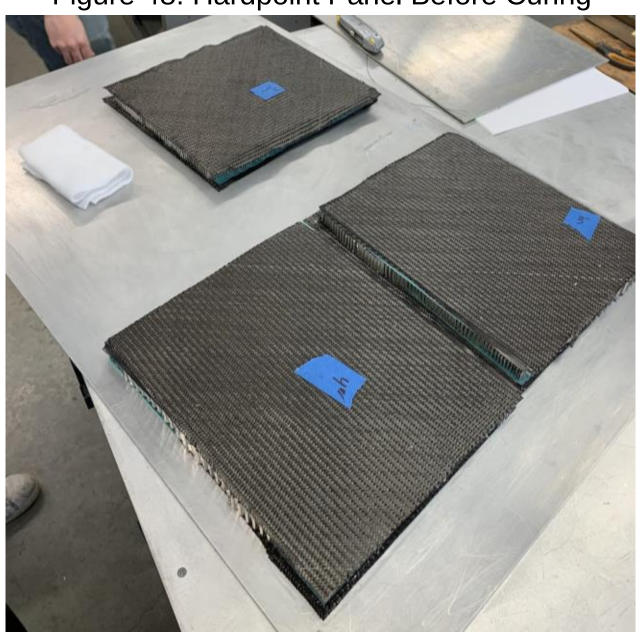


Figure 49: Three Hardpoint Panels Prepared for Curing

7.3 Outsourcing

We did not outsource any pieces for our project. Previous FSAE projects had outsourced inserts to be manufactured by Ultem. Our sponsor notified us that Ultem had dropped the project at least for the duration of this year. All of the materials we used for manufacturing and testing were provided by the Formula Team.

8. Design Verification

During Fall 2020, our Design Verification planned to involve several tests in order to determine whether the sponsor's needs were met by our design. The first two tests would determine if the current sizing meets the load conditions the design will undergo without failing. After these tests, we would be able to determine if our current sizing needed to be reiterated. Subsequent in plane and out of plane strength tests would be conducted with reiterated sizing. We would also be testing different insert materials, since our sponsor specified that they would like this data for future use, and it would also help determine whether the correct insert design choice was made. Additional tests would include weighing of individual hardpoints in order to determine whether the minimized weight target is reached. During this testing process the Manufacturing Time would be observed as we construct the hardpoints, as to determine whether the new design met the desires of our sponsor. Finally, we planned to perform FEA of the whole chassis with the hardpoints added in order to determine whether the stated stiffness requirement was met. Ideally, each test would have involved multiple samples, as to ascertain more accurate data and to perform uncertainty analysis.

Our design verification was cut down to minimal testing and the design of a testing jig. We miscalculated how long it would take to manufacture a large number of panels due to limited use of the oven in the composites lab, as well as limited shop hours.

8.1 Testing

Unfortunately, we were not able to test any hardpoint configurations due to lab time restrictions and time conflictions. Our original testing plan was to first test all of our tensile bar samples that we made, then move on to testing hardpoint configurations in the panels we made. We were able to accomplish the tensile testing for our laminate samples, but we lacked the required materials to start our hardpoint testing. All tests were done using the Instron tensile testing machine in the composites lab. The tensile bar testing followed the ASTM D3039/D3039M standard. This process consists of preparing the tensile bar samples in a way that the Instron will not damage them while testing. The required standard dimensions for accurate testing are shown in Table 15 below.

Table 15: ASTM D3039 Tensile Sample Standard Dimensions

Fiber Orientation	Width, mm [in.]	Overall Length, mm [in.]	Thickness, mm [in.]	Tab Length, mm [in.]	Tab Thickness, mm [in.]	Tab Bevel Angle,°
0° unidirectional	15 [0.5]	250 [10.0]	1.0 [0.040]	56 [2.25]	1.5 [0.062]	7 or 90
90° unidirectional	25 [1.0]	175 [7.0]	2.0 [0.080]	25 [1.0]	1.5 [0.062]	90
balanced and symmetric	25 [1.0]	250 [10.0]	2.5 [0.100]	emery cloth	—	—
random-discontinuous	25 [1.0]	250 [10.0]	2.5 [0.100]	emery cloth	—	—

Table 15 above shows the minimum required dimensions, we sized our samples accordingly. The HTS 40 samples had dimensions of 1”x10” with ten plies of thickness. The T700 samples had dimensions of 0.5”x10” with 8 plies of thickness. The dimensions of the samples were measured prior to testing. All samples were tensile tested in the Instron, which provided load, displacement, stress, and strain data. Additionally, we recorded the failure methods. The data gathered is shown below in the form of Force vs. Displacement and Stress vs. Strain plots.

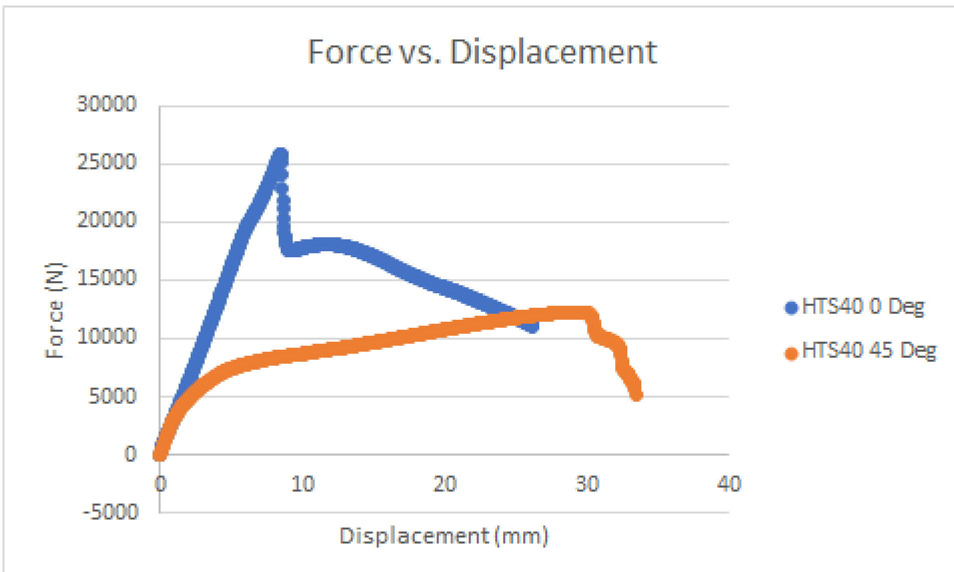


Figure 50: Force vs. Displacement for HTS 40 in both 0 and 45 directions

Figure 50 above shows the Force and Displacement of an HTS 40 sample laid up in the 0 degree direction as well as a sample in the 45 degree direction. The force increases nearly linearly for 0 direction before fracturing at a load over 25 kN. The 45 direction has a logarithmic response until fracture was achieved at a load close to 12 kN. From the plot we can see that the max load for the 0 direction is much higher than the 45 direction.

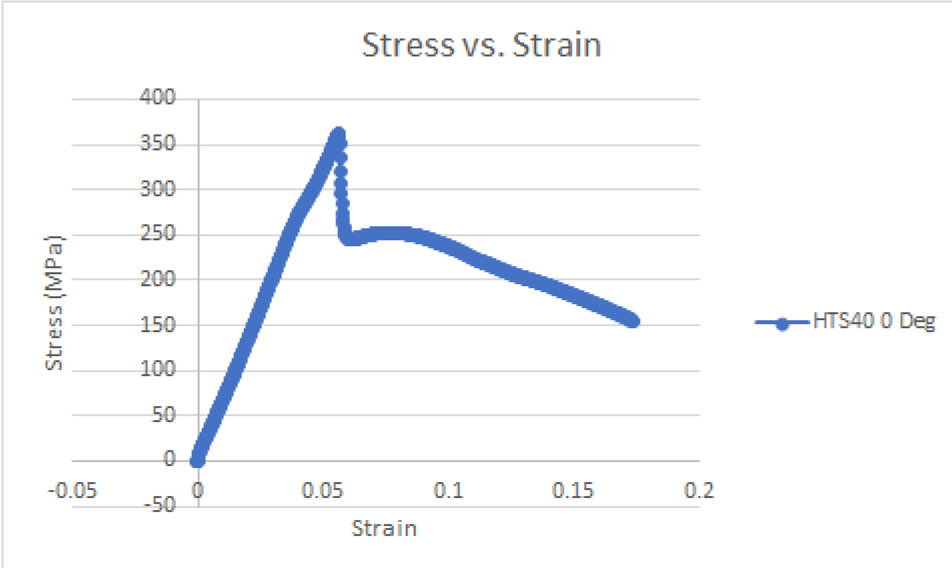


Figure 51: Stress vs. Strain plot for HTS 40 0 dir.

Figure 51 above can be used to find ultimate tensile strain as well as the modulus of elasticity by finding the slope in the linear region. The ultimate tensile strain is found by finding the maximum strain before failure.

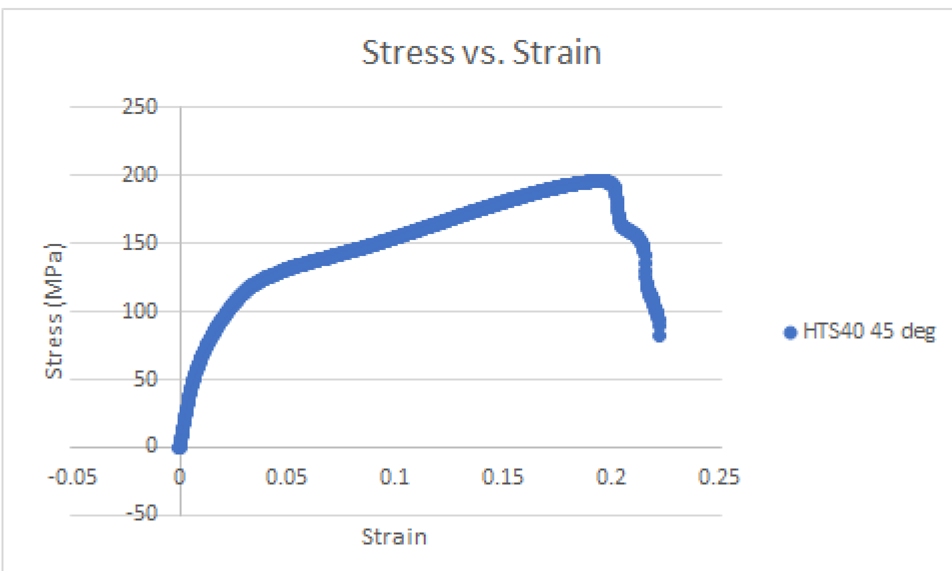


Figure 52: Stress vs. Strain plot for HTS 40 45 dir.

Figure 52 above can be used to find ultimate tensile strain as well as the modulus of elasticity for the HTS 40 in the 45 direction.

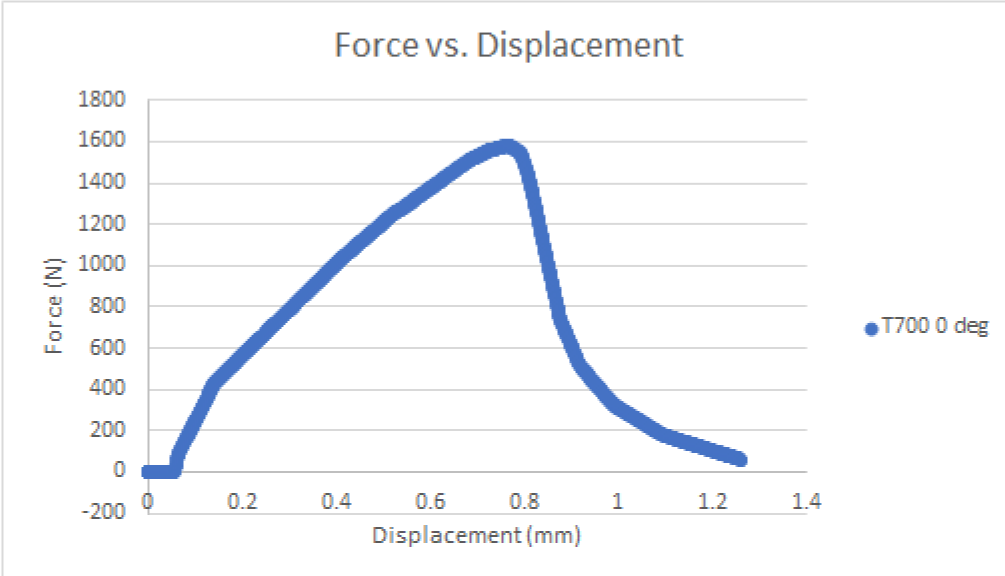


Figure 53: Force vs. Displacement for T700 0 direction

Figure 53 above shows the Force and Displacement of a T700 sample laid up in the 0 degree direction. The force increases nearly linearly before fracturing at a load over 1.6 kN.

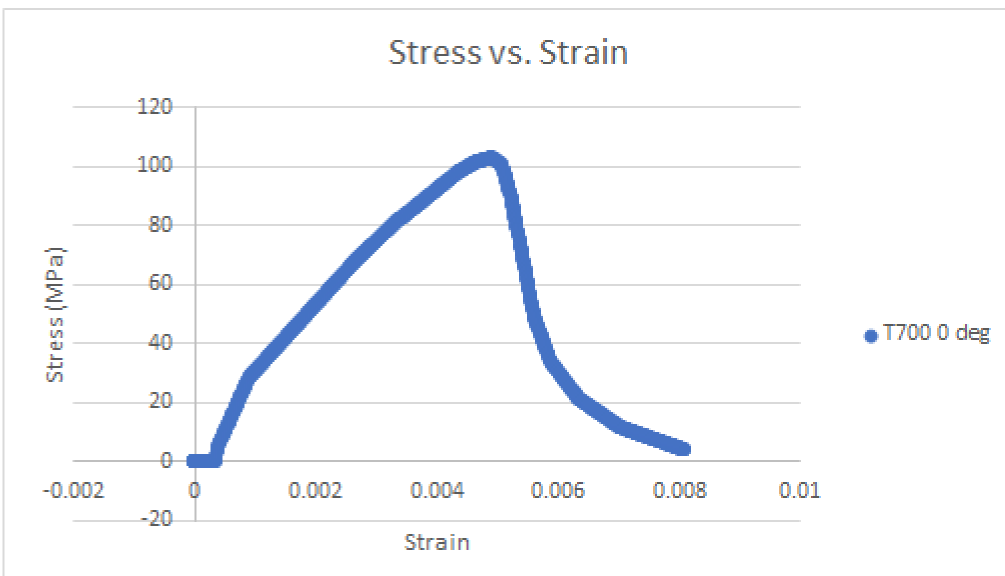


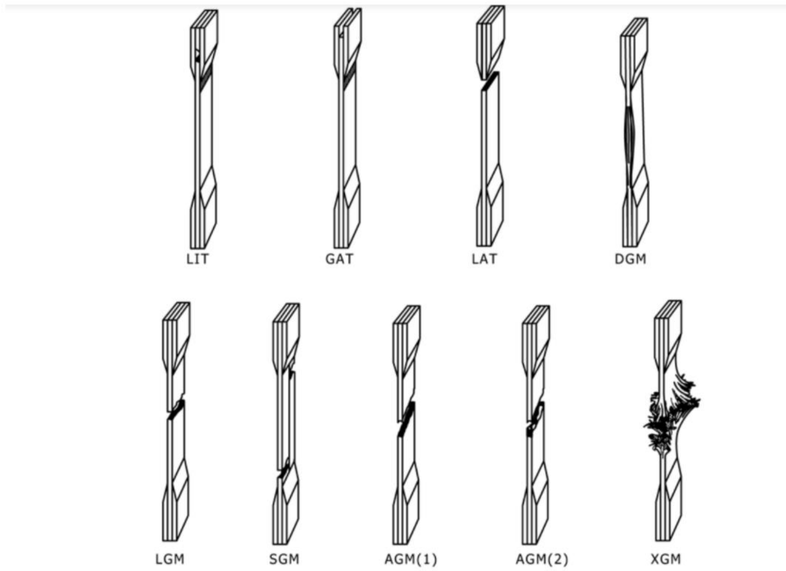
Figure 54: Stress vs. Strain plot for T700 0 dir.

Figure 54 above can be used to find ultimate tensile strain as well as the modulus of elasticity for the T700 in the 0 direction.

Table 16: Properties of Laminates based on Tensile Test data

	HTS40 0 Deg	HTS40 45 Deg	T700 0 Deg
Cross-sectional area (mm^2)	71.50	62.70	15.34
Gauge length (mm)	151.1	150.7	153.5
Pmax (N)	25848	12272	1581
Ultimate Tensile Strength (MPa)	361.5	174.8	103.1
Ultimate Tensile Strain	0.056	0.206	0.00467
Modulus of Elasticity (GPa)	6.588	5.954	45.70

Table 16 above shows key parameters for the tested laminate materials. The cross-sectional area and gauge length were both measured before testing. The rest of the parameters were calculated from the plots and data received from testing. Ultimate Tensile Strength is found by dividing Pmax by cross-sectional area of the sample. Ultimate Tensile Strain is found to be the strain before failure. Modulus of Elasticity is found by finding the slope in the linear region of the Stress-Strain plots. The main takeaway from the testing is that the expired laminate data is significantly varied from the original datasheets, which made previous analysis hard to compute and inaccurate. However, now with the new data further analysis on the hardpoints can be conducted to produce better designs. The data tells us that the HTS40 0 direction has the highest tensile strength, while T700 has the lowest strength. HTS40 45 direction has the greatest ultimate strain, while T700 had the least. This tells us that HTS40 in the 45 direction can deform the most before failing, while T700 deforms the least, but is also the weakest. We can also learn from the failure modes. From the figure below from ASTMD3039, we can classify the failure modes observed in testing.



First Character

Failure Type	Code
Angled	A
edge Delamination	D
Grip/tab	G
Lateral	L
Multi-mode	M(xyz)
long. Splitting	S
eXplosive	X
Other	O

Second Character

Failure Area	Code
Inside grip/tab	I
At grip/tab	A
<1W from grip/tab	W
Gage	G
Multiple areas	M
Various	V
Unknown	U

Third Character

Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
Middle	M
Various	V
Unknown	U

Figure 55: ASTM Failure Modes and Codes

The figures below show the failure modes experienced by a few of the samples we tested in the Instron machine.

Figure 56: Failure of Selected Samples

The sample on the left is the HTS 40 0 direction, we can classify it as LGM. It failed as we expected to, along the weave at the center of the sample. The same can be said of the middle samples of HTS 40 45 direction. They can be classified as XGM, and they both fail along the weave. Though it doesn't look like a clean break like the first sample, the weave crosses the sample diagonally, thus the failure is still along the weave. The final sample, T700, whose failure is shown in the figure below, can be classified as SAT. This sample also fails along the weave, as the weave is in a vertical orientation. Thus, the failure modes are as we expected for the samples tested.

Figure 57: Failure of T700 Sample

If our team had more time for testing, we would first test the 6 10"x12" panels we cured this quarter. The testing required for these panels involves pullout testing, where a suspension mount is pulled vertically out of a hardpoint. Additionally, shear testing needs to be done, where the suspension mount is attached to the hardpoint parallel to the panel and pulled by the Instron. Additional tests include pullout tests at different angles to simulate the max cornering scenario. The purpose of these tests is to observe failure modes, as well as to determine core sizing and insert selection. Several more panels will need to be cured and laid up. The panels that are already cured allow for testing core puck sizing. If the 3" core pucks are able to withstand the maximum load required by the team to a reasonable safety factor, then we recommend those be used over the 4" core pucks to conserve weight. Further manufactured panels should be used for testing different types of inserts and their effectiveness. We recommended the corrosion resistant aluminum alloy (5052 or 6061) inserts because they are stronger and can help compensate for weaker materials the team cannot upgrade. However, if an insert with a lower density is able to manage the load with a reasonable degree of safety, we would recommend the usage of those inserts. We recommend using three to five samples per variable change for statistical certainty. For these tests, a jig is needed to do shear testing and pullout testing at different angles. The jig we designed is covered in the section below.

8.2 Jig Design

A big part of our testing plan was designing a jig to test the panels we made. This task was given to us during week 10 of Winter quarter 2021, close to the end of our project, so our group was unable to put as much time into the design as we had hoped. Previously, we had been informed that a testing jig was already available for us to use, however this jig was unable to be located.

Our sponsor from the formula team requested that we design a testing jig for the Instron machine that can test panels at multiple angles. The reason for this is to simulate hardpoints being loaded at different points of the chassis. Our sponsor asked for a jig that can test panels at 0°, 30°,45°, and 90°. The 0° test is also known as the pull-out test, as mentioned earlier in this report. Due to time restrictions, we did not consider any shear testing. The vast majority of failures in hardpoints occur from a pull out load. Therefore, our testing jig design covers different angles of pull out.

The jig design process started with our team asking our sponsor for wants and needs of the jig. Along with the different pull-out angles, the sponsor desired the use of 0.125 in. thick steel, and 0.25 in. steel for the bottom jaw tab. Our team members came up with a couple preliminary designs to present to our sponsor. The figures below show our first iterations.

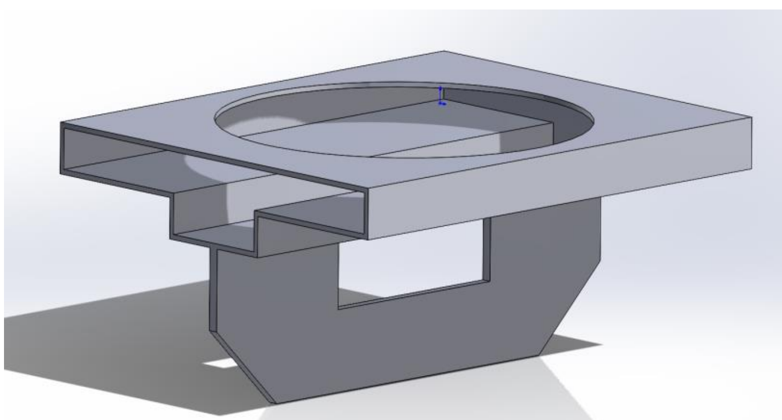


Figure 58: Preliminary Jig Design 1

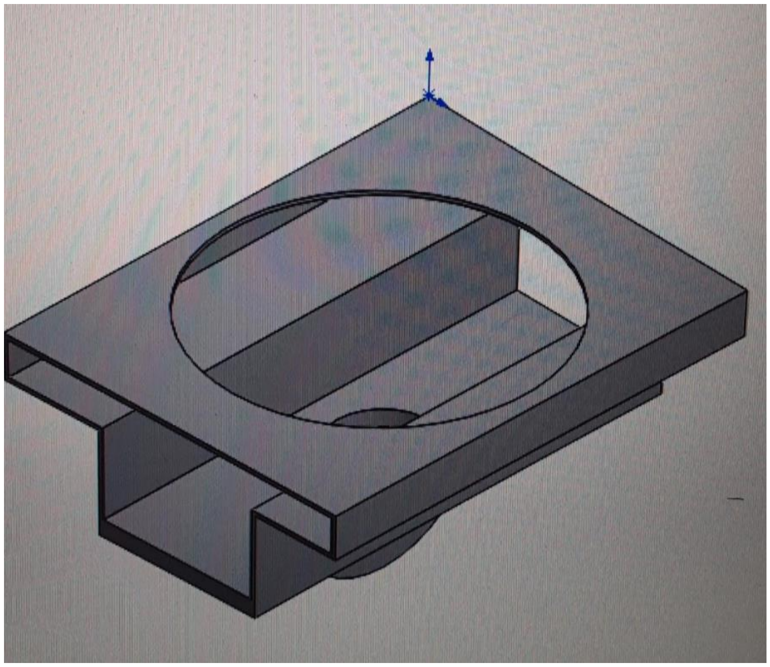


Figure 59: Preliminary Jig Design 2

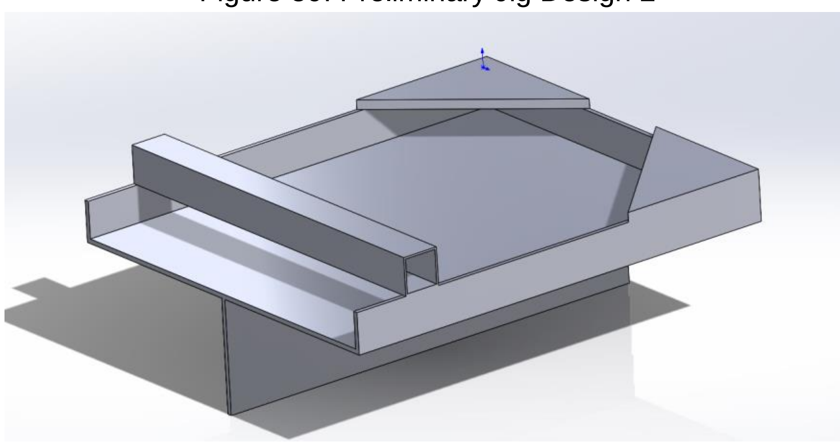


Figure 60: Preliminary Jig Design 3

After reviewing our preliminary designs, our sponsor requested the use of square steel tube stock, symmetrical constraints, and access to the back of the panel for a bolt. The square steel tube stock was requested due to a high moment of inertia compared to the plate designs we had, and the symmetrical constraints were suggested so that the load on the panel would be evenly distributed during testing. Our final design included all of the design suggestions from our sponsor. We also implemented a pin system that allows the top part of the jig to rotate with 1 degree of freedom instead of having the bottom instron jaw clamp directly onto the top part of the jig. The jig is meant to hold a sandwich panel in the rectangular space below the square tube stock. The channel below this rectangular space is meant to account for the mounting required to attach the suspension. There is an opening in the middle of the channel to allow the suspension to be attached once the panel is put into place. The panel will be secured using two dowel pins inserted once the panel has slid into place. The square holes on the connector ensure the jig does not rotate about the connecting pin, which was an issue we had with other designs. The square hole will have to be cut using the waterjet located in Mustang 60, which is capable of cutting intricate shapes with high precision and accuracy.

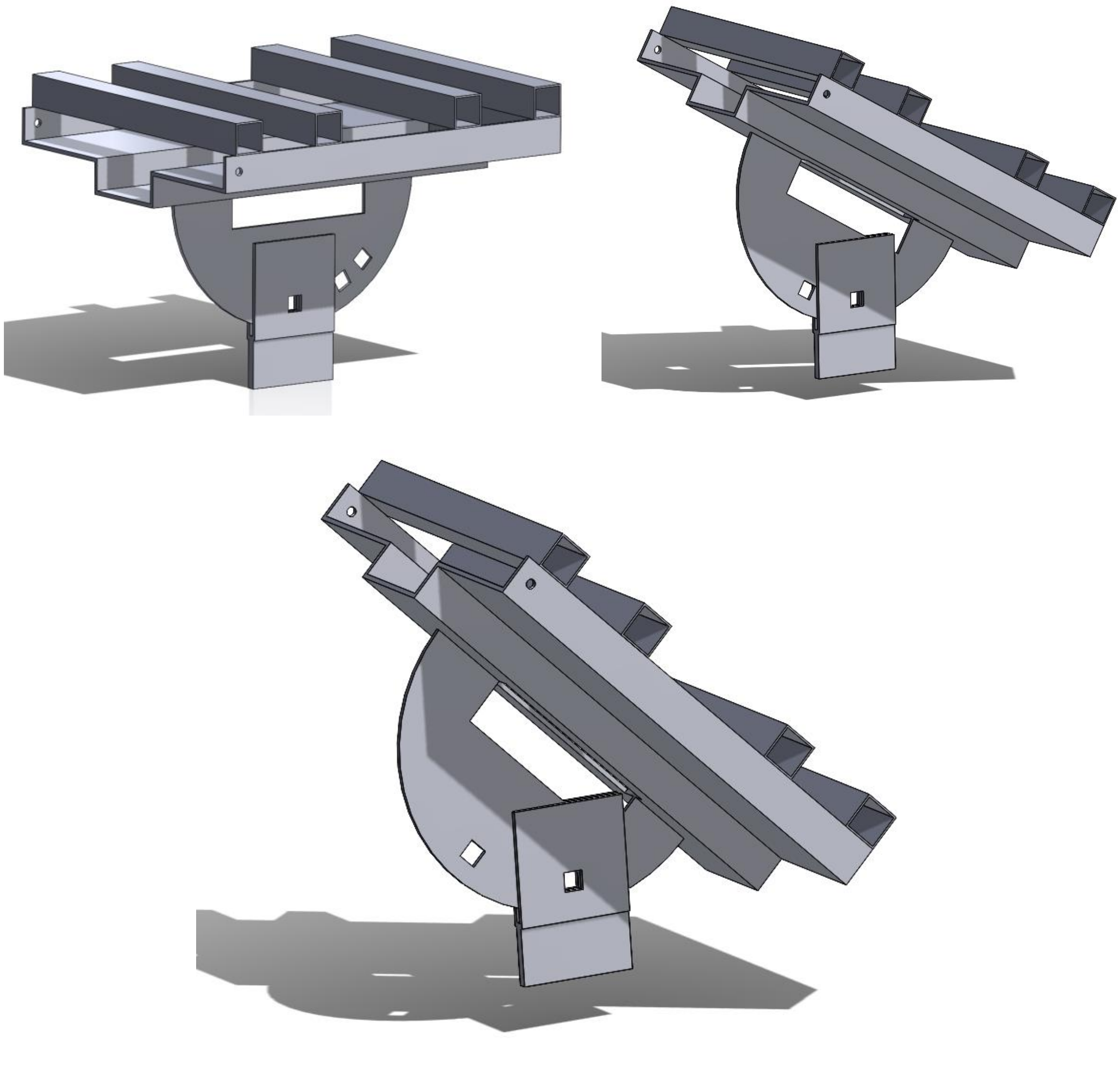


Figure 61: Final Jig Design at 0°, 30° and 45°

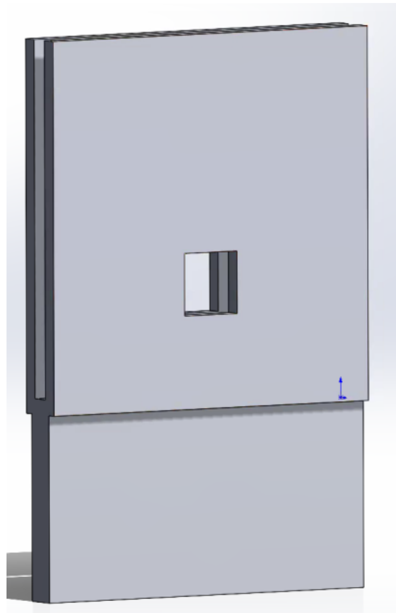


Figure 62: Lower Jig Connector

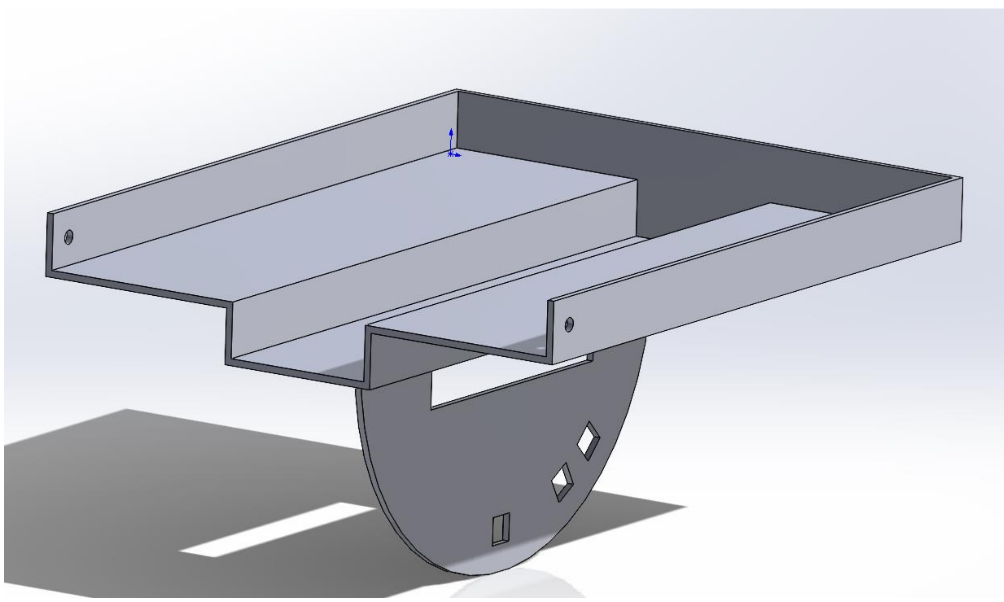


Figure 63: Upper Jig Connector

To confirm the design of the jig, we performed finite element analysis along with hand calculations for stress. We compared these two calculations to make sure the jig would not significantly deform during testing. For our load, we used the maximum amount of tensile strength that the Instron machine in the Composites lab can output. This value was 50,000 N, or 11,240.447 lbs. From here, we converted the force into a pressure by dividing by the area that the pressure is acting on. The FEA models were constrained at the points they would be during testing. For the lower connector, the bottom jaw of the instron is gripping the bottom tab, so both sides of the tab are constrained in the x, y and z directions. For the upper connector, the pin is constraining the connector in all three directions. The tube stock is welded onto the upper connector, so the two edges that make contact with the upper connector are constrained. From the hand calculations, the max deflection in the jig was located at the steel tube stock where the panel would be applying pressure. The max deflection value was 0.0805 inches. From the FEA, the max deflection was at the same location. The max deflection value for this method was 0.03 in as shown in Figure 66 below. The max deflection in the lower connector was 0.0026 in. and the max deflection in the upper connector was 0.38 in., as shown in Figures 64 and 65 below.

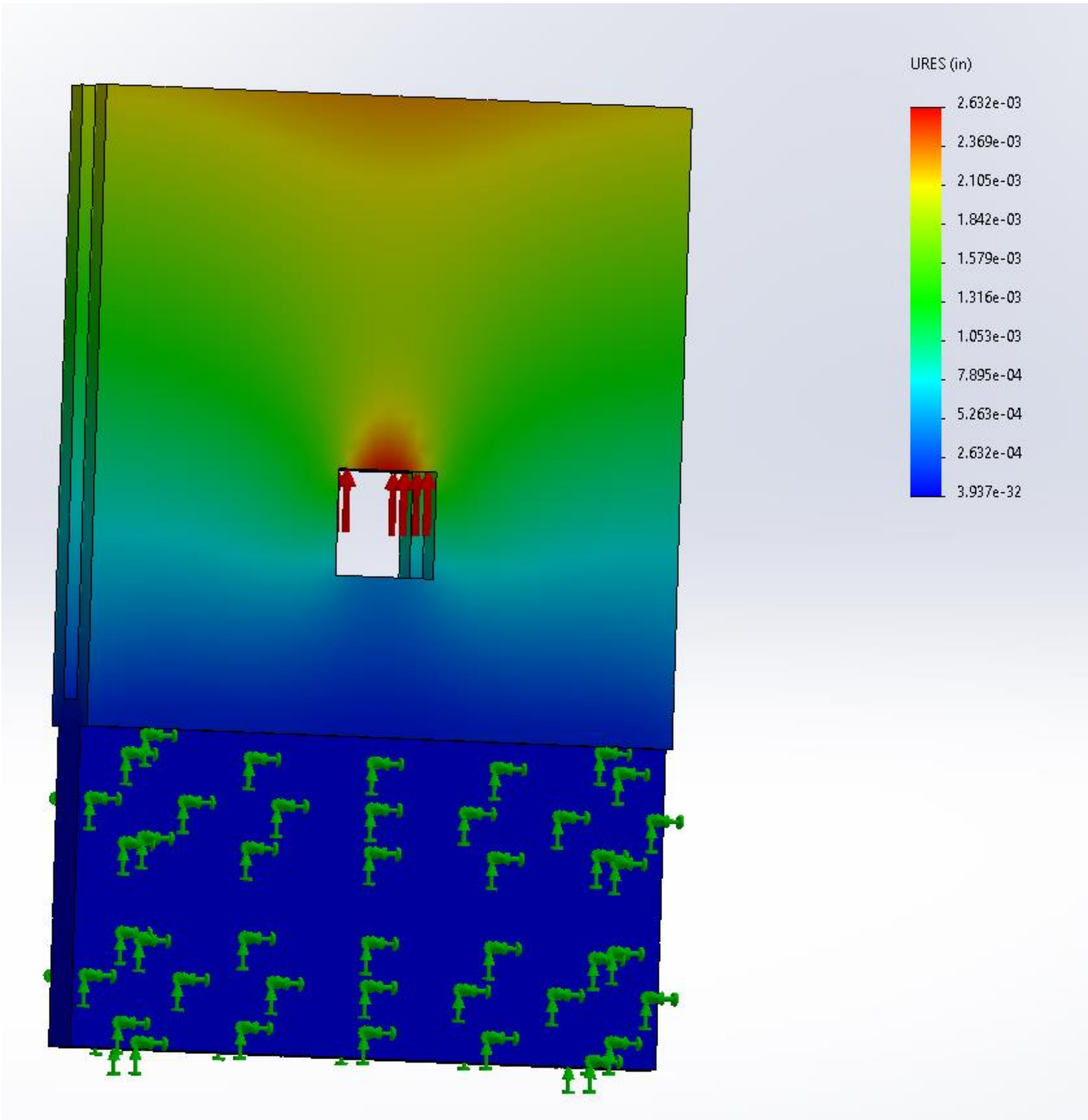


Figure 64: Deformation plot of lower connector using Solidworks FEA, Tetrahedral elements

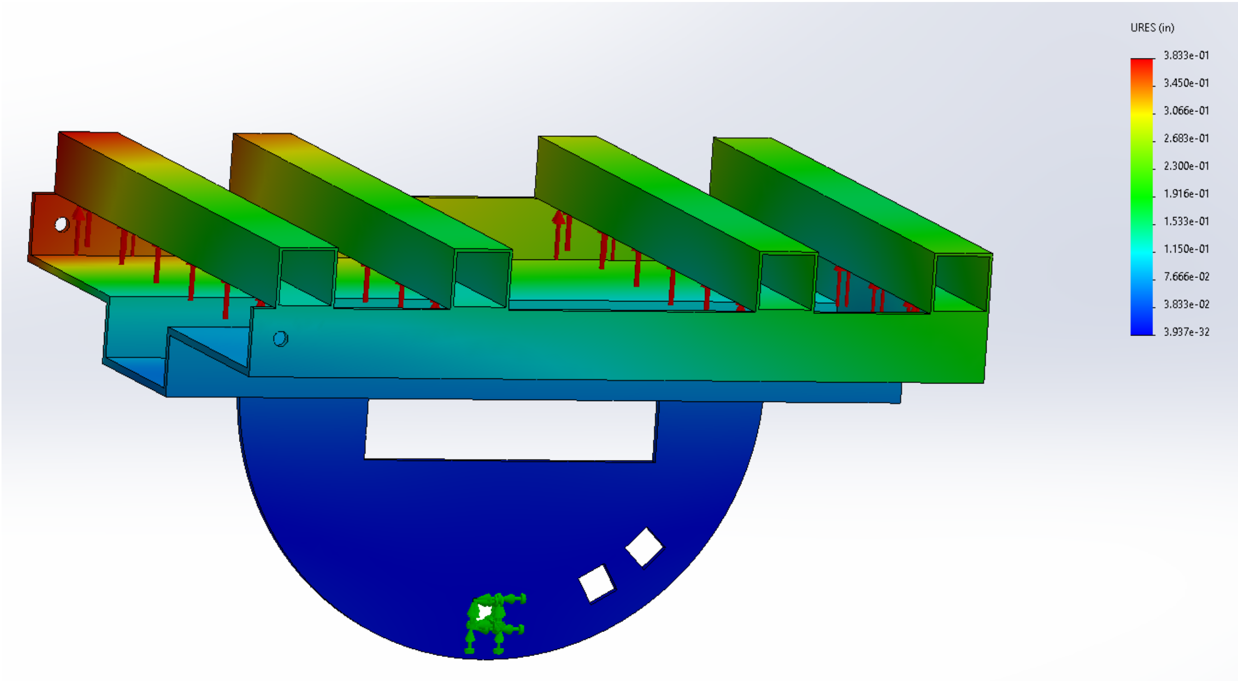


Figure 65: Deformation plot of upper connector using Solidworks FEA, Tetrahedral elements

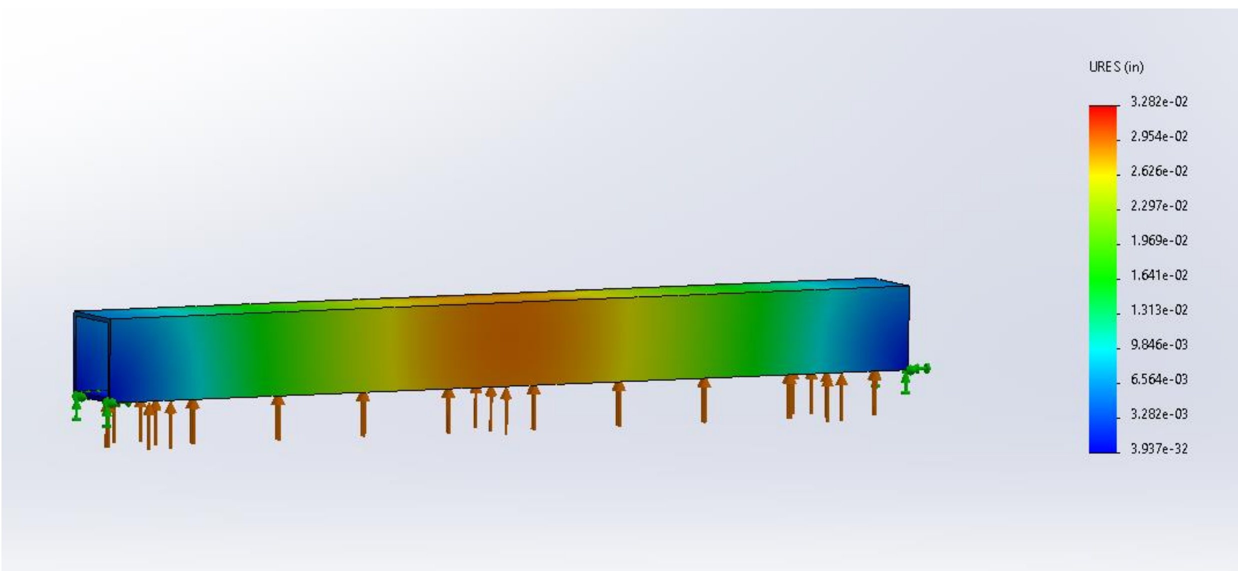


Figure 66: Deformation plot of square tube bar stock using Solidworks FEA, Tetrahedral elements

Unfortunately we were unable to physically build our testing jig this quarter. Our sponsor was unable to provide us with the steel materials we needed. Likewise, our jig design process began late into Winter quarter, near the end of our project, thus further iteration of the design may be required. For manufacturing, we recommend the pieces be cut using the water jet in Mustang 60. At this time, the water jet can be used by sending the shop techs a part file of what needs to be cut, then dropping off the required materials at the shop to build. After the part is cut, someone can pick up the pieces when notified. We recommend that the pieces then be welded together in any of the shops on campus. Areas to weld are shown in the assembly drawings in Appendix G. Each steel sheet is welded together using fillet welds on both sides. The square steel tube stock is welded onto the upper jig connector. A yellow tag is required to weld, so make sure this requirement is filled. An alternate option is to ask a shop tech to quickly weld the pieces together. Table 17 below gives a detailed Bill of Materials for the Jig.

Table 17: Jig Bill of Materials

Material	supplier	cost
1"x1"x0.125" C1008/1010 HR steel rectangular tube stock	FSAE	$0.00
3'x3'x0.125" C1008/1010 HR steel plate	FSAE	$0.00
1'x1'x0.25" C1008/1010 HR steel plate	FSAE	$0.00
4"x0.5"x0.5" C1008/1010 HR Steel bar stock (lower pin)	FSAE	$0.00
12.5"x0.128 C1008/1010 HR steel tub stock (upper pin)	FSAE	$0.00
Total		$0.00

8.3 Jig Operators Manual

This jig is to be used only with an Instron tensile testing machine. To operate it, place the lower adapter piece in the bottom jaws of the instron machine. Make sure that the jaws have a good grip on the tab, or else slipping may occur during testing. This would invalidate any test data acquired. If the jaws are not able to grip the tabs well, sand the surface of the tabs with rough sandpaper. This creates a surface that is easier to grip. Once the bottom adapter is set, adjust the top piece of the jig to the desired angle: 0°, 30°, or 45°. Carefully slide the pin through both the top and bottom jig pieces, keeping them in place. Next, place the panel in the jig. Make sure that the panel is fully secured by the steel tube stock. Next place the two dowel pins in the 0.25 in. diameter holes to secure the panel. Once this is ready, connect the suspension mount from the top instron jaw to the panel. Again, make sure that the instron jaw has a good grip on the mount. If everything is secure, the panel is ready to test.

There are a couple of safety concerns that come with the jig design. Always wear safety glasses while testing panels, since large amounts of force are being transferred onto both the panel and jig. Any of the pieces from the jig, panel, or suspension mount could snap unexpectedly, sending particles flying. The tabs that connect to the instron jaws can also slip, causing a safety hazard. When handling the jig, beware of any sharp edges that may come from the welding process, or any sharp corners. Inserting the pin into the jig can also result in pinched fingers. The jig is also decently heavy, so always wear closed toed shoes when handling in case of an accidental drop.

9. Project Management

9.1 Project Timeline Spring 2020

To stay on track with upcoming deadlines and events, we made a Gantt chart for our project using TeamGantt. A project plan for Spring Quarter 2020 is shown in figure 17 below. This includes tasks leading up to the completion of our Preliminary Design Report (PDR). Further planning for future quarters were included in the Gantt chart as time progressed. Planning with the Gantt chart helped us visualize what needed to be done, and helped us understand our current position in the scope of this long project. By the end of Spring Quarter, we have submitted our PDR Report, and we gave a presentation about our progress.

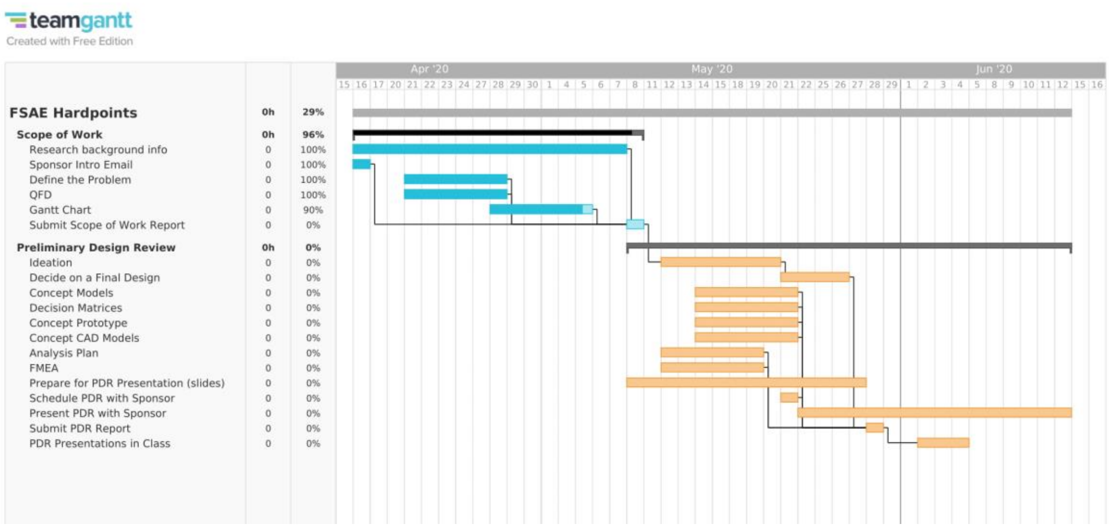


Figure 67. Gantt chart plan through the end of Spring 2020 using TeamGantt.

9.2 Project Timeline Fall 2020

As of June 2020, we submitted our Scope of Work report, and we have gone through the design process described earlier in this report. We have also presented our PDR to both the class and our sponsor. Attached below is an updated Gantt chart outlining our project goals for the summer and fall of 2020. If we stay on track with our plan, we will be ready to execute our testing plan by September 17, and we will be ready to turn in our CDR Report by October 23. To meet these goals, we must complete the tasks along our critical path.

Our main goals were to do more research and to stay in touch with our contacts. The main things researched were: how to use ANSYS, how to use Abaqus, and hardpoint manufacturing. It was recommended by our sponsor to learn both ANSYS and Abaqus because they are better suited for composite FEA than Solidworks. We learned these programs with the help of our sponsor and online instructional videos. We studied more about hardpoint manufacturing to get familiar with this process before testing. We also needed to acquire testing materials from Cal Poly Racing sponsor companies, however no materials were donated as there was no build this year. Thus, we were only able to use whatever materials were on hand, as the majority of components are too expensive for the team to purchase. We stayed in contact with Dr. Elghandour and Dr. Mello. They are professors at Cal Poly who gave us valuable information about composites, and what resources we can use on campus. Finally, we stayed in contact with certain Cal Poly Racing subteams, specifically the Engine, Chassis, Suspension and Materials teams. We were hoping to begin executing our testing plan by the first day of fall quarter, September 17. However, changing the lead contact with the team as well as getting clearance to be in certain labs set us back. After testing is completed, we will compare FEA to the pull-out and shear tests. We completed our CDR report by October 23.

Figure 68. Gantt chart plan through the end of Fall 2020 using TeamGantt.

9.3 Project Timeline Winter 2021

As of October 2020, we have presented our CDR to both our Senior Project class and to our sponsor. We have also submitted our CDR Report. We were able to begin the manufacturing process midway through January of Winter Quarter 2021. We waited until we were given access to the shed where FSAE stores all their parts. Unfortunately, due to COVID protocols, the majority of shops and labs had very limited, appointment only, availability. The limited hours, coupled with class and work schedule conflicts, made manufacturing a slow, tedious process. The first few weeks involved familiarization with composite manufacturing procedures. We began with layups of laminate, before moving on to sandwich panels. The first panels we made were to be used for laminate testing. The team mainly operates with donated material, and the carbon that was donated had expired a few years ago, rendering the data sheet they received with it inaccurate. Thus, our goal was to provide the team with accurate tensile test data by laying-up panels of carbon and testing them in the Instron machine. We cut these panels into thin samples using a tile saw, then we were able to test them in the Instron tensile machine after using epoxy to attach metal tabs that increase the accuracy of the tests. The metal tabs had to be cut and sized to fit on the samples. The samples were tensile tested and data was acquired using a data acquisition system. Next, we began to manufacture sandwich panels and hardpoints. We laid up and cured six 10"x12" panels, three with 4" high-density core pucks and three with 3" high-density core pucks. Our goal was to determine if smaller high-density core pucks. To help determine this, we planned to perform a pull-out test, however we learned that the club had no inserts. Manufacturing inserts would take too long, so that ended the manufacturing and testing portion of our project. We had a difficult time with testing and manufacturing this quarter as there were a lot of setbacks. The limited lab availability, particularly the limited availability of the curing oven made it hard to produce many panels and our timetable became longer and longer. Unfortunately, there were only two days a week available to cure panels, and the oven was shared with a composite class, so it wasn't possible to cure many panels at a time. This coupled with the lack of inserts prevented us from accomplishing any hardpoint testing this quarter. To complete the design process, the cured panels and additional panels will need to be tested to verify the design choices we have made.

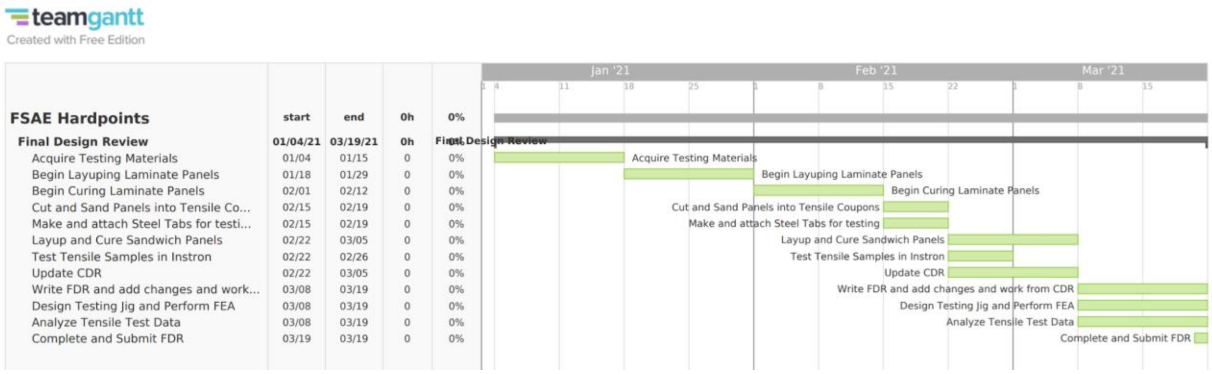


Figure 69: Gantt Chart through end of Winter 2021

10. Conclusion

The goal for this project is to optimize chassis hardpoints for the Cal Poly FSAE team through research, composite testing and computer based analysis. We were able to lay the groundwork for achieving this goal. We narrowed down the scope of the project from its conception of concerning all hardpoints, to those involved with the suspension. Through material datasheet analysis and sponsor provided materials we developed a standard list of materials to be used for testing. We narrowed down the hardpoint design to evaluate one critical variable, core puck size. To make sure the stocks of fiber on hand are able to be used for future projects, we tested carbon fiber tensile coupons for the three types of fibers the club uses to manufacture the chassis. We developed a jig design that with computer aided and hand calculated stress analysis we believe will be able to withstand the loading conditions of hardpoint testing on the instron machine. Likewise, this jig has the capability to be utilized at different loading angles to simulate the mounted suspension loading. This jig will be utilized in further testing that will need to be done to finalize the hardpoint design. The racing team or a new senior project team will be able to utilize this jig and the recommended materials we identified to perform shear and pullout tests that will determine the final geometries and materials needed for an optimized hardpoint design.

10.1 Future state of the project and recommendations

This project still requires thorough testing of the hardpoint design we have developed. We have six panels of which three panels consist of the 4” diameter core pucks and the other three contain the 3” diameter core pucks. To gain a reliable sample size of data at least four more panels equally divided between the core puck diameters should be produced. These panels then need to have center holes drilled out and inserts potted. We were unable to obtain inserts this quarter but recommend corrosive resistant aluminum alloy inserts be used for testing. Once the inserts have been potted using the available Loctite 9309, and cured for at least three days at 77℉, the hardpoints will be ready for testing. The jig we have designed will need to be fabricated using steel stock sheets, and steel bar stock ranging in thickness from 0.125 inches to 0.25 inches. Shears available at the hangar are sufficient for cutting 1/8th inch steel, however the thicker steel may need to be cut using a plasma cutter or the waterjet at mustang 60. Once the pieces are cut, the jig will need to be welded together. Upon jig assembly completion the panels will be ready to be tested in the instron machine. The main tests that will need to be run are a shear test and a pullout test. Additionally, pull out tests at the following angles, 0°, 30°, or 45°, will need to be conducted to simulate the suspension mounts during the max cornering load case. The tests will provide two key forms of data. First, the data acquisition system will provide the max loads the hardpoints are capable of handling, which helps determine if the selected design is capable of withstanding the needed loads to the needed safety factor. The other important takeaway from the testing is the failure modes observed. These failure modes will provide detailed information on which components of the hardpoint are weak and causing the failure, which will allow for reiteration of the component materials and sizing.

Depending on the results gained from panel testing, it may be decided that 3” core puck size is sufficient for withstanding suspension loading conditions. If not, a reiterative panel testing process should be performed. Ideally stress analysis software should be used to get a rough estimate of what core size will be sufficient. Testing values of 3.75”, 3.5”, and 3.25” may be necessary. If it is determined that 4” core puck diameter is the optimal size, the project should then move forward with testing lighter materials such as less dense potting compound (Loctite 9390), lighter inserts (PLA, PC), and even less dense core materials if available. Through this process, the goal of the project will be achieved at optimizing a hardpoint based on weight, strength, and specific stiffness in order to reduce the overall weight of the vehicle. We originally planned on optimizing all hardpoints on the chassis to include engine, battery, seat, wing, and motor among others. The future of this project could be carried in the direction of optimizing all vehicle hardpoints as well.

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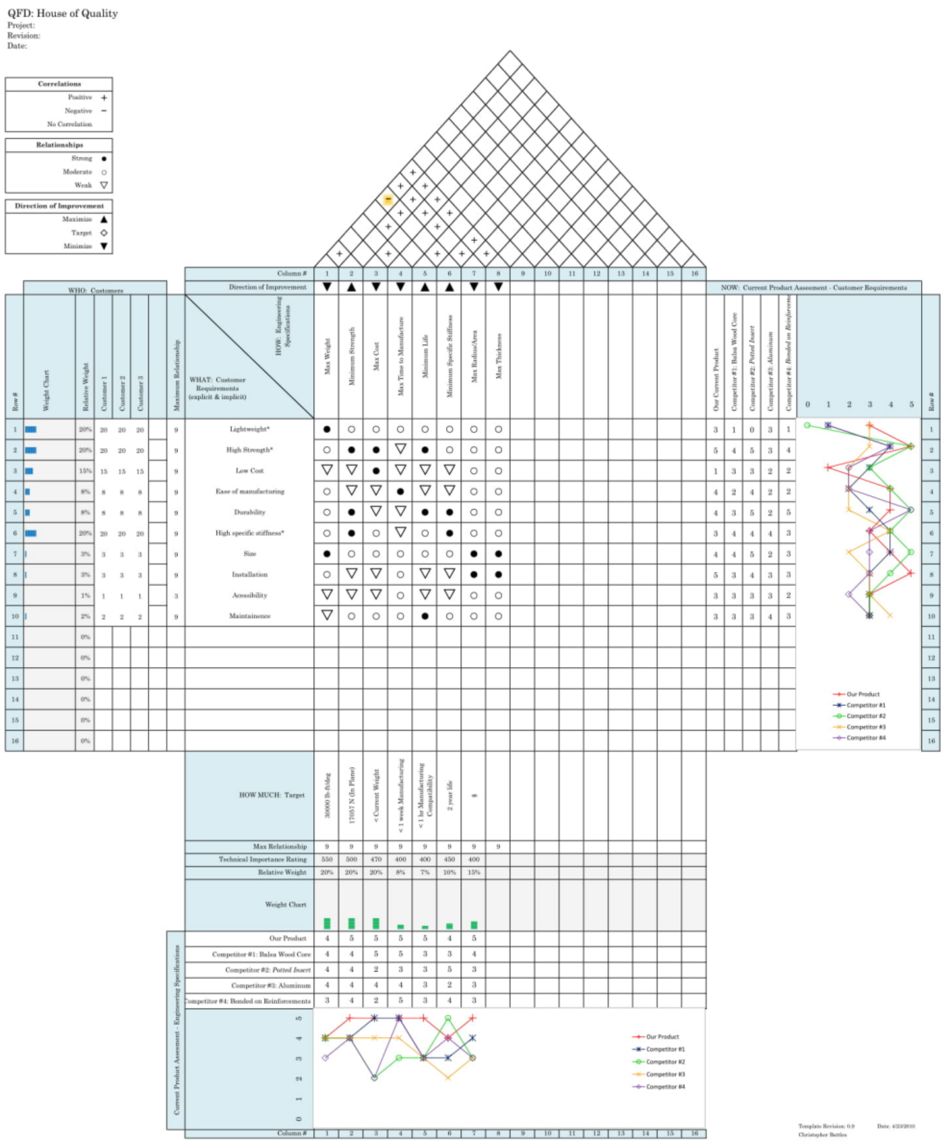
12. Appendix

Appendix A: House of Quality Chart



Appendix B: Pugh Matrices

Core Pugh Matrix

Core Material	Current (1/8 hex web cr3)	Aluminum Flex Core	G10/FR4 puck	Balsa Puck	Corecell A1200	Multiplier
Specific stiffness(E/rho)	0	1	-1	1	-1	2
Compressive strength (psi)	0	-1	2	-1	-1	2
Density/weight	0	1	-2	-1	-5	3
Tensile strength	0	0	2	-2	0	1
Shear strength	0	-1	2	-2	-1	1
Cost	0	0	-2	-1	-1	1
Total	0	2	-2	-8	-20	N/A

Potting Compound Pugh Matrix

Potting Compound	LOCTITE EA 9309NA AERO	Hysol® EA 9396	LOCTITE 9313	LOCTITE 9360	LOCTITE 9390	Multiplier
shear modulus	0	0	0	0	1	2
time to cure	0	-1	-1	-1	1	1
tensile strength	0	2	1	1	2	2
compressive strength	0	0	3	2	0	0.25
Total	0	3	4.75	1.5	7	N/A

Laminate Pugh Matrix

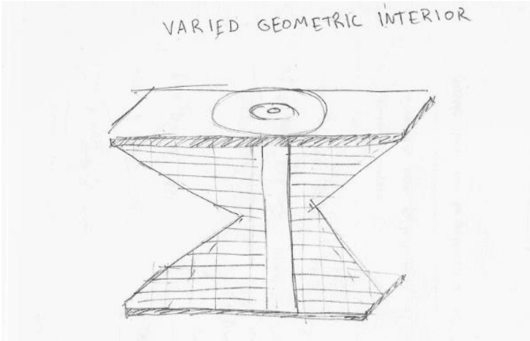
Laminant	Tencate TC275	HTS 40 (current)	Toray T700 (current)	Toray-cetex TC1100	T1100G	Multiplier
Tensile Strength	0	0	0	2	1	2
Impact Strength	0	0	0	0	0	1
Resistance to Heat	0	0	0	0	-1	1
Specific Stiffness (E/rho)	1	0	0	1	1	2
Cost	0	0	0	0	0	1
Shear Strength	0	0	0	1	1	2

Density	2	0	0	1	1	2
Total	5	0	0	14	7	N/A

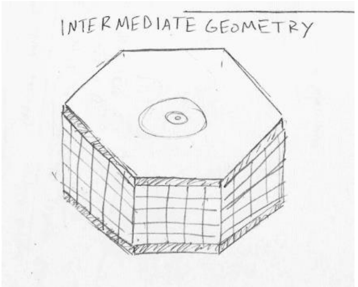
Insert Material Pugh Matrix

Insert Material	**Current (Aluminum)**	**Titanium**	**Polymer**	**Steel**	**Multiplier**
Compressive Strength	0	1	-2	1	1
Tensile Strength	0	1	-2	1	1
Density/Weight	0	-1	1	-2	2
Cost	0	-2	1	-1	1
Total	0	-2	-1	-2	N/A

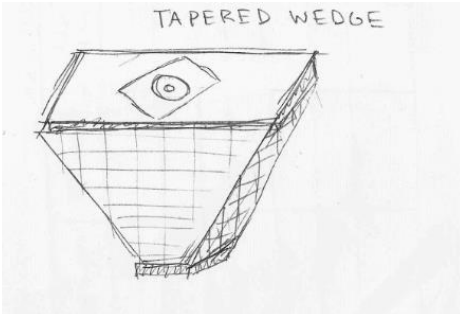
Appendix C: Design Concepts



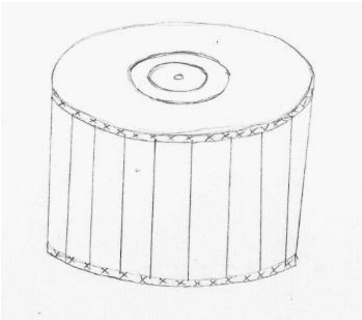
Square Hardpoint with varied geometric interior



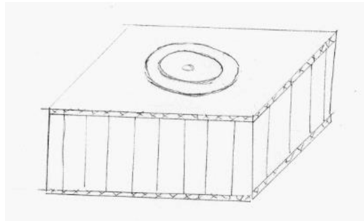
Hexagonal Hardpoint



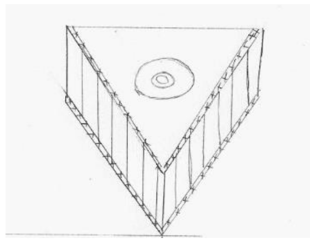
Tapered Square Hardpoint



Circular Hardpoint

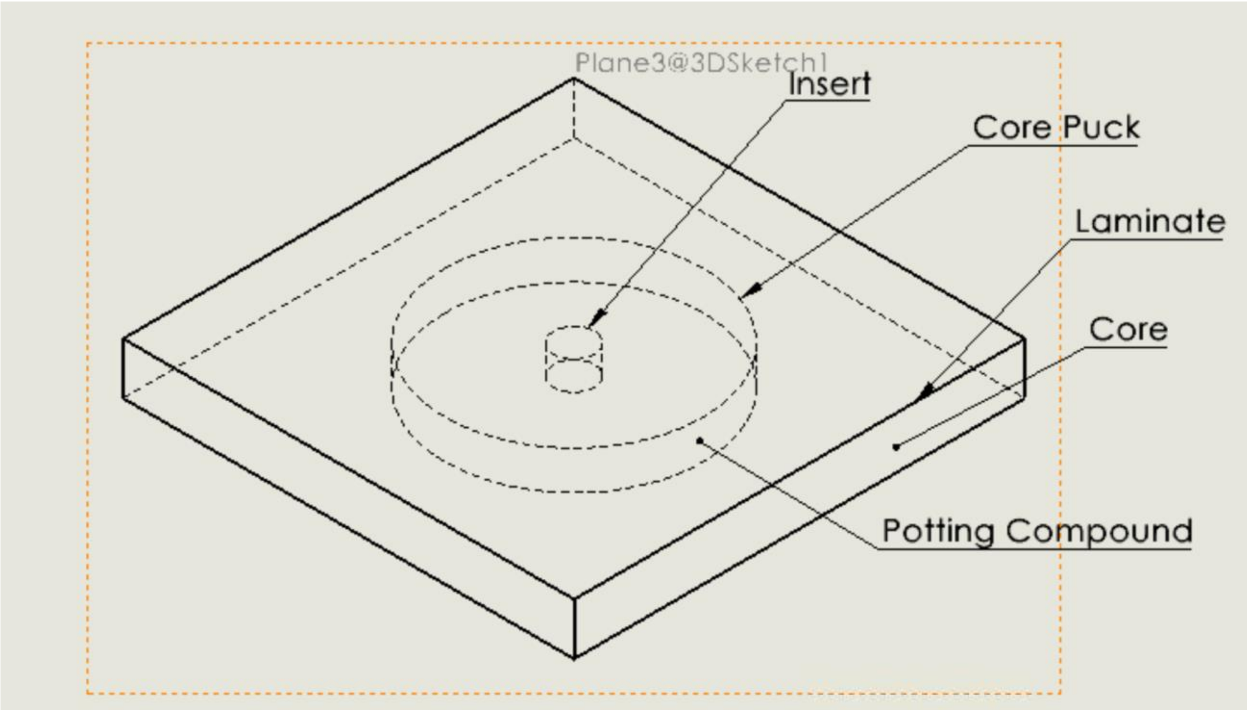


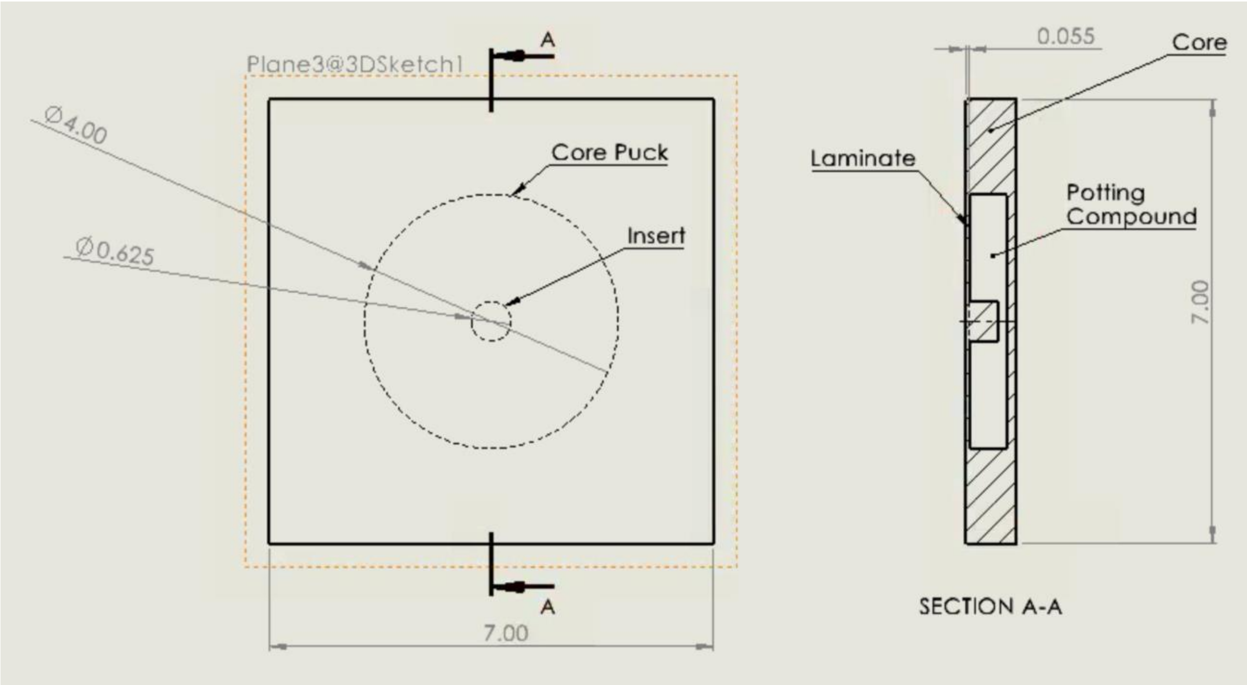
Square Hardpoint



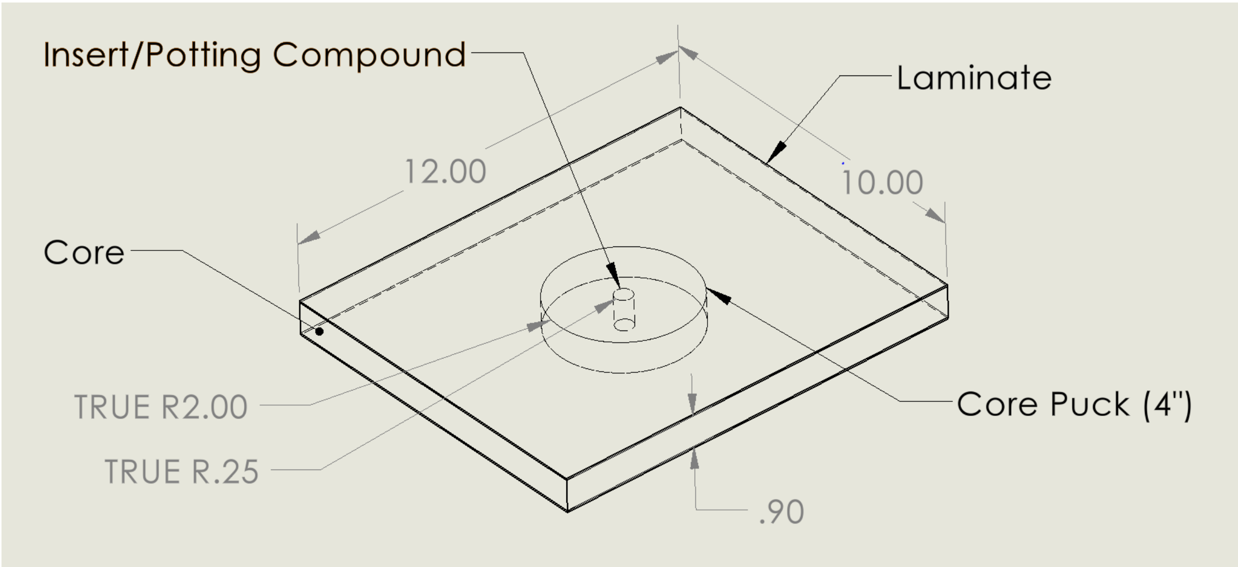
Triangular Hardpoint

Appendix D: Initial Design Drawings and Isometric View

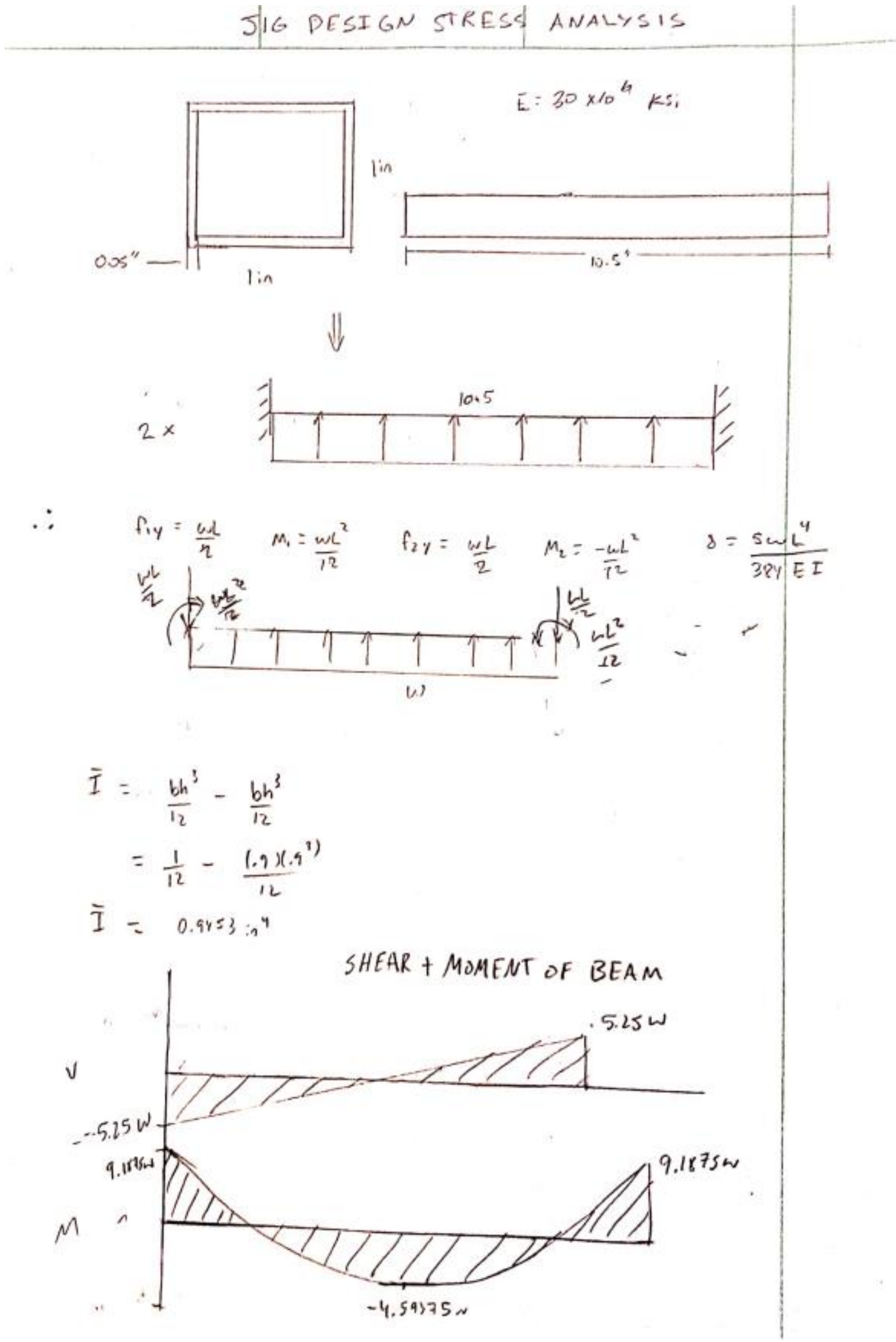




Appendix E: Final Design Drawings and Isometric View



Appendix F: Jig Hand Calculations For Stress



BENDING STRESS IN BEAM

allowing for 2 beams

$$\sigma_{max} = \frac{9.1875\, w\,(0.5)}{(2)\ 0.9453}$$

$\sigma_{max} = 2.4297\, w$ — bending stress bar stock beams

Max stress by load $= \frac{F}{A}$

$$\sigma_{max} = \frac{5.25\, w}{2A}$$ ← 2 beams

$A = (1'' \times .05^2)\,2 + 2(.95 \times .05)$

$A = 0.155$

$$\sigma_{max} = \frac{5.25\, w}{2(.155)}$$

$\sigma_{max} = 13.46\, w$ — shear stress bar stock

Convert distributed load to point load

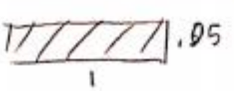
point load → $F = w A$ ← contact area of barstock

$A = 10.5'' \times 1'' \times 2$

$A = 21\ in^2$

$w = \frac{F}{21}$

BAR STOCK MOUNT STRESS

4 mounting points: 

$A = 4(1)(.05)$

$A = 0.2\ in^2$

$$\sigma = \frac{5.25w}{.2}$$

$\boxed{\sigma = 26.25w}$ — Tensile stress bar stuck mount

PIN HOLE STRESS

$A: 0.126 in^2$

$$\sigma = \frac{5.25w}{0.126in^2}$$

$\boxed{\sigma = 41.66w}$ — sheer stress experienced by pin

Location of highest stress @ PIN hole

$\sigma = 41.66w$

$$\sigma = \frac{41.66(F)}{21}$$

$\sigma = 1.9803F$

$$E = \frac{\sigma}{\epsilon}$$

$$30 \times 10^6 = \frac{1.9803F}{\epsilon}$$

$\boxed{F = (\epsilon)(15.149 \times 10^6) \text{ lbs}}$

Assume $\varepsilon \approx 0.02$

$F = 303000$ lbs ← Rough estimate of total point load before jig failure.

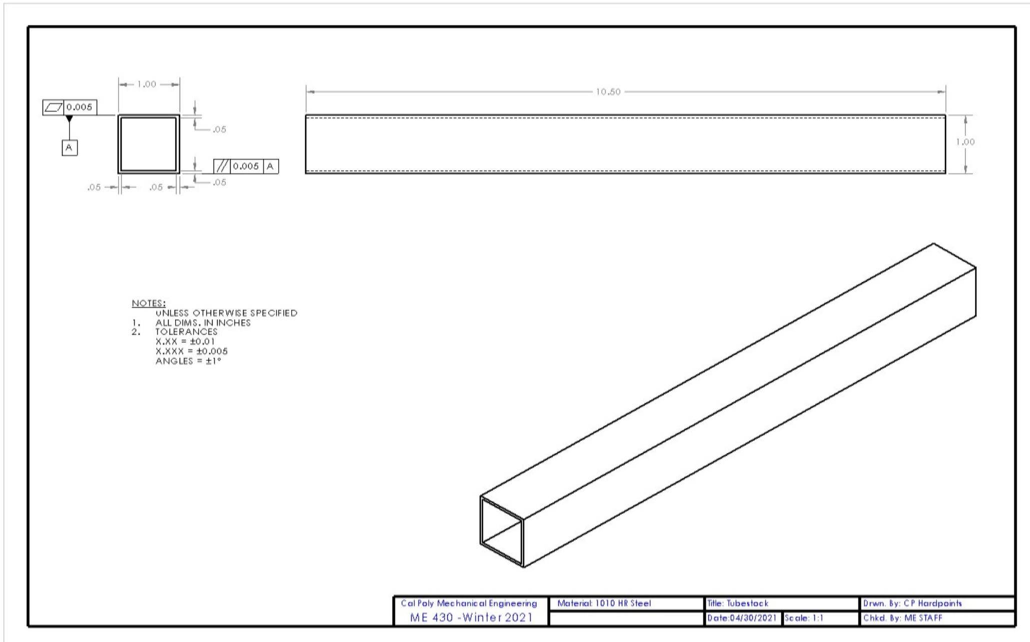
$$\delta = \frac{5wL^4}{384EI}$$

$$\delta = \frac{5\left(\frac{3.03\times10^5}{21}\right)(10.5)^4}{384\,(30\times10^6)(0.9453)}$$

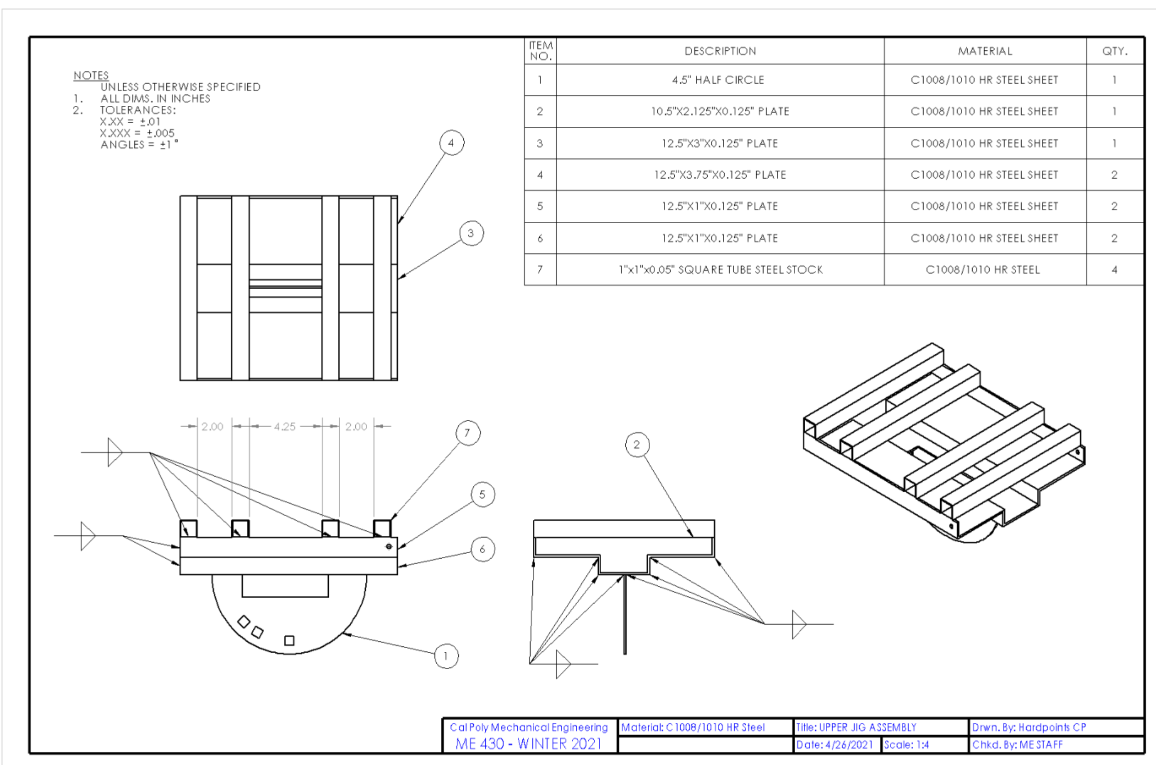
$\boxed{\delta = 0.0805 \text{ inches}}$ — Max Barstock deflection before jig failure

Appendix G: Drawings for Jig Design

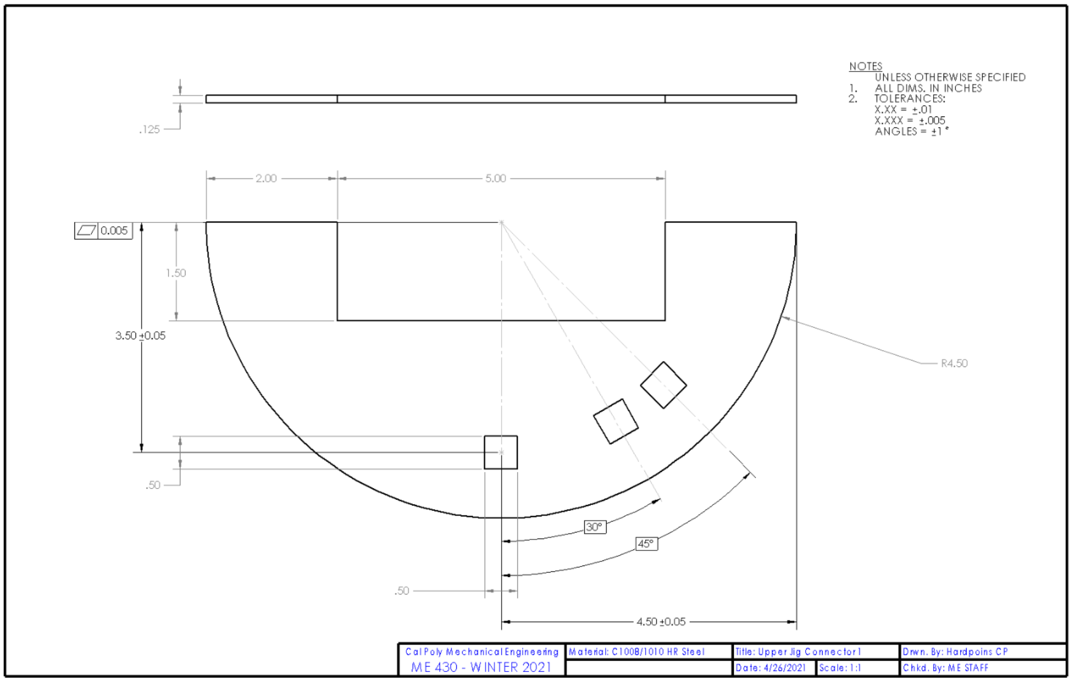
Attachment: Part drawing for square steel tube stock



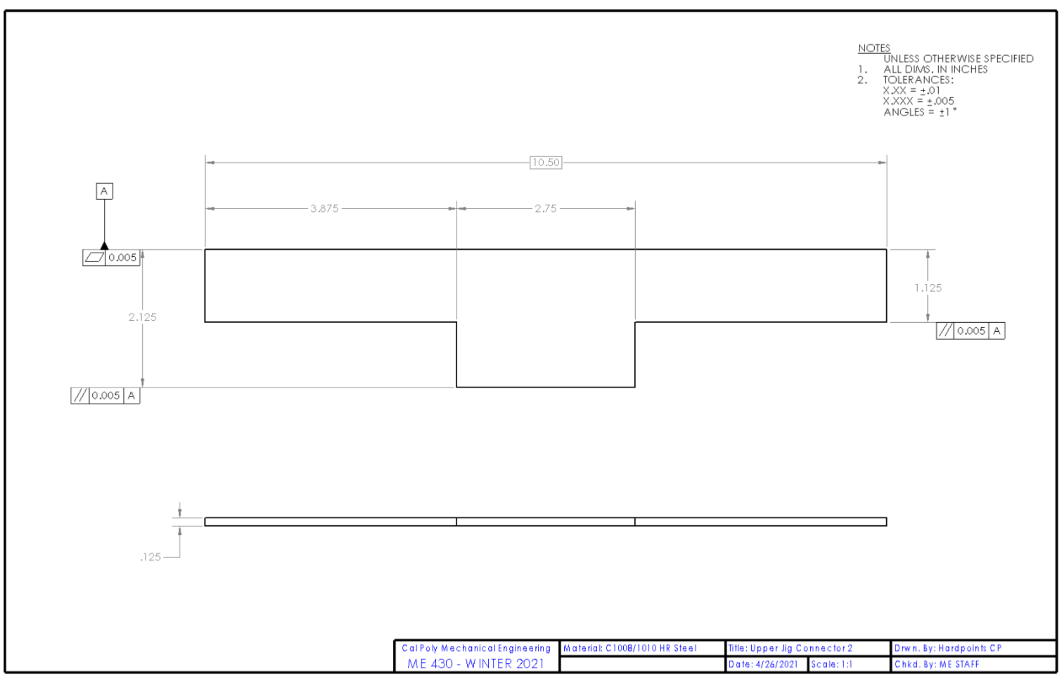
Attachment: Assembly drawing for Upper jig connector



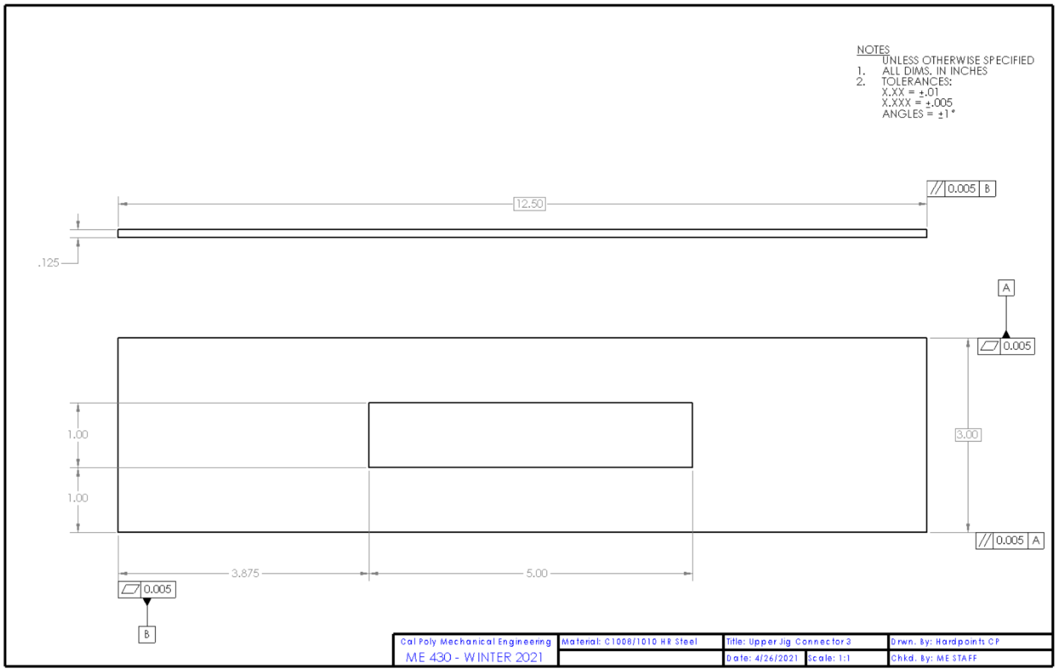
Attachment: Part drawing for Upper jig connector (1)



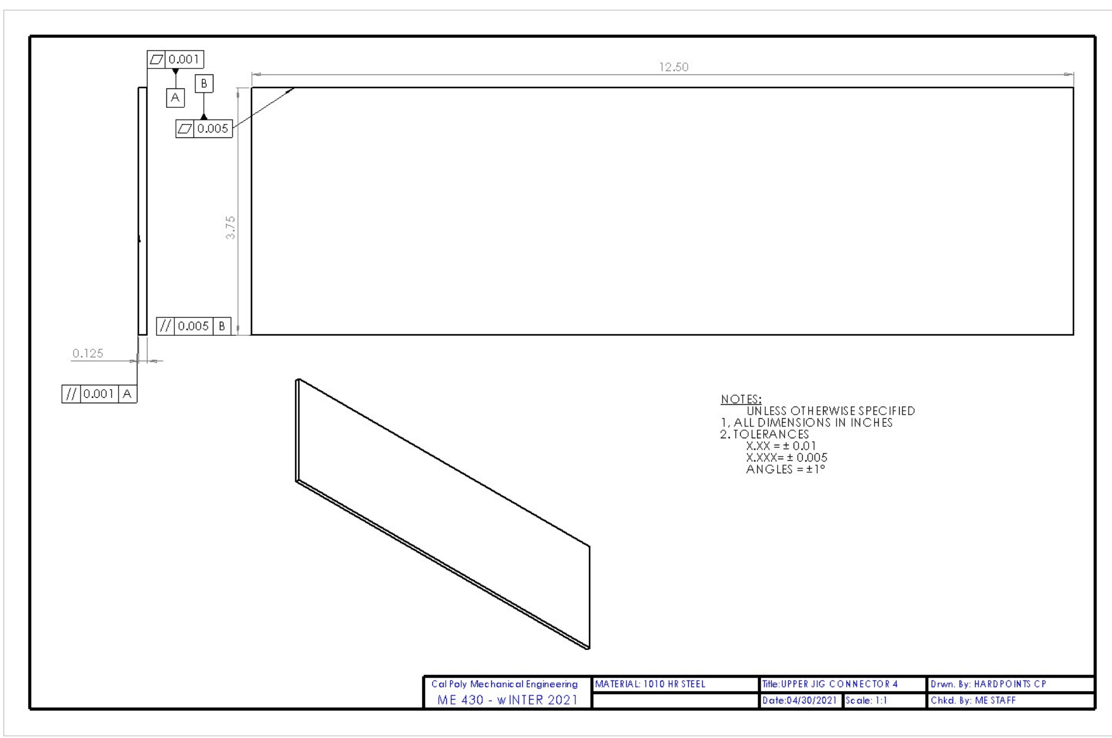
Attachment: Part drawing for Upper jig connector (2)



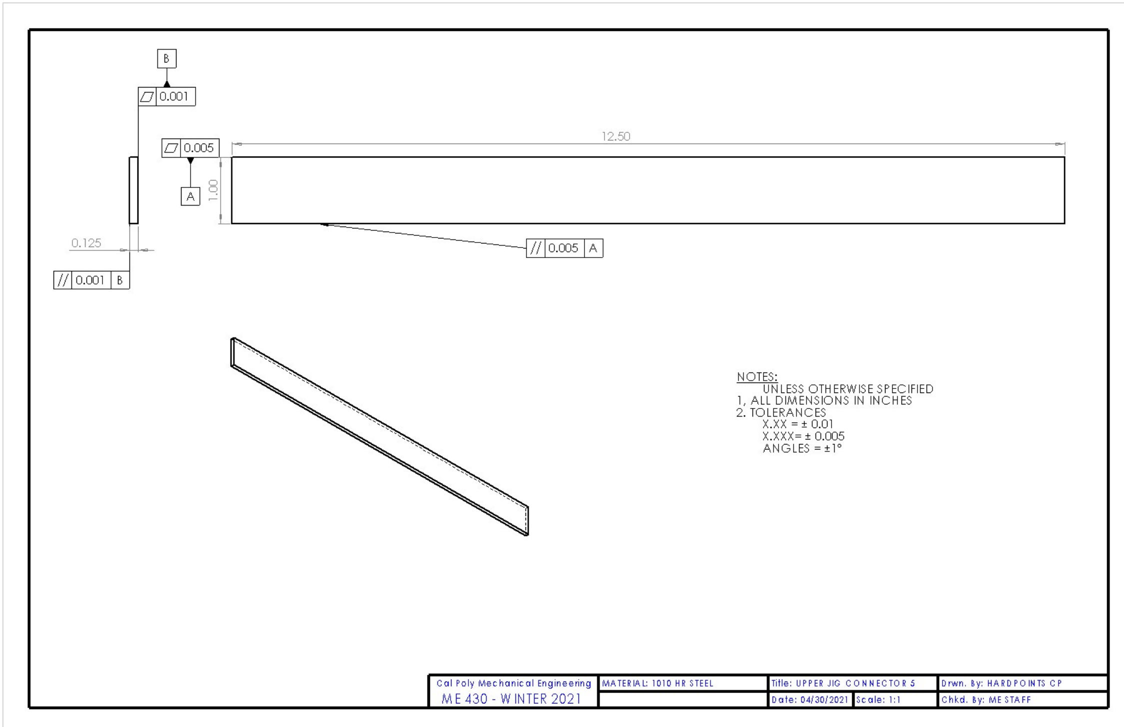
Attachment: Part drawing for Upper jig connector (3)



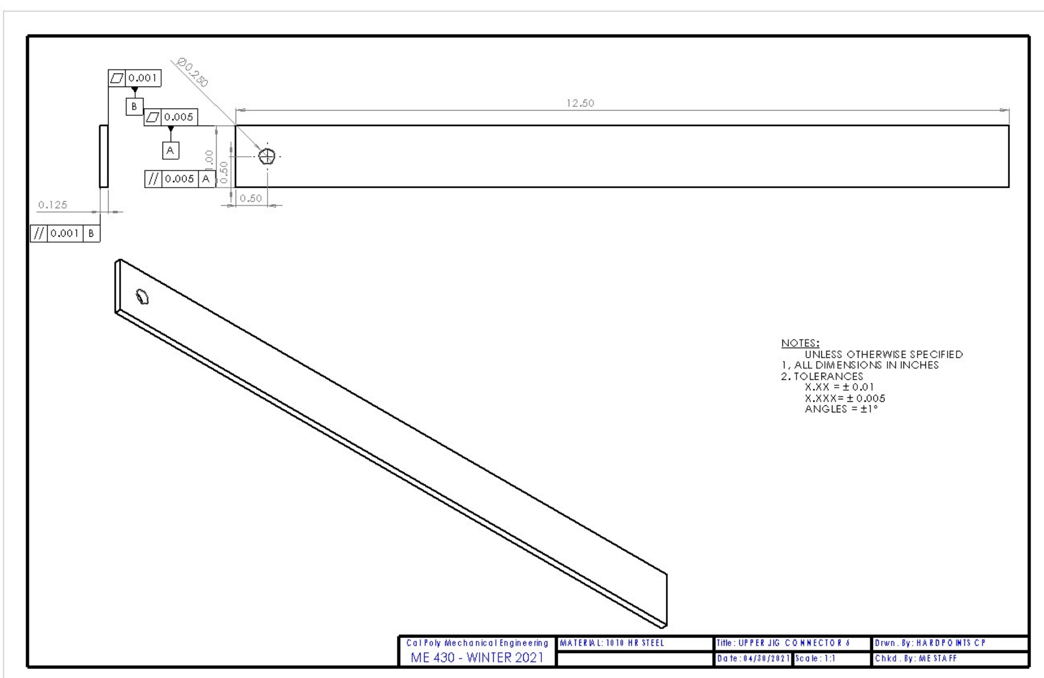
Attachment: Part drawing for Upper jig connector (4)



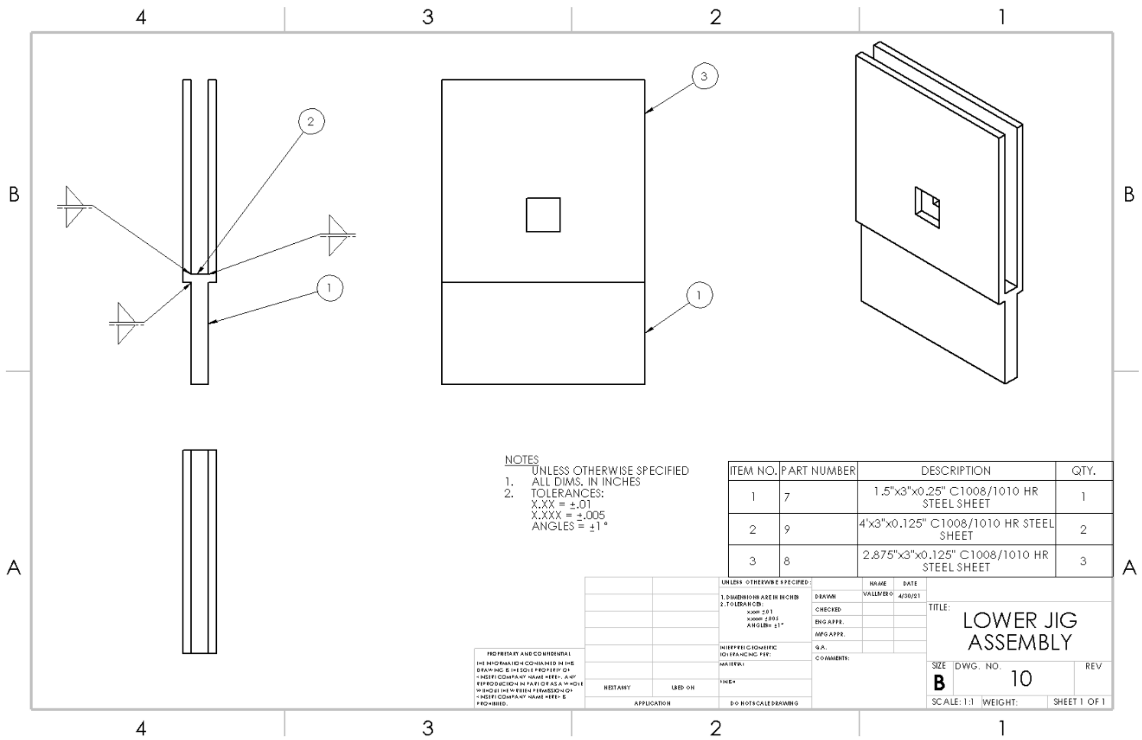
Attachment: Part drawing for Upper jig connector (5)



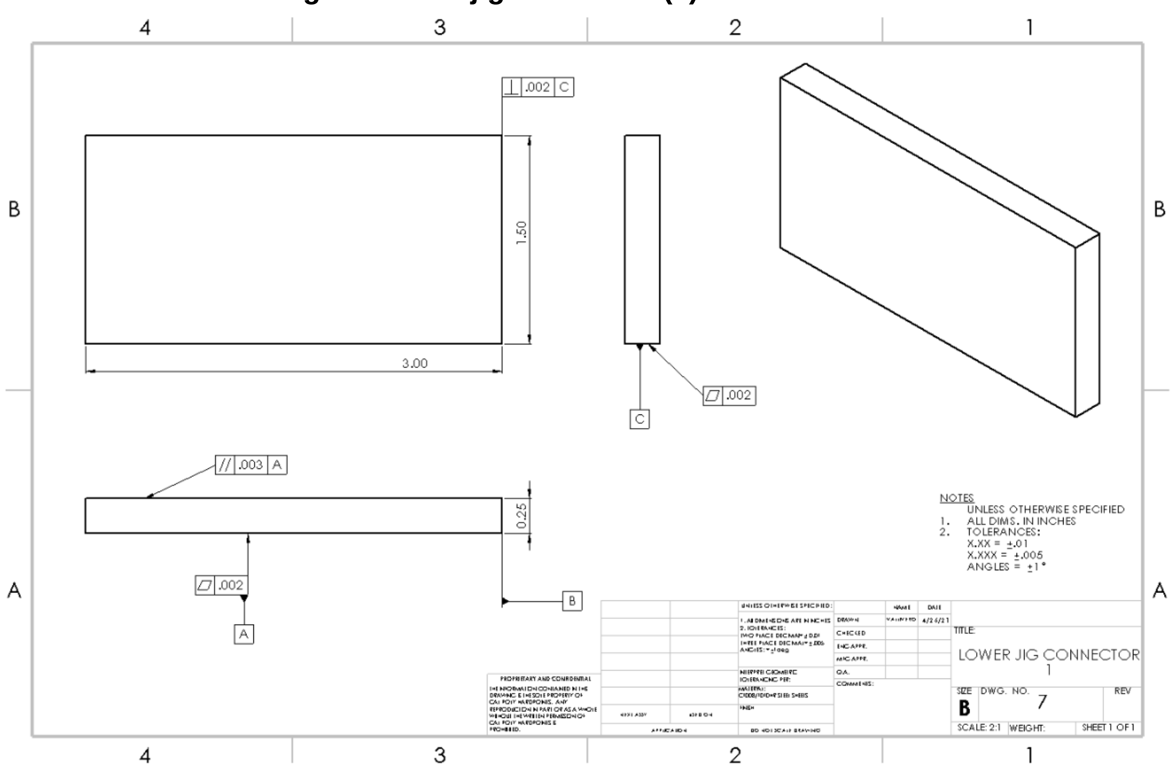
Attachment: Part drawing for Upper jig connector (6)



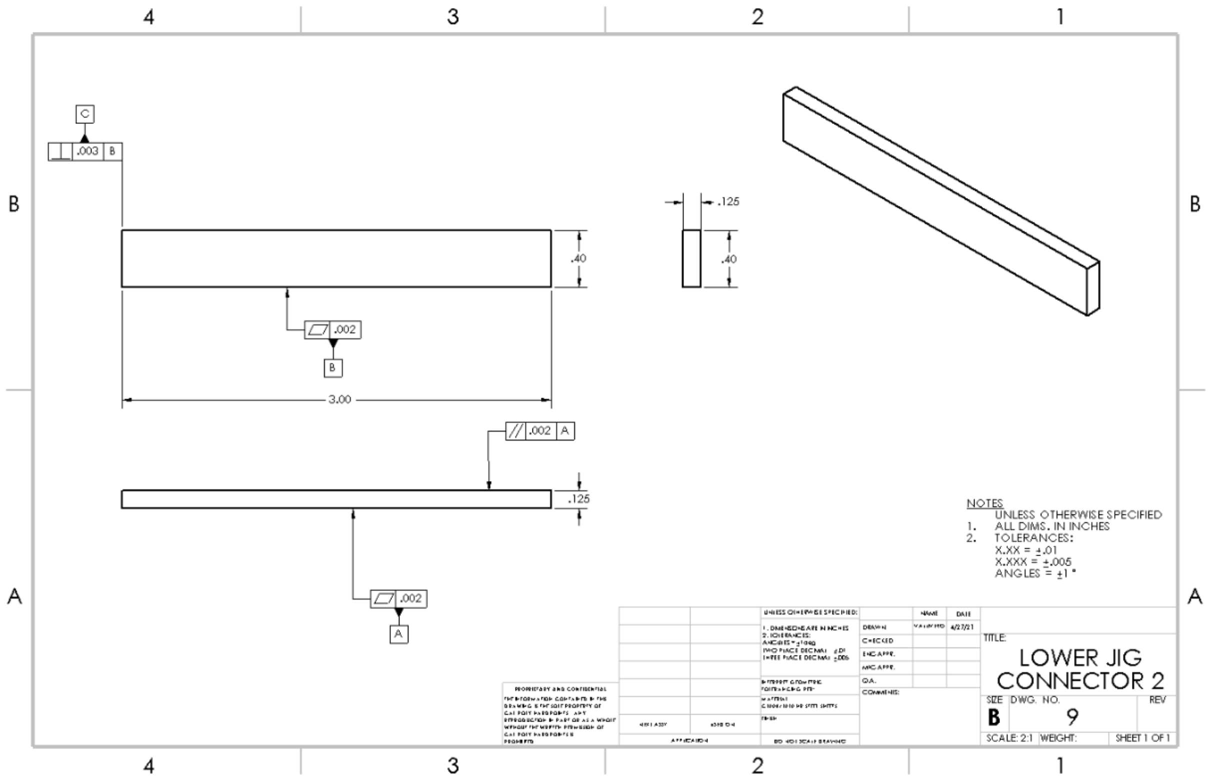
Attachment: Assembly drawing for Lower jig connector



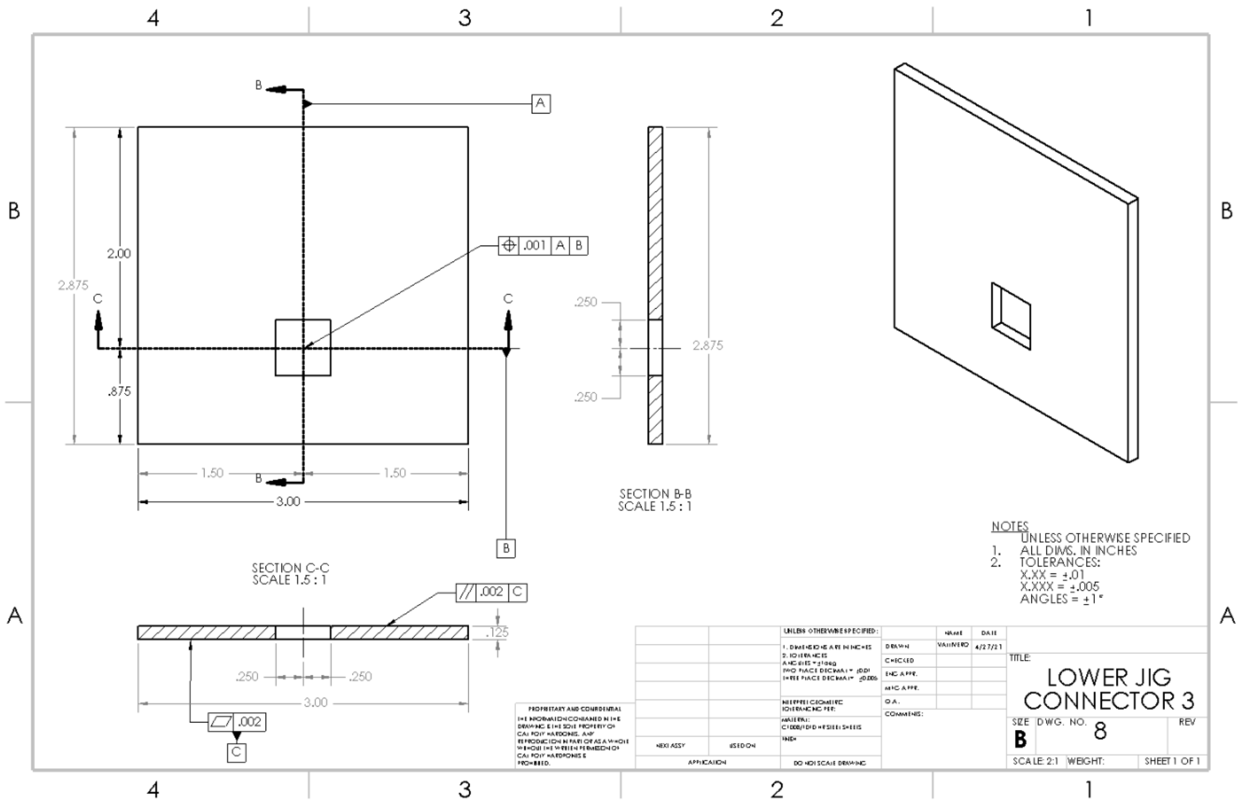
Attachment: Part drawing for Lower jig connector (1)



Attachment: Part drawing for Lower jig connector (2)



Attachment: Part drawing for Lower jig connector (3)



Appendix H: Bill of Materials

Hardpoints BOM

Material	Supplier	Cost
HTS Multidirectional Prepeg (skin)	FSAE	$0.00
T700 Unidirectional Cloth (skin)	FSAE	$0.00
Toray-cetex TC1100 (skin)	Toray/Donation	$0.00
5052 Aluminum Honeycomb 3.1 lbm/ft^3 (Core)	FSAE	$0.00
5052 Aluminum Honeycomb 4.4 lbm/ft^3 (Core)	FSAE	$0.00
Aluminum Flex Core	Donation	$0.00
Loctite 9309 (Potting Compound)	FSAE	$0.00
Loctite 9390 (Potting Compound)	Pilot's HQ/Donation	$0.00
Polycarbonate (insert)	FSAE	$0.00
Ultem (insert)	FSAE	$0.00
Aluminum (insert)	FSAE	$0.00
Redux 312UL Adhesive Film	Donation	$0.00
Total		$0.00

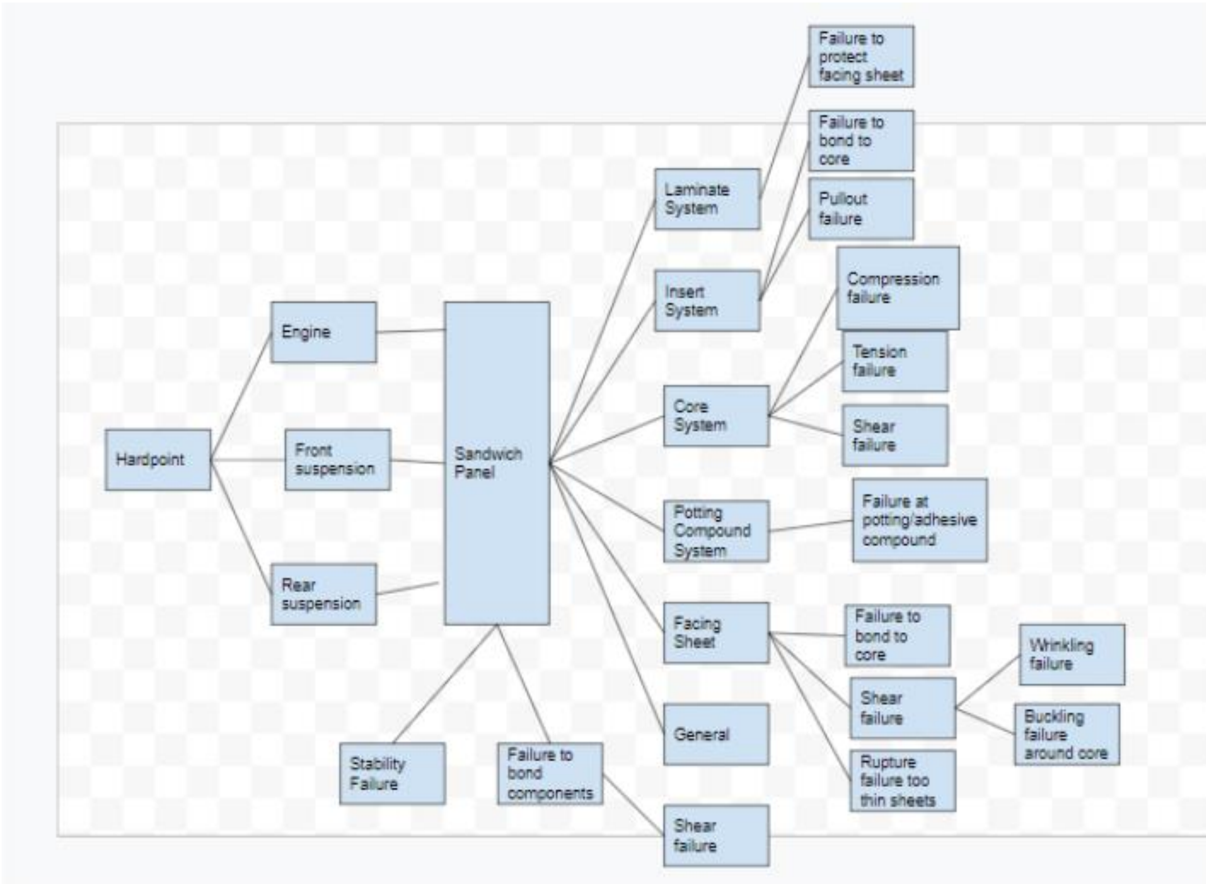
Jig BOM

Material	supplier	cost
1"x1"x0.125" C1008/1010 HR steel rectangular tube stock	FSAE	$0.00
3'x3'x0.125" C1008/1010 HR steel plate	FSAE	$0.00
1'x1'x0.25" C1008/1010 HR steel plate	FSAE	$0.00
4"x0.5"x0.5" C1008/1010 HR Steel bar stock (lower pin)	FSAE	$0.00
12.5"x0.128 C1008/1010 HR steel tub stock (upper pin)	FSAE	$0.00
Total		$0.00

Appendix I: Design Verification Plan

Report Date: 10/23/20			Sponsor: Cal Poly FSAE						Component/Assembly			REPORTING ENGINEER:	
			TEST PLAN							TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsi	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Strength	In-plane Load Strength Test	3408.39 N (In Plane)	All	DV	TBD	B	11/2/2020	11/15/2020				
2	Strength	Out of plane Strength Test	7397.9 N (Out of Plane)	All	DV	TBD	B	11/2/2020	11/15/2020				
3	Strength	In-plane Load Strength Test with Ultem Inserts	3408.39 N (In Plane)	All	DV	TBD	B	11/2/2020	11/15/2020				
4	Strength	Out of plane Strength Test with Ultem Inserts	7397.9 N (Out of Plane)	All	DV	TBD	B	11/2/2020	11/15/2020				
5	Strength	In-plane Load Strength Test with Polycarbonate Inserts	3408.39 N (In Plane)	All	DV	TBD	B	11/2/2020	11/15/2020				
6	Strength	Out of plane Strength Test with Polycarbonate Inserts	7397.9 N (Out of Plane)	All	DV	TBD	B	11/2/2020	11/15/2020				
7	Strength and Sizing	In-plane Load Strength Test with iterated sizing	3408.39 N (In Plane)	All	DV	TBD	B	11/16/2020	11/22/2020				
8	Strength and Sizing	Out of plane Strength Test with iterated sizing	7397.9 N (Out of Plane)	All	DV	TBD	B	11/16/2020	11/22/2020				
9	Weight	Weight Measurement of Hardpoints	TBD	All	DV	TBD	B	11/2/2020	11/15/2020				
10	Manufacturing Time	Time to Manufacture Hardpoints	TBD	All	PV	TBD	C	11/2/2020	11/15/2020				
11	Specific Stiffness	FEA for Chassis Stiffness	30,000 lbft/deg	All	DV	TBD	B	11/16/2020	11/22/2020				

Appendix J: FMEA



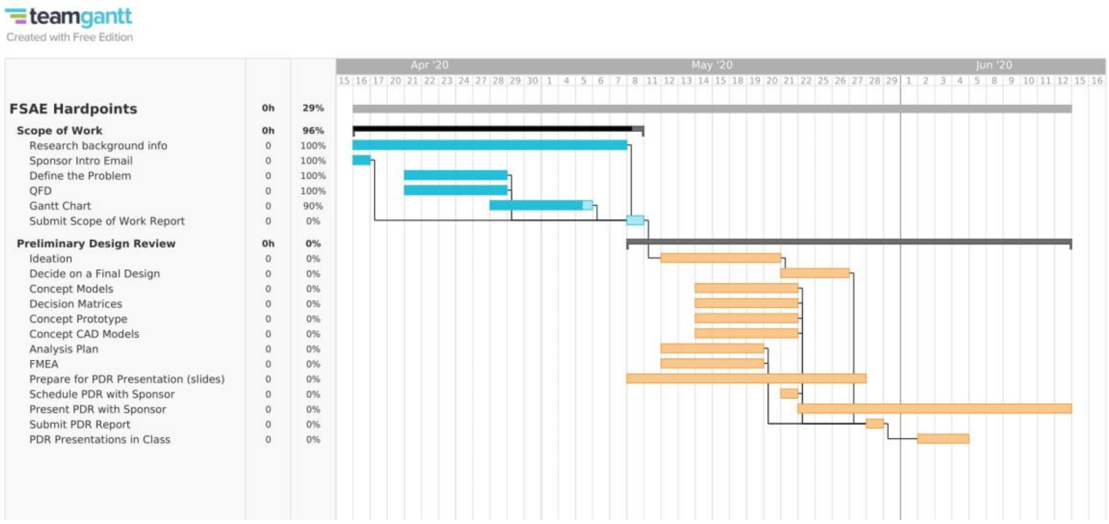
Appendix K: Jig Operators Manual

This jig is to be used only with an instron tensile testing machine. To operate it, place the lower adapter piece in the bottom jaws of the instron machine. Make sure that the jaws have a good grip on the tab, or else slipping may occur during testing. This would invalidate any test data acquired. If the jaws are not able to grip the tabs well, sand the surface of the tabs with rough sandpaper. This creates a surface that is easier to grip. Once the bottom adapter is set, adjust the top piece of the jig to the desired angle: 0°, 30°, or 45°. Carefully slide the pin through both the top and bottom jig pieces, keeping them in place. Next, place the panel in the jig. Make sure that the panel is fully secured by the steel tube stock. Once this is ready, connect the suspension mount from the top instron jaw to the panel. Again, make sure that the instron jaw has a good grip on the mount. If everything is secure, the panel is ready to test.

There are a couple of safety concerns that come with the jig design. Always wear safety glasses while testing panels, since large amounts of force are being transferred onto both the panel and jig. Any of the pieces from the jig, panel, or suspension mount could snap unexpectedly, sending particles flying. The tabs that connect to the instron jaws can also slip, causing a safety hazard. When handling the jig, beware of any sharp edges that may come from the welding process, or any sharp corners. Inserting the pin into the jig can also result in pinched fingers. The jig is also decently heavy, so always wear closed toed shoes when handling in case of an accidental drop.

Appendix L: Gantt Charts

Attachment : Gantt Chart plan through Spring 2020, made on TeamGantt



Attachment : Gantt Chart plan through the end of Fall 2020, made on TeamGantt

Attachment : Gantt Chart plan through the end of Winter 2021, made on TeamGantt