**ME 43: Senior Design Project**

FALL 2012

# Design and Manufacture of Carbon Fiber Ukulele

# FINAL REPORT


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# Executive Summary

As composite materials become more commonplace, they are increasingly replacing other materials in a wide range of industries due to their strength, weight, and wear resistance. Carbon fiber, specifically, has been found to be an excellent substitute for wood in many musical instruments as it affords many advantages over the traditional wood while remaining visually and acoustically appealing. The goal of this work is to explore the use of carbon fiber musical instruments by constructing a carbon fiber ukulele and developing a complete manufacturing process. It is desired that the prototype and manufacturing process produce an aesthetically pleasing instrument whose tone is comparable to a typical ukulele. It is also important that the complete manufacturing process incorporates industry standard materials.

In the design of the ukulele, an important consideration was the requirement of bracing. Traditional wooden instruments require bracing on the soundboard to prevent warping due to string tension. It was unclear whether this was required for a carbon fiber instrument, as carbon fiber is a much stronger material. It was found that bracing, despite its ability to mitigate the displacement and stress of the soundboard, was not required for this application. Furthermore, it was decided that incorporating bracing into a first prototype would complicate the manufacturing process. Traditional ukuleles also typically have a separate neck and body that are joined at the heel. For this project, this was modified so that the neck and body are a single piece, as a neck joint would greatly decrease the strength of the instrument and would be cause significant complications during assembly. The soundboard and headplate were designed to rest along the entirety of the body, and the fretboard was designed to sit on top of the neck portion of the soundboard. Following complete construction, readily available hardware purchased from vendors would have been assembled to complete the instrument.

In manufacturing, a typical carbon fiber process involves laying wet pieces of carbon fiber into a mold and pulling a vacuum, removing excess resin and conforming the carbon fiber to the shape of the mold. In this project, it was decided that a vacuum infusion process would be more appropriate. In vacuum infusion, the setup is done dry and resin is pulled through the part via a vacuum pump. This method allows for more setup time, decreasing the likelihood of errors, allows for more consistent carbon fiber to resin ratios than in a typical wet layup process, and generally produces a higher-quality part.

Further operations that could not be performed in-house were required in order to complete the product. The machining of the mold and water jet cutting were both farmed-out to local companies. The mold required distinct curves that could not performed on the equipment available, while a waterjet was used to cut carbon fiber sheets to the exact size required. Other methods for cutting would have been much less precise, and would have required extra hours of sanding to get all parts to the exact size required.

A number of issues were encountered in this project. A working ukulele is not currently available as the body is stuck in the mold. All other components, however, are ready for assembly. Moving forward, the manufacturing process will be refined and the body removed in order to complete the goals of this project and continue the manufacturing of carbon fiber instruments.

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# 1) Introduction

### 1.1) Background and Project Statement

The ukulele is a small, guitar-like instrument that typically employs four nylon or gut strings. Its main components are labeled below in Figure 1. The ukulele is made up of a body (the sides and bottom), a soundboard (the top face of the body) which typically incorporates a circular soundhole, a separate neck attached to the body through a heel, a fretboard which sits on the neck, and a headstock located at the end of the neck. A typical ukulele's hardware includes a bridge and saddle below the soundhole, a nut at the end of the neck, fretwire along the fretboard, and tuning pegs attached to the headstock. The strings are tensioned between the saddle and the nut, and when the strings of the instrument are plucked, vibrations are induced in the air inside the body, which produces the instrument's sound.

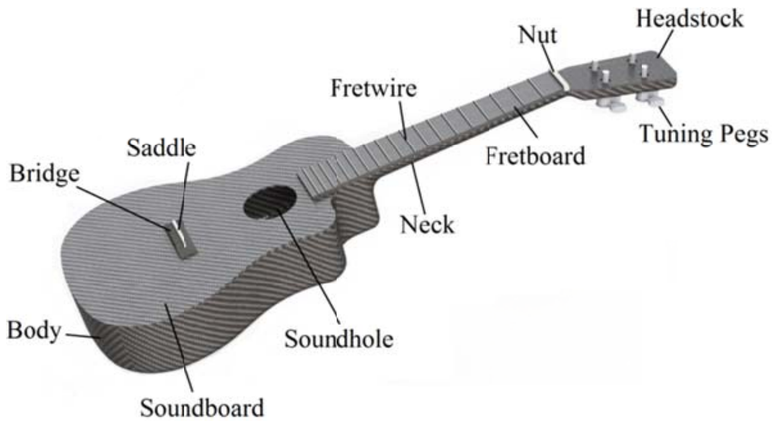



**Figure 1 - Ukulele Schematic**

String instruments such as the guitar, ukulele, violin and cello are traditionally made out of wood; however, there is a rapidly growing interest among manufacturers in building instruments with composite materials, such as carbon fiber. Carbon fiber offers several significant advantages over conventional wood; it is stronger, which results in requiring less extraneous bracing material; it is lighter, and it is considerably more resistant to changes in temperature and humidity. Additionally, recent advances in composite materials and manufacturing have resulted in instruments that achieve comparable sound quality to their high-quality wooden counterparts. These qualities have significant implications for professional musicians who perform at outdoor venues, where extremes in temperature and/or humidity would have drastic detrimental effects on wooden instruments, as well as for amateur musicians who enjoy using their instruments outdoors or while travelling.

The goal of this project is to design and manufacture a concert ukulele using carbon fiber. The concert ukulele's small size and relatively simple geometry made it a very feasible instrument choice given the project's time and budget constraints, and the team's access to facilities with the necessary manufacturing capabilities.

### 1.2) Scope and Design Goals

For this project, the team decided to manufacture the body, neck, soundboard, fretboard, and headplate using carbon fiber. The hardware components would be bought off the shelf.

The design goals of this project are listed below:

- Achieve comparable aesthetic and acoustic quality to a traditional wooden ukulele
- Use less bracing material than traditional wooden ukuleles
- Achieve a final overall weight lower than that of traditional wooden ukuleles
- Achieve increased resistance to changes in temperature and humidity through the use of carbon fiber
- Incorporate industry-standard materials and processes
- Develop reliable and comprehensive manufacturing processes for each of the different components

# 2) Design

### 2.1) Design Considerations

There were a number of design features and manufacturing options that were considered for the ukulele. In the initial design phase, one of the preliminary design options that were considered was the use and type of soundboard bracing. Most ukuleles have bracing on the soundboard to prevent warping caused by the tension in the strings. Since carbon fiber is a much stronger material than wood, the design would ideally not need any bracing as it would dampen the vibrations of the soundboard and would add weight to the instrument.

Various types of bracing methods are used in wooden ukuleles, and the most common type is a radial bracing. A finite element analysis (FEA) was performed on a control soundboard with no bracing, a soundboard with radial bracing, and a soundboard with square bracing (Figure 2) to evaluate the effect of bracing on the stress and displacement of the soundboard.

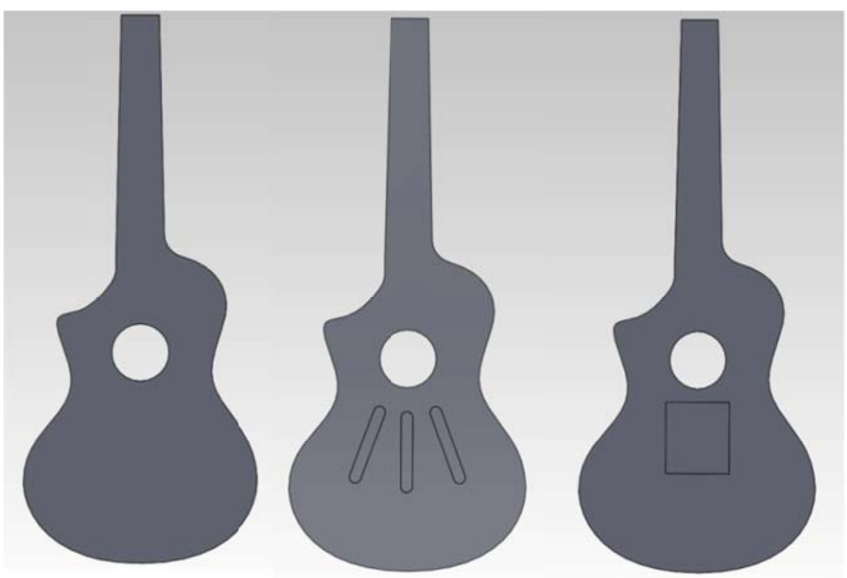


**Figure 2 - From left: No Bracing, Radial Bracing, and Square Bracing**

For the analysis, 30lb of force (the amount of string tension on a typical ukulele) was applied to the bridge and saddle of the ukulele as seen in Figure 3.

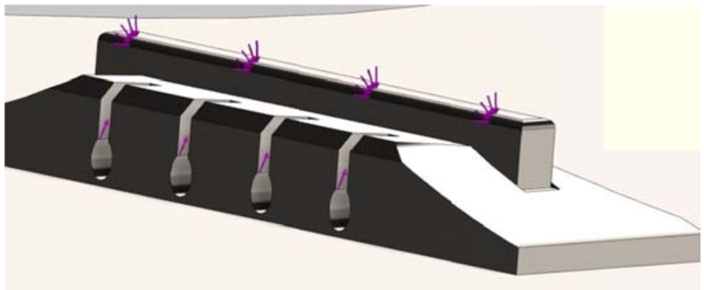


**Figure 3 - FEA: Forces on Bridge**

The results of the FEA are shown below for all three cases. Figure 4 is a displacement analysis while Figure 5 is a stress analysis.

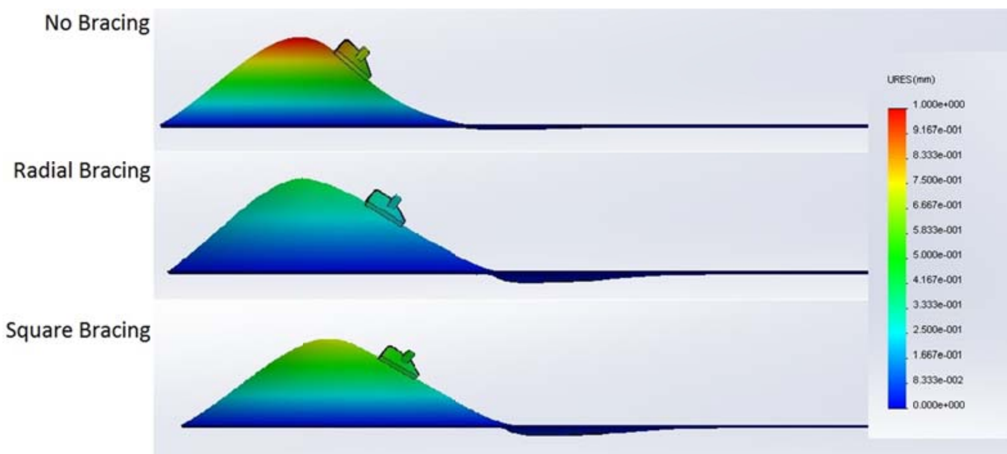



**Figure 4 - FEA: Displacement Analysis**

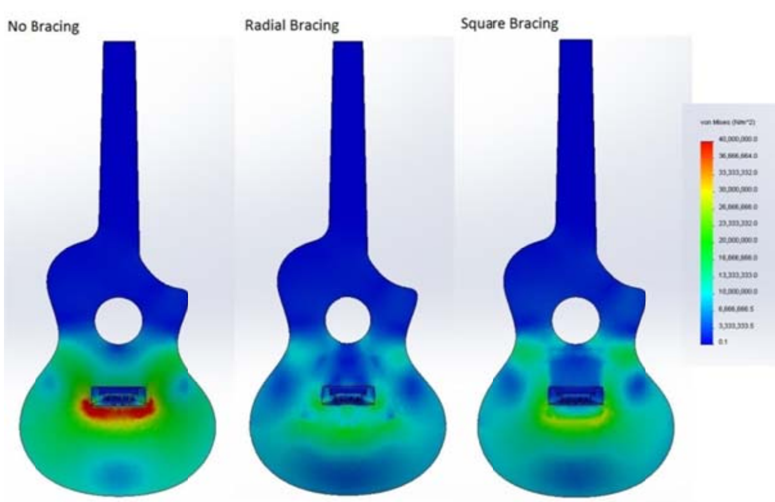



**Figure 5 - FEA: Stress Analysis**

From these results, it is shown that either type of bracing succeeds in limiting both the displacement and the stress experienced by the soundboard. However, as the approximate yield strength of carbon fiber is 508 MPa, a lack of bracing should by no means cause any permanent damage to the instrument. The radial bracing performed slightly better than the square bracing, limiting displacement to 0.67mm and stress to 22 MPa versus 0.75mm and 29 MPa respectively for the square bracing. In addition, the radial bracing used less material, and would therefore dampen the soundboard less than the square bracing would.

Despite these results, after talking to a contact at Blackbird Guitars, a company that makes and sells carbon fiber instruments including ukuleles, it was concluded that bracing would not be required for the project. In addition, foregoing bracing on the soundboard would simplify the manufacturing process.

The constraints of manufacturing capabilities and the layup process also became important design considerations. Traditional ukuleles have sharp corners between various parts, such as between the back and the sides of the instrument. This would be extremely difficult to achieve because it would require a very fine tool and would render the manufacturing process both very expensive and very time-consuming. Consequently, it was decided that a feasible design of the instrument would have to incorporate rounded corners.

The constraints of the layup process for the ukulele also introduced a design feature conflict between instrument playability and manufacturability. Most traditional wooden ukuleles have a well-rounded corner where the neck of the ukulele meets the body, however, some instruments feature a cutout (Figure 6) to facilitate playing notes located higher up on the fretboard. Incorporating this feature, however lengthens and complicates the layup process, as it is difficult to lay carbon fiber around sharp corners. It was decided that despite the predicted manufacturing difficulties, a cutout would be included in the design for increased playability and unique aesthetics. This manufacturability of this design feature later proved to be much more challenging than anticipated.

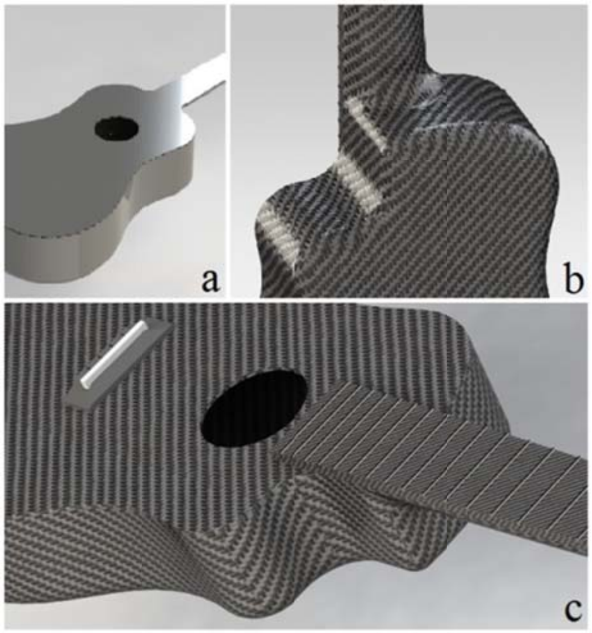



**Figure 6 - a: No cutout, b: Cutout from rear, c: Cutout**

### 2.2) Design Solution

The carbon fiber ukulele was designed to be concert-sized, which reflects an existing size class in the instrument family. Most of the major dimensions such as overall length, scale length and soundhole diameter, were adapted from dimensions of traditional wooden ukuleles. The mold, or tool for the body was to be made of Renshape, which is an industry-standard foam material that is both very machinable and is able to hold contours well. The tool dimensions, such as minimum radius and minimum draft angle, were determined based on the manufacturing constraints of the available machining facilities. Important ukulele and mold dimensions can be found below in Tables 1 and 2.

Figure 7 - Orthographic Views of CAD Model

| Property | Value |
|---|---|
| Overall Length | 55.97 cm |
| Scale Length | 38.22 cm |
| Body Width (at top) | 21.7 cm |
| Body Depth | 6.0 cm |
| Soundhole Diameter | 5.08 cm |
| Neck Width (at head) | 3.5 cm |
| Minimum Radius | 6.35 mm |
| Headstock Angle | 15° |
| Number of Frets | 19 |

Table 1 - CF Ukulele Dimensions

| Property | Value |
| --- | --- |
| Material | RenShape 460 |
| Mold Depth | 101.6 mm |
| Minimum Radius | 6.35 mm |
| Minimum Draft Angle | 1.5° |
| Surface Finish | N/A* |

Table 2 - Body Mold Dimensions

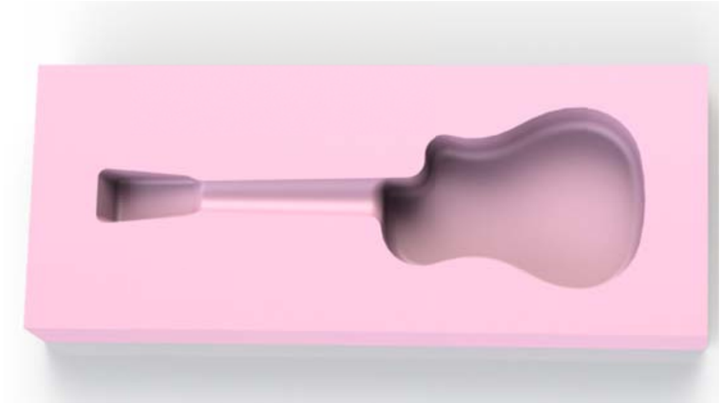


Figure 8 - Body Mold CAD Model

It was desired that the carbon fiber ukulele share the aesthetics of a conventional ukulele, and as seen in Figure 9, the typical contours of a ukulele were retained, though many of the tighter corners were relieved with fillets to allow for easier layup and machining processes. A cutout was also added so that the rounding of the corner between the neck and the body would not impede playing ability higher up on the fretboard. Finally the curves between the upper and lower bout of the ukulele were also relaxed to allow for easier layup.

Typical wooden ukuleles feature a separate body and neck that are attached via a heel, which is located at the end of the neck. A key feature of the design of the carbon fiber ukulele is that the body, neck and headstock are all one continuous, open-top piece. One major effect of this feature is that it allows for more air to vibrate within the cavity, which should produce sound at an increased volume. Another implication is that the instrument would be stronger as a result of less individual pieces bonded together. It was uncertain as to whether this design feature would result in an easier manufacturing process; having less components to attach together could require less total assembly time, however, the layup process around the complex geometry of the continuous piece could be very difficult and time-consuming.

Figure 9 - CF Uke CAD Render

### 2.3) Materials

It was decided that the team would manufacture the body, neck, headplate, fretboard and soundboard out of carbon fiber. The hardware components would be bought off the shelf. Table 3 displays each of the instrument's components, its selected materials, and its corresponding manufacturing process, which will be discussed in detail in the next section.

| **Part** | **Material** | **Method of Construction/Source** |
|---|---|---|
| Body, Neck and Head Plate | Carbon Fiber | Layup on custom mold/tool<br>Vacuum Infusion Process (VIP) |
| Soundboard | Carbon Fiber | Layup on Flat Tool<br>VIP<br>Waterjet-cut |
| Fretboard | Carbon Fiber | Layup on Flat Tool<br>Vacuum Bagging<br>Waterjet-cut |
| Mold/Tool | RenShape 460 (Foam) | CNC Machined |
| Fretwire | 18% Nickel Silver | Off-the-shelf |
| Bridge | Wood/Plastic | Off-the-shelf |
| Saddle and Nut | Bone | Off-the-shelf |
| Tuning Pegs | Stainless Steel | Off-the-shelf |

**Table 3- CF Ukulele Components**

# 3) Manufacturing

### 3.1) Background

An important part of this project was deciding on a manufacturing process. Carbon fiber layup is typically done via a vacuum bagging process that can be seen in Figure 10 below.

The carbon fiber sheets are individually placed onto a tool and are coated with resin before the next sheet is added. After this is done, peel ply is placed over the carbon fiber so that subsequent material will not get stuck to the part. Above this, an infusion media is placed to facilitate the flow of air and resin. This setup is surrounded by a vacuum bagging film that is sealed to the tool with sealant tape. A vacuum is then pulled on the tool to help conform the carbon fiber to the tool and to remove any excess resin from the part.

Another, more recently developed method, is a vacuum infusion process (VIP), or resin infusion process, shown in Figure 11.

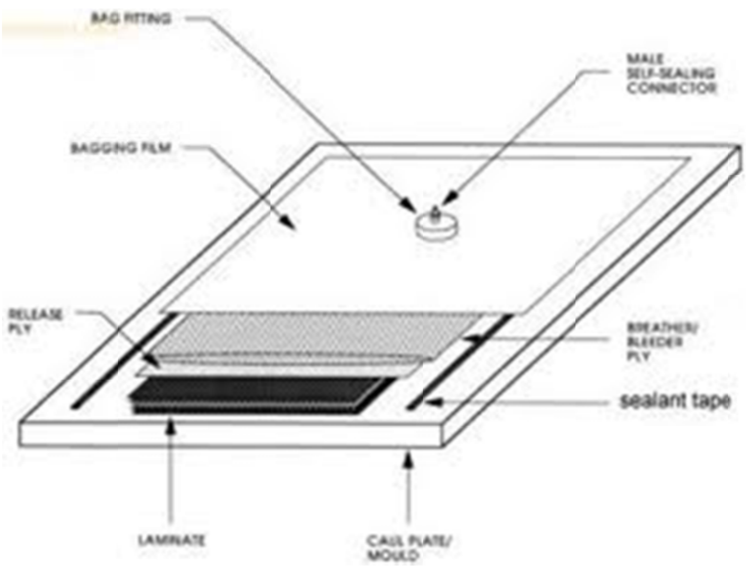



Figure 10 - Vacuum Bagging

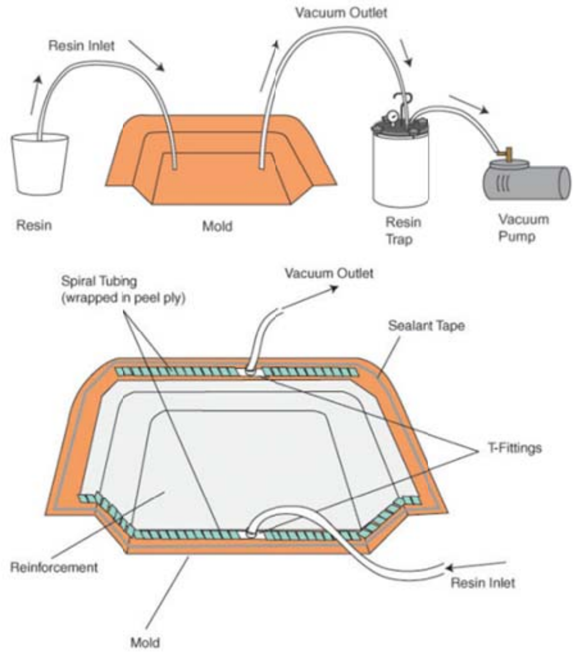



Figure 11 - Vacuum Infusion

In this process, the layup of the carbon fiber sheets is performed dry, without the introduction of resin until the setup is complete. Once the carbon fiber, peel ply, flow media, and bagging film are set up, the line to the resin is clamped and a vacuum is pulled over the entire part. The resin line is then released, and resin is pulled through the part and into the resin trap.

For this project, it was decided that a VIP would be preferred to the typical wet layup with vacuum bagging. There are a number of reasons this decision was made. First, a VIP is cleaner, as it does not require the messy process of layering carbon fiber with resin by hand. Additionally, the resin and hardener mixture has a gel time, which denotes a limited amount of time with which to work with the mixture. Because of this, VIP would also be preferable because it allows more time for setup, as resin is not introduced until all other components are ready. This significantly reduces the likelihood of working past the gel time of the resin and producing a partially completed part. Lastly, a successful VIP gives a much better fiber-to-resin ratio than a typical layup process. When making carbon fiber parts, it is desirable to have as little resin as possible while still ensuring that all the carbon fiber has been wet.\With a typical layup process, an ideal process may lead to a 50:50 ratio of carbon fiber to resin, whereas with vacuum infusion, it is possible to get a ratio upwards of 60:40.

### 3.2) Materials

Preliminary material research was conducted during the design phase of the instrument to determine materials that were manufacturable, cost-effective, and high-quality. The ultimate goal of the project was to produce three ukuleles, and so the sizing or amount of each of the various materials was based on the expectation that three instruments would be made. This section categorically discusses the various materials and products selected for the ukulele project. A comprehensive list of materials can be found in the appendix.

| **Mold & Prototype** | | | |
|---|---|---|---|
| **Item** | **Description** | **Vendor** | **Quantity** |
| RenShape 460 | 4" x 20" x 60" | Freeman | 1 |
| Chemlease Mold Cleaner EZ | 1 gallon | Freeman | 1 |
| Chemlease 2180 Primer | 1 quart | Freeman | 1 |
| Chemlease 15 Sealer | 1 quart | Freeman | 1 |
| Chemlease One FS Release Agent | 1 gallon | Freeman | 1 |
| | | | |
| **Layup Material** | | | |
| **Item** | **Description** | **Vendor** | **Quantity** |
| Carbon Fiber Twill | Twill, 50" Roll, 3K | US Composites | 8 |
| Vinyl Ester Resin | 1 Gallon w/ Hardener Kit | Fibre Glast | 1 |
| DIVINYMAT | 32" x 48" Sandwich core, perforated | Fibre Glast | 3 |
| Super 77 Spray Adhesive | Sticks dry material | Freeman | 1 |
| Glass Surface | From Picture Frame | Goodwill | 1 |
| | | | |
| **Vacuum Infusion Process** | | | |
| **Item** | **Description** | **Vendor** | **Quantity** |
| Strechlon 200 Bagging Film | Bag stretches 500%, 60" wide, 5 yd roll | Fibre Glast | 2 |
| Polyester peel ply | 60" wide, 3 yd roll | Fibre Glast | 1 |
| Sealant tape | 25' roll | Fibre Glast | 4 |
| Flow Media | Easy Gardner BirdBlock©: Protective Mesh Covering | MacMaster-Carr | |
| PVC Tubing | 1/2" ID 11/16" OD | MacMaster-Carr | 50 |
| Single Barbed Tube Fitting Tee | 1/2" tube ID, nylon, packs of 10 | MacMaster-Carr | 2 |
| Vacuum Guage | Steel Case, 2"Dial, 1/4 bottom conn 30"Hg-0 | MacMaster-Carr | 1 |
| Threaded Pipe Fitting | 1/4" pipe NPT aluminum | MacMaster-Carr | 1 |
| Single Barbed Tube Fitting Adapter | 1/2" Tube to 1/4" NPT male pipe packs of 10 | MacMaster-Carr | 1 |
| Spiral Tubing | 1/2" OD, 100' spool | MacMaster-Carr | 1 |
| Nalegene© Bottle | 32 oz, | Tufts | 1 |
| Barbed Male:Male Fitting | ½” ID | Home Depot | 3 |
| | | | |
| **Hardware/Assembly** | | | |
| **Item** | **Description** | **Vendor** | **Quantity** |
| Fret Wire | Narrow #147 | Stewart-MacDonald | 4 |
| Bridge | | Stewart-MacDonald | 3 |
| Nut | | GraphTech | 3 |
| Saddle | | GraphTech | 3 |
| Tuning Machines | Sperzel 3+3 Trim-Lok Tuning Machines Black | Musician's Friend | 2 |
| Kerfed Lining | For Mandolin | Stewart-MacDonald | 18 |
| Epoxy Adhesive | 3M Scotch-Weld DP 420 (Black) | Grainger | 2 |
| Strings | Concert Uke Strings | Aquila Nygut | 3 |

**Table 4 - CF Ukulele Materials**

### *3.2.1) Mold*

RenShape 460, supplied by Freeman Manufacturing & Supply Company, was the selected material for the mold because of its application versatility, machinability, and dimensional stability. A glass surface from a large, used, picture frame was used as a tool surface for all the flat pieces (soundboard, head plates, and fretboard). This surface was appropriate for layup because it was flat and had a very smooth finish. The Chemlease mold cleaner, primer, sealer and release agent were selected to match the RenShape, as suggested by technical experts from Freeman Supply.


**Figure 11 - Renshape 460 and Glass Surface**

### *3.2.2) Layup*

Carbon fiber twill was purchased from US Composites; it was of a relatively generic kind used in many applications and was chosen for its balance of performance and price. The instrument is not by any means a performance product, so special specifications of carbon fiber were deemed unnecessary. The Super 77 Spray Adhesive was a reliable and recommended adhesive for use with carbon fiber layup.

### *3.2.3) Vacuum Infusion Process*

Vinyl Ester Resin and its corresponding hardener from Fibre Glast had specific chemical properties, notably, low viscosities, that made them particularly suited for resin infusion. The bagging film, peel ply, and sealant tape from Fibre Glast were selected because they were all specifically designed to be used for effective vacuum infusion. Miscellaneous items such as fittings, tubing, clamps, and vacuum gauges were purchased from MacMaster Carr and Home Depot. It should be noted that most of the layup and infusion materials are not reusable, and that the likelihood of unsuccessful attempts was taken into account when deciding on the quantity of each material to put on order. Additionally, mixing buckets, measuring cups, nitrile gloves, respirators, and spring clamps were used.

### *3.2.4) Flow Media*

Divinymat, also from Fibre Glast, was initially selected to be a flow media and structural core, but due to reasons discussed in the next section, an alternative flow media was required. After some additional research as to what properties are necessary in an effective flow media, the team decided to use plastic bird netting (see Figure 13) because it was relatively cheap, and it was readily available. The material, in fact, worked surprisingly well, as described in the next section.

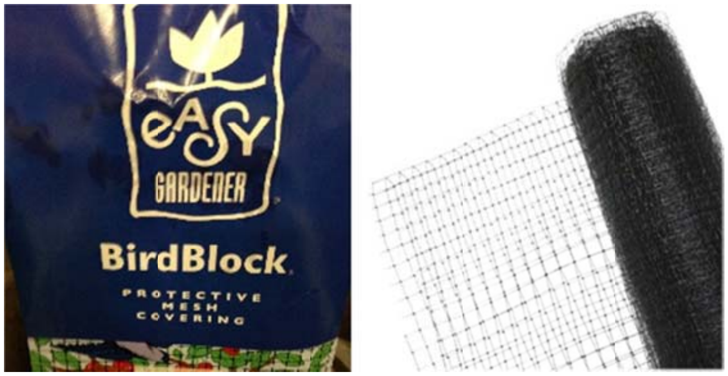



**Figure 12 - Flow Media: Easy Gardner BirdBlock: Protective Mesh Covering**

*3.2.5) Resin Trap*

**Figure 13 - Nalegene© Resin Trap**

As mentioned above, the vacuum infusion process involves the use of a resin trap to contain excess resin while maintaining a vacuum through the part. Research revealed that existing, dedicated products were extremely expensive, so it was decided that one would be constructed using readily available materials. A plastic 32 oz Nalgene© bottle was acquired, and two holes were drilled into the plastic cap to accommodate the two ½” ID tubing. Barbed male-to-male tube fittings were installed at the trap ends of the tubing, and the tubing was secured to the cap using sealant tape. A plastic cup was placed inside the trap to collect any excess resin, so that it could be discarded after an infusion process instead of accumulating in the trap.

*3.2.6) Hardware*

The purchased ukulele fretwire, bridge, saddle, and nut were selected based simply on cost. The Aquila strings were selected because of their popularity among ukulele players. Mandolin kerfed lining was also acquired, because research showed that it was commonly used for assembling ukuleles. The 3M Scotch Weld Epoxy Adhesive was selected for both its suitability for the materials used in this project, and its black color.

### 3.3) Construction Phase

This section discusses each layup process that was performed, reflects on challenges encountered, and notes changes that were made to account for earlier problems. Exhaustive and step-by-step layup and infusion procedures for all carbon fiber parts manufactured in this project, in addition to ukulele assembly instructions, can be found in the appendix.

#### *3.3.1) Soundboard #1*

The goal of the very first layup process of the project was to produce a piece of carbon fiber sizeable enough for a soundboard and a head plate to be cut out. The carbon fiber was laid out on the glass tool and Divinymat was used as a flow media. Two lengths of spiral tubing were placed on either side of the carbon fiber sheets, lengthwise. While under vacuum, the resin very slowly moved across most of the carbon fiber, moving slightly farther along the edges than in the center (See Figure 15). After the piece had cured, it was found that the Divinymat was very difficult to separate from the carbon fiber, despite the presence of peel ply. The Divinymat was originally supposed to be used as a structural core for the carbon fiber, however, after realizing it wasn't necessary due to the low stresses involved, and because of the difficulty it would present in ensuring that the it would not be visible after waterjet cutting, it was decided that it would function well solely as a flow media. However, because it was designed to be used as a structural core, the Divinymat absorbed a high volume of resin, became very rigid, and allowed more bonding between itself and the carbon fiber than had been anticipated. It was eventually removed from the part through the use of wooden wedges that were advanced along the carbon fiber, although this did not occur until the second soundboard layup was under vacuum. Incomplete infusion was partially attributed to the resin bucket being placed on the floor, requiring the vacuum to pull the resin up about 3' before it was able to enter the part.

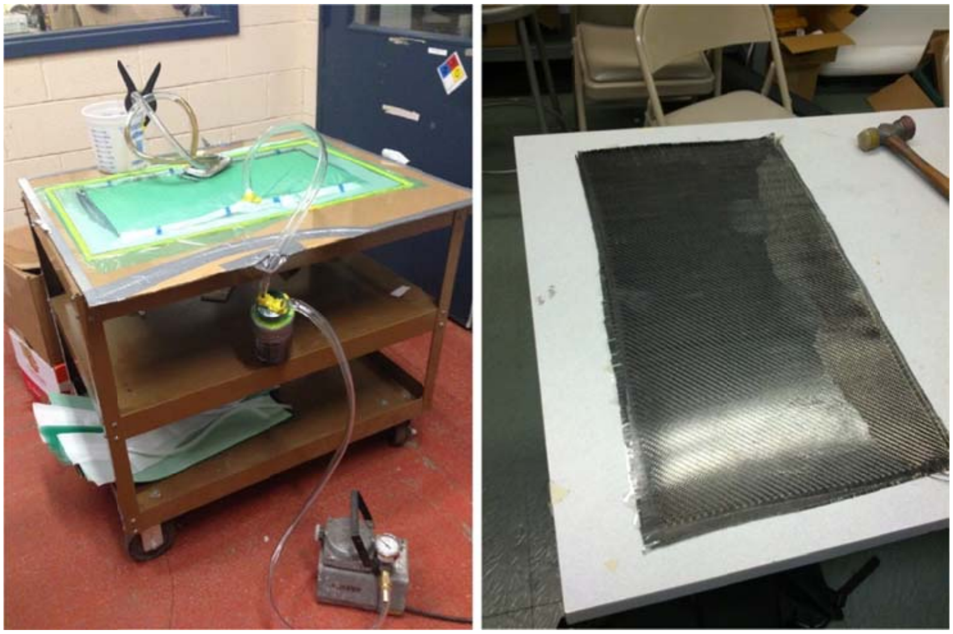


**Figure 14 - 1st Soundboard Layup**

*3.3.2) Soundboard #2*

Because the first soundboard layup process achieved only partial resin infusion of the carbon fiber, and the Divinymat was stuck fairly well to the part, it was decided that a second layup was necessary. It was decided that using two vacuum lines along the edges of the part and a resin inlet through the center might yield a more complete infusion of the part. Furthermore, instead of using Divinymat again as a flow media, the mesh backing of the Divinymat was utilized as it was both readily available and less likely to cause a difficult separation process. During infusion, the resin bucket was initially placed above the part. After resin pooling began occurring near the inlet, it was realized that a siphon had inadvertently been created. This was rectified, although there was still a sizeable amount of resin pooling along the spiral tubing of the inlet. Some of this excess resin was gently pushed outward to help further infuse the part. Some time later, a leak was noticed as air begin entering the resin inlet tubing from the part. It took a few minutes before the source of the leak was discovered and sealed with sealant tape. A sizeable amount of air had entered the tube, and so the resin inlet was sealed sooner than anticipated to prevent the air from being pulled into the part. It is possible this leak formed as a result of the resin distribution performed earlier due to pooling. This part had more complete infusion than the first layup, but there were still areas that had not been properly wet.

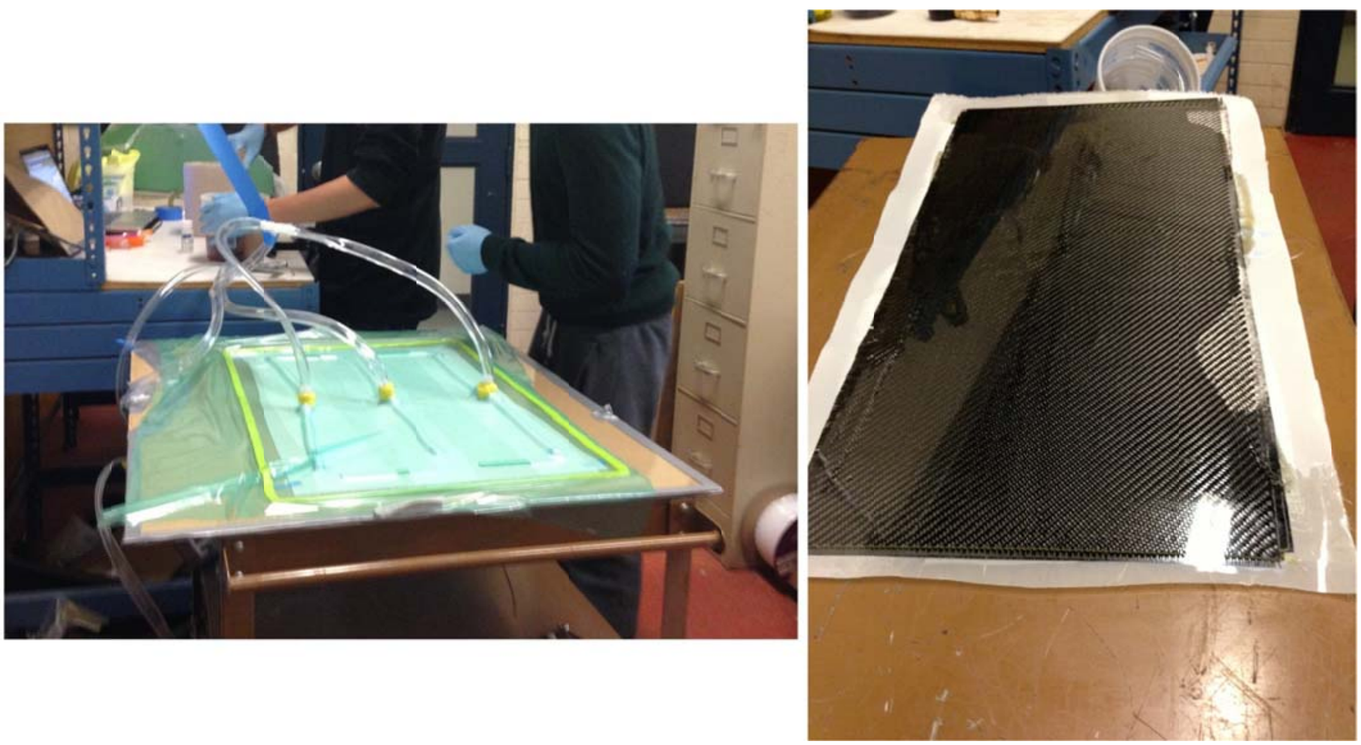


**Figure 15 - 2nd Soundboard Layup**

*3.3.3.) Fretboard*

It was decided that a wet layup would be a better method for the fretboard as it was uncertain whether it would be possible to pull resin through the 16 layers of carbon fiber given the difficulties already experienced with resin flow. In addition, bird netting was purchased from Home Depot and used an alternative flow media. The wet layup was performed on sheet of vacuum film in attempt to keep the tool clean. After the carbon fiber sheets were assembled, they were placed on top of a thin layer of resin that was spread onto the tool to help ensure a smooth finish. After a vacuum had been pulled, a piece of excess resin slightly smaller than a hockey puck had been removed from the part. This was the first time that resin had passed entirely through the part and into the resin trap.

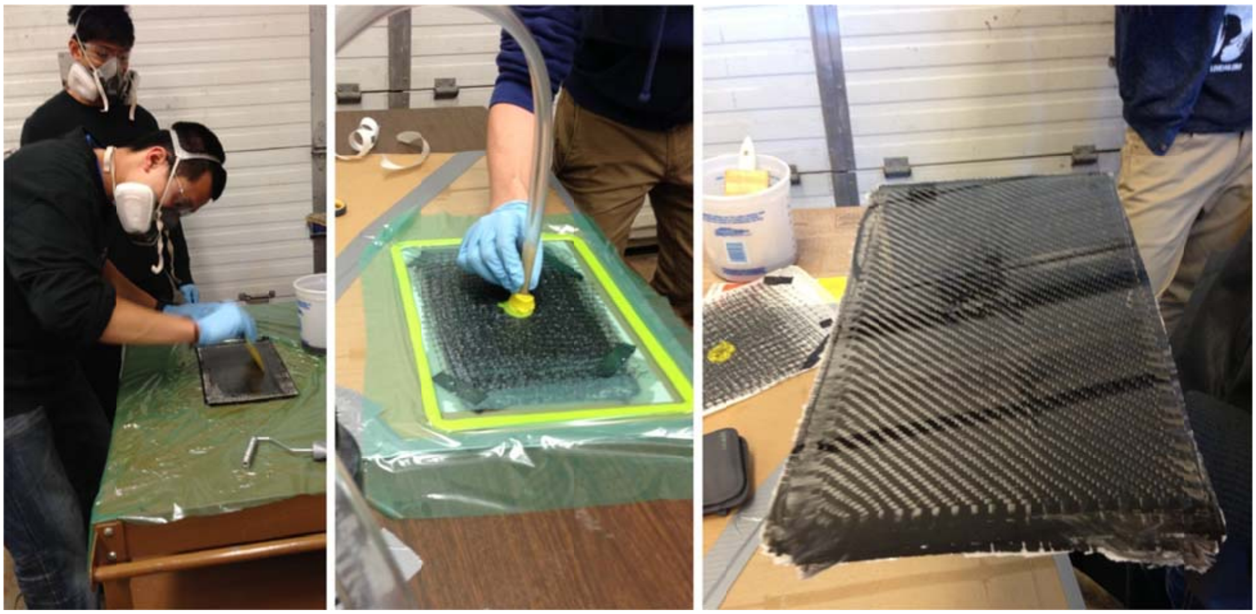


**Figure 16 - Fretboard Layup**

*3.3.4) Body*

Due to the previous success of the bird netting as flow media, it was decided to continue using it in the body layup. The mold was first extensively prepared with several layers of cleaning agent, primer, sealer, and release agent. Next, the carbon fiber, peel ply, and flow media were laid into the mold. This laborious process took several hours and after pulling a test vacuum, it was discovered that there were large areas of the geometry where the vacuum bag did not adequately conform to the mold and would almost certainly ensure bridging. It was decided a repeat of the entire layup process was necessary to help ensure that a quality part be produced. During this second layup process, increased attention was given to the ability of each layer to simultaneously conform to the entire surface of the mold. A much larger vacuum bag was cut, so that excess could be placed inside the cavity of the mold itself. This way, the vacuum would not rely solely on the ability of the vacuum bag to deform itself to the mold. After the resin was mixed and a vacuum was pulled, the resin moved considerably quicker through the part than in any of the previous vacuum infusion processes. Complete wetting of the visible layer of carbon fiber occurred within 7 minutes, whereas in previous infusion processes, the resin had gelled before this occurred. It was decided to allow the vacuum to continue to pull resin, as it was unclear whether or not every layer of carbon fiber had been wet.. The resin line was clamped off 15 minutes after infusion had begun. A small leak did occur during this process. Its exact location was not found, but pressure was maintained on the resin inlet tube and this greatly mitigated the flow of air from the part into the resin line. This air also contributed to the decision to clamp of the resin line.

After the part had cured, it was found to be extremely difficult to remove the part from the mold without damaging the part itself. The body was allowed to stay in the mold pending the Senior Design presentation and with plans to remove it after winter break.


**Figure 17 - Body Layup**

**Figure 18 - CF Body Piece in Mold**

**3.4) Contracted Work**

*3.4.1) Waterjet Cutting*

It was determined that waterjet cutting would be the most efficient way to cut all of the flat pieces (the soundboard, head plate, and fretboard) to match the designs because it functioned much like a laser cutter and would not require dedicated cutting tools. Much like a laser-cutter, the DXF files could be easily loaded onto the machine and used to produce parts with an accuracy of within .010”. Waterjet machines function by forcing a water and abrasive media mix through the plate at pressures around 50,000 psi.

Figure 19 - Water Jet Cutting

S&T Precision Plate Cutting was contracted to undertake the waterjet cutting of the flat carbon pieces to produce the soundboards, head plates, and fretboards of the ukulele. The only issues encountered during this process were the small chips made in parts being cut. In waterjet cutting, the plate rests on rigid steel slats, below which is a pool of water that absorbs the high pressure spray. While the water successfully absorbs the spray from the nozzle after it passes through the part, the rigid steel slats disperse the spray in a multitude of directions (this phenomenon can be observed in the video attached in the appendix). As carbon fiber has brittle fracture behavior due to the resin, chips of the part had the potential to break off whenever the high pressure water reflected off the steel slats. While the issue was purely aesthetic, changes such as sandwiching the carbon piece between pieces of plywood before cutting might increase the quality of the finished part for the future. This way, any ricochets from the water off the slats would be absorbed by the plywood and not the part.

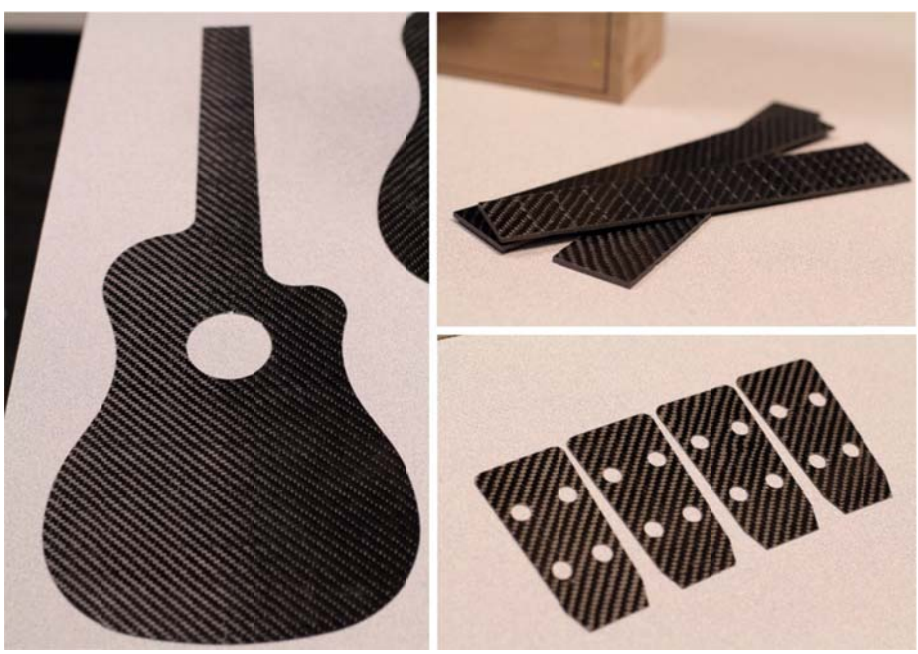


Figure 20 - Water Jet-Cut Components

*3.4.2) CNC Milling*

As mentioned in the design section, one of the goals in this project was to use industry-standard materials and also develop reliable processes to manufacture these components. To create a body that matched the design intents performed in SolidWorks, a custom tool was necessary. While there are many ways of producing tools, it was determined that milling of RenShape modeling foam would be both efficient and produce a high-quality mold. RenShape 460 is designed for applications such as this, and in addition there are a number of available off-the-shelf chemicals that work with this machinable foam to create a high-quality tool surface.

While the Mechanical Engineering Department at Tufts had the resources of its own machine shop, the 3D surfacing that was required as part of this process surpassed the capabilities of the machine shop and therefore a third party contractor was necessary. Cantabrigian Mechanics was therefore contracted, as their machinist had experience in programming 3D surface milling. The machining process was very quick, as RenShape cuts very easily while having a very high quality surface finish. A combination of cylindrical end mills and ball end mills were used to achieve the desired specifications. A picture below shows the finished product after the machining process.

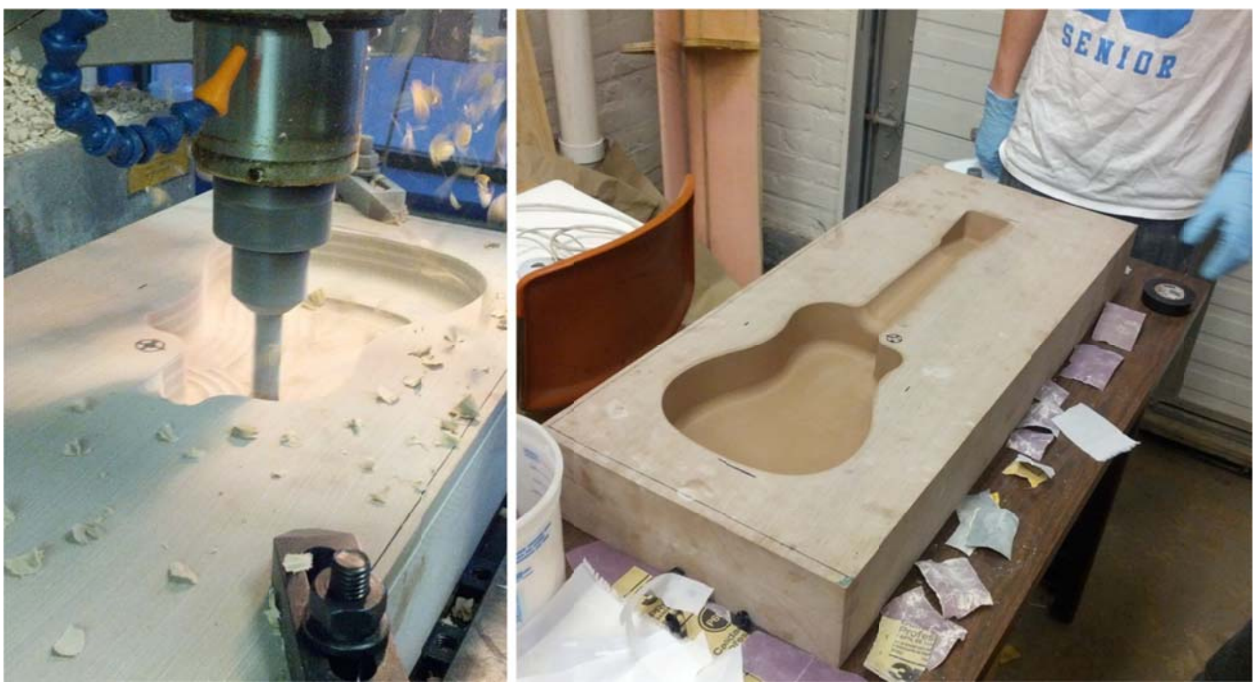



**Figure 21 - CNC Machined Body Mold**

## 3.5) Challenges

There were a number of challenges that were encountered during the manufacturing process that ultimately resulted in an unfinished ukulele at the time of this writing. As mentioned in the body layup section, the part was stuck to the mold after the curing process and unable to demold properly. The manufacturing process was scheduled such that the flat pieces were manufactured first, as the relative simplicity of a flat piece would allow the group to correct any manufacturing process issues before moving to a challenging part. However, there were still a number of unsolved issues that resulted in an unfinished prototype ukulele. The details of these issues is listed below.

### *3.5.1) Design*

One of the issues that made the body layup process especially challenging was the choice of the design. The issue was simply that the body's designed shape made it extremely tough to lay carbon fiber into without risking a part with possible bridging and voids. During the design phase, the emphasis of creating a prototype true to the size and shape of a traditional concert ukulele was much more than creating something that was more easily manufactured. Instead of simplifying the geometry to allow for easier composite layup, a cutout was put into the body and tight radii were introduced.

### *3.5.2) Engineering Setup*

It was apparent from the beginning that in order to create high quality composite parts, the manufacturing process had to be very tightly controlled and understood. This meant that detailed procedure documents would be necessary to avoid as many problems as possible. In addition to this, the decision to use vacuum infusion process to produce the parts introduced another level of challenge as the resin had to be pulled through the composite.

While there were many resources available, including a detailed white-paper document from composites supplier Fibre Glast (see the appendix), the engineering setup created was still not as efficient as it could have been. This led to some of the issues encountered during the layup process, like the lack of flow media use which led to parts that were not completely infused, the resin trap leaking air and the bagging issues encountered particularly with the body layup.

### *3.5.3) Body Mold/Tool*

The design and specifications of the body mold made a much larger challenge during the layup process. One of the issues in the specifications of the mold that attributed to the inability to demold was the surface finish of the mold. While the intents of the design were properly replicated by CNC machining, the surface of the mold was left as it was when the RenShape modeling foam was received. Its coarse textured surface was similar to a coarsely sanded wood and as a result was easy for the vinyl resin to adhere to. In addition to this, the interior surfaces of the mold were sanded at up to 2000 grit sandpaper, but it may have been necessary to additionally polish and buff all surfaces (including the non-body surfaces) of the mold to make it easier for parts to demold.

The second big issue of the design of the mold had to do with the draft angles. While it was initially thought that a 1.5 degree draft angle was enough to allow for easy demolding, the design of the body should have prioritized manufacturability over the desire to be as similar to a traditional wooden ukulele. The use of aggressive draft angles (5+ degrees) would have made both layup and demolding even easier.

Figure 22 - CF Body Piece in Mold

# 4) Conclusion

### 4.1) Lessons

While the current lack of a finished prototype was an obvious disappointment in the outcome of the project, there were a number of lessons learned from the design and manufacturing processes.

The first lesson was the scope of the project. An emphasis was placed on producing the deliverable prototype and not on developing the proper engineering process to allow for successful manufacturing. The team overlooked the importance of developing a reliable engineering process for the complex vacuum infusion process. As much as engineering is about the design and justification for how something is constructed, it is also about developing the process with which to produce a part, and that aspect was neglected in this project.

The project required both design and manufacturing to create a final product: the design to create the correct dimensions and ensuring that the parts would all fit with each other, and the manufacturing to actually produce the parts designed in SolidWorks. The importance of design for manufacturing was not taken into account and the group had considered the aesthetics more than it had considered if the prototype was something that was easy to manufacture. Rather than creating a prototype that looked very much like a traditional ukulele, a much more simplified design would have been easier to produce, with subsequent iterations becoming more complex in the future.

Lastly, working with contractors effectively and specifying the exact product could have improved the outcome of the project. While sending a CAD model of the part to a contractor is often sufficient, it oftentimes does not include supplemental notes like surface finish which turned out to be a critical part of the mold. Better communication with third party vendors would have helped in producing the mold exactly the way it was needed.

**4.2) Future Work**

The project currently still has many loose ends, not the least of which is an unfinished ukulele prototype. While there were difficulties during the manufacturing stage, the project will still continue to push forward to produce a working prototype.

The first step begins with removing the carbon fiber body piece from the mold and performing any necessary rework on the mold. Feasible methods of safe removal are still being researched. To achieve the desired surface finish, the mold surface would need to be faced down, sanded, and polished. Before further manufacturing, an additional change would be to revise the written procedures to be robust and reliable. While the current procedures are useful, they need to be improved to address a number of manufacturing challenges faced.

As all the other required components are already on hand, assembly of the ukuleles is dependent on producing the bodies. If the first body part can be salvaged, it will be fixed and prepared to be used in the first prototype. Following successful completion of the first prototypes, the process will be iteratively revised and repeated to create additional ukuleles.

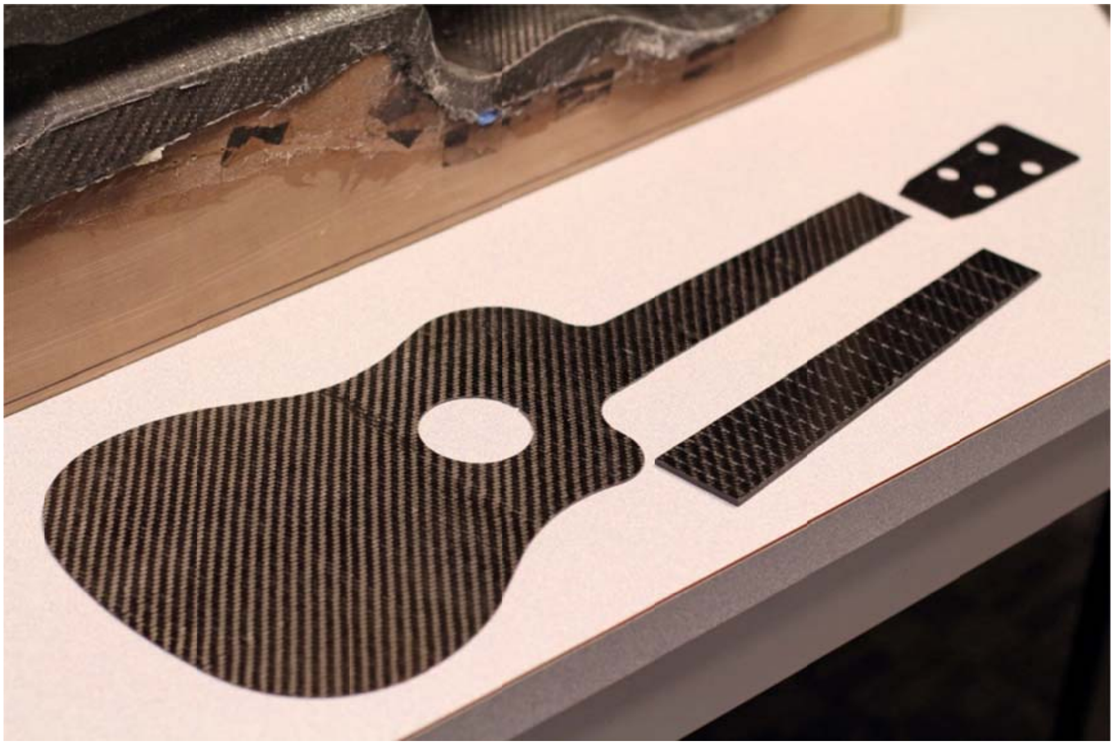
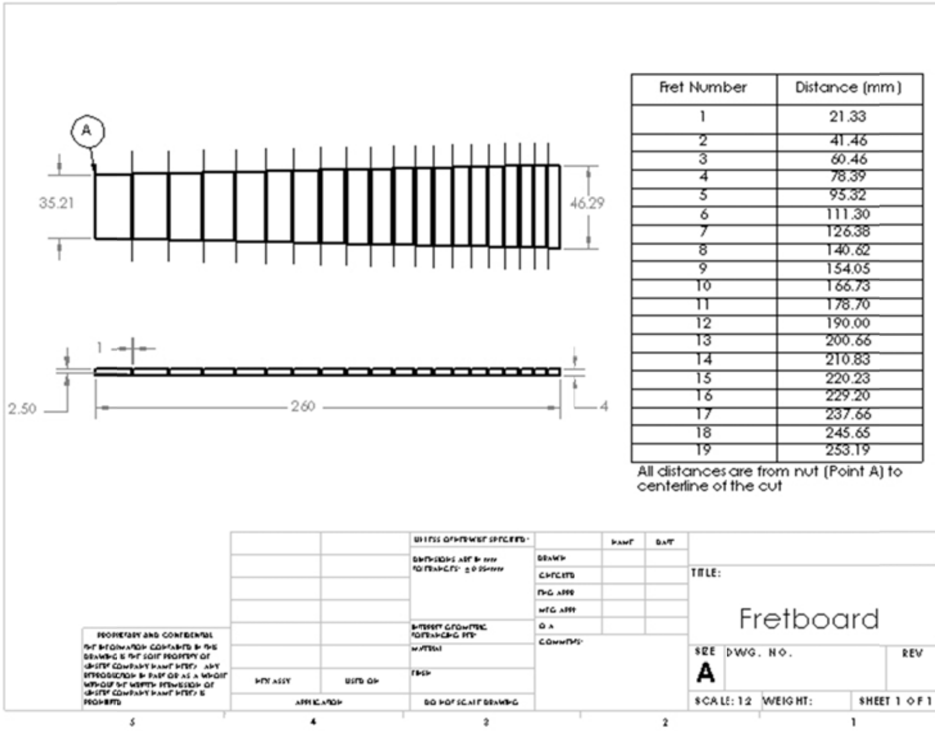


**Figure 23 - CF Ukulele Components**

# Appendix A – Engineering Drawings



| Fret Number | Distance (mm) |
|---|---|
| 1 | 21.33 |
| 2 | 41.46 |
| 3 | 60.46 |
| 4 | 78.39 |
| 5 | 95.32 |
| 6 | 111.30 |
| 7 | 126.38 |
| 8 | 140.62 |
| 9 | 154.05 |
| 10 | 166.73 |
| 11 | 178.70 |
| 12 | 190.00 |
| 13 | 200.66 |
| 14 | 210.83 |
| 15 | 220.23 |
| 16 | 229.20 |
| 17 | 237.66 |
| 18 | 245.65 |
| 19 | 253.19 |



Figure 1- Fretboard Drawing

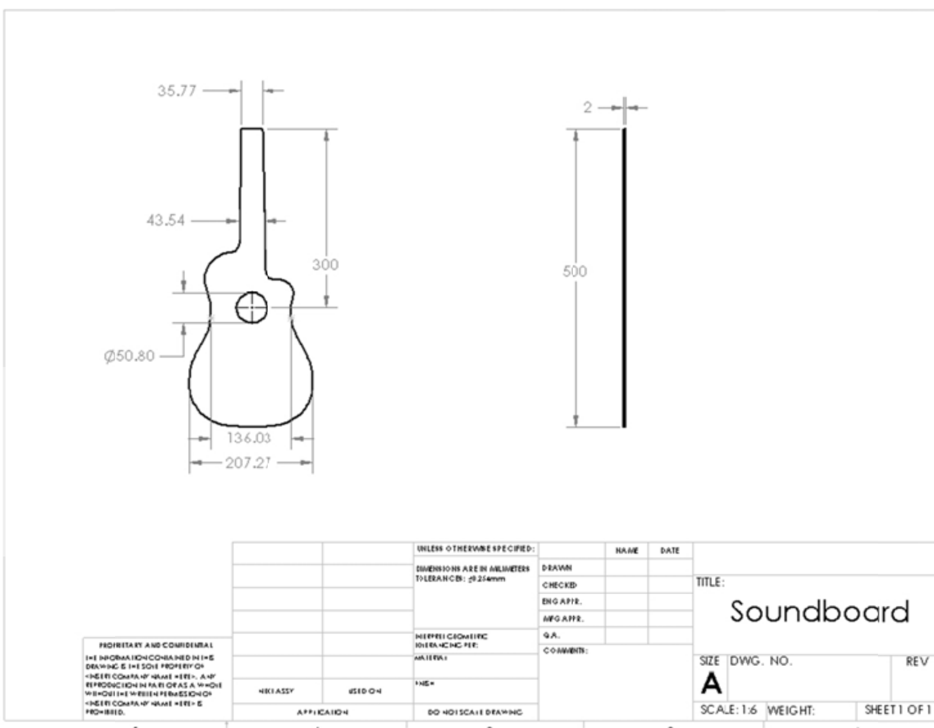



Figure 2 – Soundboard Drawing

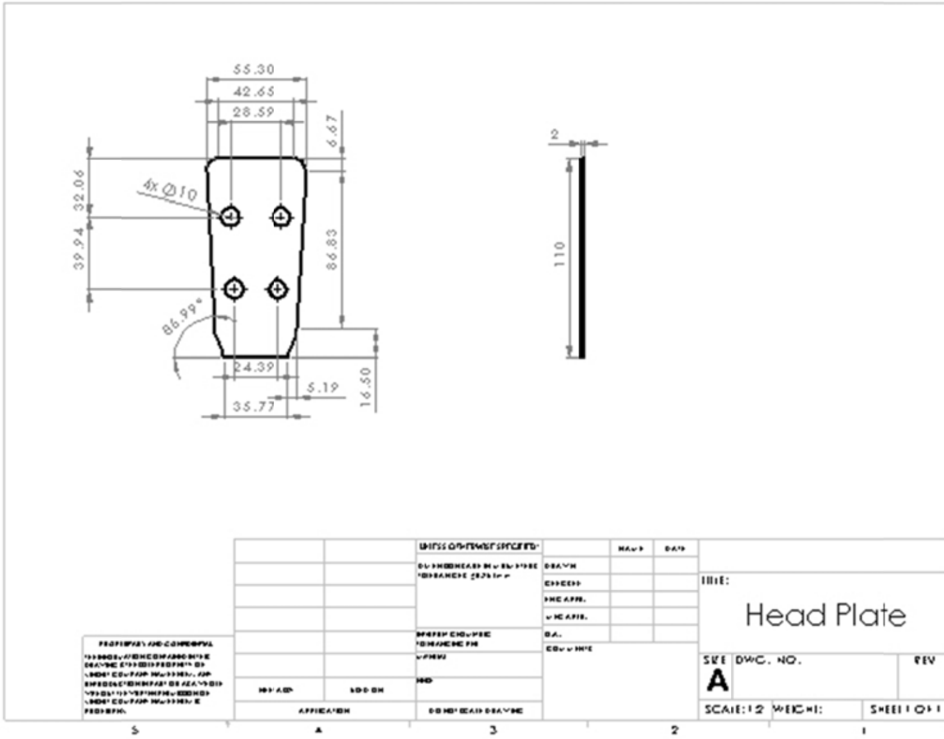



Figure 3 - Head Plate Drawing

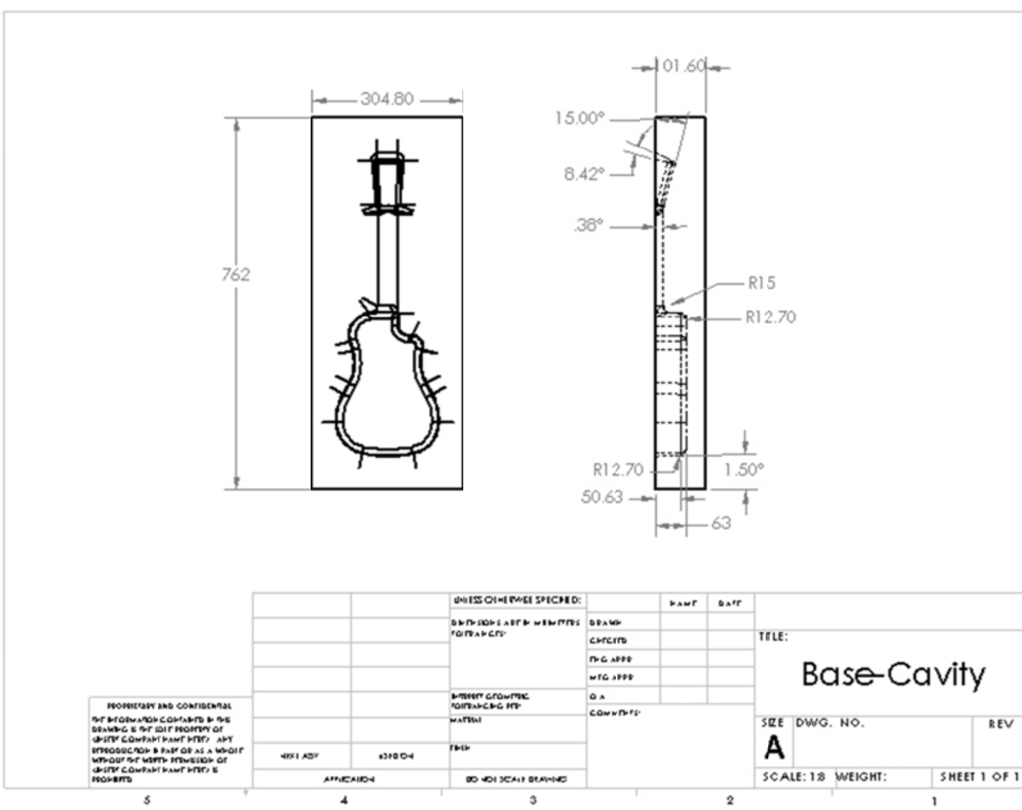



Figure 4 – Body Mold Drawing

# Appendix B – Ukulele Materials List

| | | | | | | |
|---|---|---|---|---|---|---|
| **Freeman** | | | | | | |
| **Item** | **Description** | **Part Num** | **Quantity** | **Price** | **Amount** | |
| RenShape 460 | 4" x 20" x 60" | 75222 | 1 | $908.60 | $908.60 | http://www.freemansupply.com/RenShape460MediumH.htm |
| Chemlease Mold Cleaner EZ | 1 gallon | 58194 | 1 | $44.50 | $44.50 | http://www.freemansupply.com/ChemleaseMoldClean.htm |
| Chemlease 2180 Primer | 1 quart | 58212 | 1 | $77.75 | $77.75 | http://www.freemansupply.com/ChemleaseMPP2180Mo.htm |
| Chemlease 15 Sealer | 1 quart | 58002 | 1 | $48.25 | $48.25 | http://www.freemansupply.com/Chemlease15SealerE.htm |
| Chemlease One FS Release Agent | 1 gallon | 58474 | 1 | $132.25 | $132.25 | http://www.freemansupply.com/ChemleaseOneFSEZSe.htm |
| | | | | *Subtotal* | *$1,211.35* | |
| **Fibre Glast** | | | | | | |
| **Item** | **Description** | **Part Num** | **Quantity** | **Price** | **Amount** | |
| Vinyl Ester Resin KIT | 1 Gallon w/ Hardener Kit | 1110-A | 1 | $84.95 | $84.95 | http://www.fibreglast.com/product/General_Purpose_Vinyl_Ester_Resin_just_resin_1110/Vinyl_Ester_Resins |
| DIVINYMAT | 32" x 48" Sandwich core, perforated | 1024-A | 3 | $29.95 | $89.85 | http://www.fibreglast.com/product/DIVINYMAT_01024_A/Vacuum_Bagging_Vacuum_Infusion |
| Strechlon 200 Bagging Film | 5 yd roll | 1678-C | 2 | $19.95 | $39.90 | http://www.fibreglast.com/product/581/h |
| Polyester peel ply | 60" wide, 3 yd roll | 583 | 1 | $29.95 | $29.95 | http://www.fibreglast.com/product/Polyester_Release_Peel_Ply_583/Vacuum_Bagging_Films_Peel_Ply_Tapes |
| Sealant tape | 25' roll, Yellow | 580-A | 4 | $7.95 | $31.80 | http://www.fibreglast.com/product/yellow-sealant-tape-00580/Vacuum_Bagging_Films_Peel_Ply_Tapes |
| | | | | *Subtotal* | *$276.45* | |
| **US Composites** | | | | | | |
| **Item** | **Description** | **Part Num** | **Quantity** | **Price** | **Amount** | |
| Carbon Fiber Twill | Twill, 50" Roll, 3K | FG-DCT57 | 8 | $25.50 | $204 | http://www.uscomposites.com/shortroll.html |
| Spreader | For wet layup, 25 pack | SQ-05PK | 1 | $10.00 | $10.00 | http://www.shopmaninc.com/brushes.html |
| | | | | *Subtotal* | *$214* | |
| **MacMaster-Carr** | | | | | | |
| **Item** | **Description** | **Part Num** | **Quantity** | **Price** | **Amount** | |
| PVC Tubing | 1/2" ID 11/16" OD | 5233K67 | 50 | $0.61 | $30.50 | http://www.mcmaster.com/#5233K67 |
| Single Barbed Tube Fitting Tee | 1/2" tube ID, nylon, packs of 10 | 2974K25 | 2 | $6.54 | $13.08 | http://www.mcmaster.com/#2974K251 |
| Vacuum Guage | Steel Case, 2"Dial, 1/4 bottom conn 30"Hg-0 | 4004K62 | 1 | $10.10 | $10.10 | http://www.mcmaster.com/#4004K62 |
| Threaded Pipe Fitting | 1/4" pipe NPT aluminum | 44705K3 | 1 | $5.86 | $5.86 | http://www.mcmaster.com/#44705K344 |
| Single Barbed Tub Fitting Adapter | 1/2" Tube to 1/4" NPT male pipe packs of 10 | 2974K12 | 1 | $5.79 | $5.79 | http://www.mcmaster.com/#2974K129 |
| Spiral Tubing | 1/2" OD, 100' spool | 7432K53 | 1 | $49.74 | $49.74 | http://www.mcmaster.com/#7432K53 |
| 3M Aerosol Adhesive | #77 24 Fluid oz | 7610A11 | 1 | $20.60 | $20.60 | http://www.mcmaster.com/#7610A11 |
| | | | | *Subtotal* | *$135.67* | |
| **Stewart-MacDonald** | | | | | | |
| **Item** | **Description** | **Part Num** | **Quantity** | **Price** | **Amount** | |
| Fret Wire | Narrow #147 | | 4 | $3.36 | $13.44 | http://www.stewmac.com/shop/Fretting_supplies/Stewart-MacDonald_Fretwire/Narrow_Fretwire.html |
| Bridge | Drilled | | 3 | $8.98 | $26.94 | http://www.stewmac.com/shop/Bridges,_tailpieces/Ukulele_bridges/Ukulele_Bridge_with_Saddle.html |
| Kerfed Lining | To bond to side of body with soundboard | | 15 | $1.97 | $29.55 | http://www.stewmac.com/shop/Bodies,_necks,_wood/Mandolin_kerfed_lining_strips/Kerfed_Lining_For_Mandolin.html |
| | | | | *Subtotal* | *$69.93* | |
| **GraphTech** | | | | | | |
| **Item** | **Description** | **Part Num** | **Quantity** | **Price** | **Amount** | |
| Nut | black | | 3 | $13.65 | $40.95 | http://graphtech.com/product-283-2/ |
| Saddle | black | | 3 | $13.65 | $40.95 | http://www.graphtech.com/product-202-2/ |
| | | | | *Subtotal* | *$81.90* | |
| **Musician's Friend** | | | | | | |
| **Item** | **Description** | **Part Num** | **Quantity** | **Price** | **Amount** | |
| Tuning Machines | Sperzel 3+3 Trim-Lok Tuning Machines Black | | 2 | $74.99 | $149.98 | http://www.musiciansfriend.com/accessories/sperzel-33-trim-lok-tuning-machines |
| | | | | *Subtotal* | *$149.98* | |
| **Grainger** | | | | | | |
| **Item** | **Description** | **Part Num** | **Quantity** | **Price** | **Amount** | |
| Epoxy Adhesive | 3M Scotch-Weld DP 420 (Black) | | 2 | $28.85 | $57.70 | http://www.grainger.com/Grainger/SCOTCHWELD-Epoxy-Adhesive-2RUC7?cm_sp=IO-_-IDP-_-RR_VTV70300505&cm_vc=IDPRRZ1 |
| | | | | *Subtotal* | *$57.70* | |
| **Other** | | | | | | |
| **Item** | **Description** | **Part Num** | **Quantity** | **Price** | **Amount** | **Vendor** |
| Misc Items | Gloves, Zip Ties, Bucket, Resin Line Holders | | - | $50.00 | $50 | Misc |
| Glass Surface | For Flat layup | | 1 | $15.00 | $15 | Goodwill |
| Barbed Male:Male Tube Fitting | 1/2" ID for resin trap | | 3 | $2.00 | $2.00 | Home Depot |
| Spring Clamps | | | 4 | $5.00 | $5.00 | Home Depot |
| Bird Netting | 1cm netting for use as flow media | | 1 | $15.00 | $15.00 | Home Depot |
| Nalgene Water Bottle | Resin trap | | 1 | $15.00 | $15.00 | Target |
| | | | | *Subtotal* | *$102* | |
| | | | | ***Total*** | ***$2,298.98*** | |

# Appendix C – Manufacturing Processes

## Ukulele Body

### Materials Needed

1. 1.5’x1.5’ carbon fiber sheets for body(4x)
2. 1.5’x1’ carbon fiber sheets for neck and headstock(4x)
3. Super 77
4. Flow media (6x)
5. 2' length spiral tubing
6. 5’ length spiral tubing
7. Peel ply
   a. 1 sheet slightly larger than CF
   b. 2'x3" and 5’x3” to cover spiral tubing
8. 3' lengths Tubing (3x)
9. T-fittings (2x)
10. 4’x3’ bagging film
11. Sealant tape
12. 500mL resin

- **Mold Prep**

1. If first time:
   a. Clean mold with Chemlease mold cleaner (2-3 coats)
      i. Wipe on with one cloth
      ii. Wipe off while still wet
   b. Prime mold with Chemlease primer (2 coats)
      i. Wipe on-leave on. Coat enough to shine but not run
      ii. 30 minutes between each coat
      iii. 1-2 hour cure time after last coat
   c. Seal mold with Chemlease 15 sealer
      i. Wipe on film with cloth
      ii. Wipe off with another cloth when film starts to evaporate
      iii. Let cure for 1 hour
   d. Apply mold release
      i. Wipe on light film (should shine but not run on vertical mold surface) with cloth
      ii. When no longer filming, apply more mold release to cloth

iii Let dry for 15 minutes between coats
iv Apply 5-7 coats. Cure for 30 minutes after last coat
1 Masking Tape Test
a Cracking and popping when clean
b Comes off nice when sealed
c Should barely stick when released
2 Reapply 1-2 coats mold release when needed if mold release seems to not work.

- **Prepare layup**
  1. Lay one sheet of carbon fiber into body of mold. Make sure it reaches all corners and curves of mold. Cut slits into carbon fiber to conform around curves as necessary.
  2. Lay one sheet of carbon fiber into neck of mold. This sheet should partially cover the sheet of carbon fiber in the body. Again, cut slits into carbon fiber as necessary.
  3. Do 3 more layers of this. Cut off excess carbon fiber sticking out of mold and push down a small width of carbon fiber around the mold surface.
  4. Completely cover carbon fiber with peel ply. Peel ply should conform to curves as carbon fiber does and should extend beyond carbon fiber on mold surface.
  5. Place flow media over peel ply. Should all carbon fiber and peel ply inside the mold. Lightly secure this all with tape so that flow media and everything below it is stable and won’t move around.

- **Prepare vacuum**
  1. Wrap spiral tubing in peel ply so that it doesn’t stick to mold and so vacuum bag is not sucked into tubing.
  2. Place 2’ length spiral tubing along the length of the mold. T fitting should be in center of the body for resin supply.
  3. Place 5’ length of spiral tubing around ukulele on the surface of the mold. Should be one continous piece of spiral tubing. Both ends should terminate at the t-fitting, which is placed above headstock for resin-out line.
  4. Place sealant tape along edges of bagging film. Place each corner of bagging film at each corner of the mold surface and secure film to mold. Each side should have a large “doggy tail”. This ensures that bagging film will actually conform to contours of mold.
  5. Wrap sealant tape around one end of tubing. Cut a small hole in the bagging film above the t-fitting in the center of the body and attach the end of the tubing with sealant tape to this t fitting over the hold.. Mold sealant tape so that it forms a good seal with the bagging film. This is the resin-supply line
  6. Perform this operation with the other t-fitting for the resin-out line. Attach the other end of the resin-out line to the resin trap. The other line on the resin trap should be attached to the vacuum pump.

- **Vacuum Infusion Process**

  1. Seal the resin-in line with a clamp and slowly pull a vacuum. Help push bagging film into mold and ensure all sides of the mold have contact with carbon fiber. Then pull total vacuum to ensure there aren't leaks.
  2. Place breathing masks on and prepare resin in resin supply bucket.
  3. Ensuring air will not be pulled, place resin line in bucket and remove clamp to allow resin flow.
  4. Continue until all material has been wet. Do not turn off vacuum.
  5. Clamp off resin supply line, be careful not to apply too much force to line so that a leak is formed at bagging film.
  6. Continue to apply a vacuum until resin has sufficiently gelled (~6 hrs)
  7. Let resin cure until hard (another 6 hours)

- **Removal, cleanup, and post-processing**

  1. Carefully remove body from mold
  2. Remove dried resin from supply bucket and trap.
  3. Wearing masks, cut off excess carbon fiber with a band saw. Get as close to correct dimensions as possible.
  4. Sand and machine top surface of body so that it is flat and level. Do the same with the headstock (at a 15º angle to body) so that head plate can be correctly attached later.
  5. Cut holes in headstock for tuning machines. Each tuning machine needs one locating hole and one hole for the actual tuning peg.

# Ukulele Soundboard and Head Plate

## Materials Needed

1. 2'x1' carbon fiber sheets (4x)
2. Super 77
3. 2'x1' infusion mesh (6x)
4. 2' lengths spiral tubing (3x)
5. Peel ply
    a. 1 sheet slightly larger than CF
    b. 2'x3" to cover spiral tubing (3x)
6. 3' lengths Tubing (2x)
7. T-fittings (2x)
8. 22"x32" bagging film
9. 250mL resin

- **Prepare Tool**
    1. If first time
        a. Clean mirror/surface
        b. apply light coat of mold release (should shine but not run). When film is no longer forming, add more mold release to cloth.
        c. let dry 15 minutes. Apply 5 total coats (possibly up to 7)
            i. Masking Tape Test
                1. Cracking popping it is clean
                2. come off nice when sealer
                3. Release agent shouldn't release too easily
        d. After last coat, let sit 30 minutes
    2. Carefully lay sheets of carbon fiber onto tool, applying a light amount of super 77 between each sheet.
    3. Cover carbon fiber with peel ply. Cover this with the layers of infusion mesh. Lightly secure everything with tape so it won't move.
- **Prepare Vacuum**
    1. Wrap spiral tubing in peel ply.
    2. Place spiral tubing lengthwise along opposite edges of carbon fiber sheets.
    3. Insert t-fittings at midpoints of tubing.
    4. Place sealant tape around edges of carbon fiber and peel ply.
    5. Place bagging film over carbon fiber and secure along sealant tape.
    6. Pierce small hole through bagging film and attach line (2-3' for all) from resin supply to the resin-in line of the setup. When attaching line to t-fitting, wrap end of tubing in sealant tape and mold the sealant tape into the bagging film. At resin supply, make sure line is secured to side of bucket and will not accidentally pull in air.

7. Repeat the above for the resin-out line, except attach the other end to the resin trap. Last tubing line connects resin trap to vacuum.

- **Vacuum Infusion Process**

1. Seal resin-in side with clamp, pull vacuum to ensure good seal.
2. Place breathing masks on and prepare resin in resin supply bucket.
3. Ensuring air will not be pulled, place resin line in bucket and remove clamp to allow resin flow.
4. Continue until all material has been wet. Do not turn off vacuum.
5. Clamp off resin supply line, be careful not to apply too much force to line so that a leak is formed at the bagging film.
6. Continue to apply a vacuum until resin has sufficiently gelled (6hrs)
7. Let resin cure until hard (another 6 hrs)

- **Removal, cleanup, post processing**

1. Carefully remove laminated carbon fiber piece from surface
2. Cut to size with waterjet based on DXF file
3. Remove dried resin from supply bucket and trap

# Fret Board Layup

## Materials Needed

1. 1’x6” carbon fiber sheets (16x)
2. 1’x6” infusion mesh (6x)
3. 14”x8” Peel ply (1x)
4. 3’ Tubing (2x)
5. 18”x12” bagging film (for vacuum)
6. 3’x2’ bagging film (for wet layup)
7. 250mL Resin + hardener

- **Prepare Tool**

  1. If first time
     a. Clean mirror/surface
     b. apply light coat of mold release (should shine but not run). When film is no longer forming, add more mold release to cloth.
     c. let dry 15 minutes. Apply 5 total coats (possibly up to 7)
     d. After last coat, let sit 30 minutes
        i. Masking Tape Test
           1. Cracking popping it is clean
           2. Come off nice when sealed
           3. Barely stick after mold release
  2. Lay sealant tape onto surface around where carbon fiber will be. Leave about 1.5” between carbon fiber and tape.
  3. Cut a hole in the center of the bagging film. Wrap near the end of a length of tubing with sealant tape. Push tubing through the hole and place sealant tape around end of tubing on the other side of the bagging film. Make sure this connection is secure.

- **Wet Layup**

  1. Place 1st layer of carbon fiber onto larger piece of bagging film.
  2. Place breathing masks on and mix resin
  3. Place small amount of resin onto carbon fiber. Saturate carbon fiber and remove excess resin from piece using spreader.
  4. Carefully lay next piece of carbon fiber on top of this sheet using a roller to ensure there are no air bubbles. Make sure carbon fiber sheets are properly aligned when laying sheets down.
  5. Repeat this process until last sheet of carbon fiber has been placed and had resin applied to it. Keep an eye on the clock if you’re using a resin with a short gel time

- **Vacuum Bagging**

1. Apply a small amount of resin to tool surface where carbon fiber will be placed.
2. Remove carbon fiber from bagging sheet and place onto tool.
3. Cover carbon fiber in peel ply and flow media.
4. Place bagging film onto this and secure along sealant tape
5. Secure the other end of tubing that is through the bagging film to the resin trap. Other line connects resin trap to vacuum.
6. Pull a vacuum and keep vacuum pump running for 6hrs
7. Turn off vacuum and let part sit for another 6 hrs

- **Removal, Cleanup, Post-processing**

1. Carefully remove materials covering carbon fiber
2. Remove carbon fiber piece from tool surface
3. Remove and dispose of excess resin from resin trap.
4. Cut 3 fretboards out of carbon fiber piece using water jet
5. Machine fret slots into fretboards to .065” depth using a .025” diameter, .075” depth, 2 flute HSS cylindrical end mill.
6. Wearing breathing masks and protective gloves, break edges of fretboards using 400-grit sandpaper. Smooth the edges with high grit sandpapers (1000, etc)
7. Insert frets into fretboard slots with mallet.

# Final Assembly of Uke

## Materials Needed

1. Carbon fiber body, soundboard, head plate, and fretboard
2. Kerfed Lining
3. 3M DP420 epoxy
4. Bridge, saddle, nut
5. 4 Tuning machines
6. Strings

## Assembly Process

1. Line edges of body cavity (but not the neck or headstock) with kerfing. Attach to body using DP420 and allow toset with light clamping.
2. While this is setting, attach fretboard to the soundboard using DP420. Also place bridge onto soundboard using DP 420. Lightly clamp these and let them set. Also
3. After both of these processes are complete, place DP420 along edges of soundboard underside and place onto body. Make sure DP420 will make contact with kerfing and all edges of the neck. Apply light clamping to this and let it set.
4. Apply DP420 to edges of the head plate and place onto headstock. Apply light clamping and let it set.
5. Insert saddle and nut. Attach tuning machines to headstock.
6. String the ukulele and tune.

# Appendix D – Links to Videos and References

Waterjet cutting & mold 3D surface machining video:
http://www.youtube.com/watch?v=t_1fXsB5ZIU

Ukulele body vacuum infusion process video:
http://www.youtube.com/watch?v=nYlSO7yu18c

Fibre-Glast Vacuum Infusion Document:
http://cdn.fibreglast.com/downloads/vacuuminfusion.pdf

# Appendix E – Project Proposal

**ME 43: Senior Design Project**
FALL 2012

# Design and Manufacture of Carbon Fiber Ukulele

## Proposal

Alex Chan
Emmanuel Runes
Chris Smith

Advisor: Chris Rogers

Submitted to: Gary Leisk, Paul Lehrman
September 28th, 2012

# Statement of Need

The consistent and accurate manufacture of musical instruments is an interesting problem, particularly when dealing with wooden instruments. Working with wood is often inconsistent and the quality of each finished product is difficult to ensure. By substituting appropriate composites for wood, it should be possible to streamline this process, reduce the margin for error, and hopefully make improvements to the acoustic quality of the instrument by reducing the amount of bracing and other extraneous parts of the instrument that serve to improve the strength of the finished product. As composites are much more durable and can withstand more environmental abuse, a well-designed carbon fiber instrument will not only be more durable in cases such as dropping the instrument, but it will also be impervious to effects of humidity (the instrument should survive complete water immersion).

Several problems arise when building ukuleles out of carbon fiber. The quality of the instrument body will be highly dependent on the mold, so the design and construction of the mold will be very important. Several ukuleles also have an arched back to make the tone deeper and fuller. Building a mold that features this arch will be more difficult than building a mold with a flat back, so the available manufacturing capabilities will need to be assessed before a decision can be made on that design aspect. The best way to minimize the amount of bracing on the top will also have to be determined. It is likely that carbon fiber will be strong enough to not require bracing the same way wood does, but there is still the possibility that the top will have to be strengthened in some way to ensure that warping will not occur due to the tension from the strings. This could be done with alternative forms of bracing or by arching the top. Arching the top would require another mold and this would have to be taken into account when planning for the construction phase. Below is a list of design specifications determined for this project based on preliminary research.

Design Specifications:

- Dimensions: Concert-size ukulele
    - Scale Length: ~38 cm
    - Overall Length: ~58 cm
    - Soundhole Diameter: 5 cm
    - Geared Tuning Pegs

- Carbon-fiber/fiberglass constructed components
    - Body
    - Neck
    - Soundboard
    - Fretboard (optional. Wood or Plastic may be used)

- Hardware
    - Bridge: machined, rapid prototyped, or off-the-shelf
    - Nut: off-the-shelf
    - 19 frets: off-the-shelf
    - Tuning pegs (geared): off-the-shelf

# Strategy

The strategy we propose involves substituting carbon fiber for conventional wood. Carbon fiber is a useful composite but using it presents a few challenges in a number of areas. The team will need to be aware of the limits imposed by the molding process on how the ukulele can be designed. While conventional ukulele bodies are created with sharp edges from separate pieces of wood meeting at right angles, the entire back side as well as the neck of the ukulele will be one contiguous piece of carbon fiber, which will not fit into such sharp features. The heel of the ukulele will need to be redesigned and the sharp angles between the neck and body will need to be removed. Simply filleting those edges will not allow access to frets located higher up the neck. A cut-out may be the best solution because it allows for the smooth transitions needed to actually manufacture the instrument without negatively affecting playing at the higher frets.

Additionally, the soundboard design will be different from traditional wooden ones as conventional bracing substantially damps the vibration (and in effect the loudness) of the soundboard. Bracing is used in acoustic instruments to prevent the soundboard from warping from the string tensions it is required to withstand. The use of composites allows for the possibility of integrating any necessary reinforcements within the actual soundboard piece, through the use of composite core materials sandwiched by the carbon fiber. This will keep the weight down while providing necessary stiffness; less weight on the soundboard will result in a louder sound produced by the ukulele.

# Schedule

The Gantt chart below (Fig 1) displays an initial schedule for this project. The chart is divided into several project phases, which are then subdivided into specific tasks. Several important dates are presented in the chart to mark the expected completion of the different stages. The first major stage will be designing the ukulele using CAD software. This stage will include both designing the various components of the instrument such as the body, neck and soundboard, as well as an extensive FEA analysis of the soundboard. This stage will overlap with the subsequent parallel stages of constructing a simple physical prototype and designing the mold using CAD software. A physical prototype is expected to be completed by October 15th, and the design will be revised based on an assessment of the aesthetic features.

The next two stages will be to decide on and acquire all necessary materials, and to finalize logistics of, and methodologies used in the construction stage. Construction is projected to begin on October 22nd, and will extend over the following 7 weeks, with the last two weeks scheduled to be a troubleshooting phase. The dates for the final presentation and final submission of the deliverables have not yet been finalized; however, the project is expected to be complete by December 10th.

The Gantt chart also highlights a few key dates of when the three presentations are scheduled, in addition to when important documents such as the progress report will be due (October 15th). The first presentation is expected to include early CAD designs, a preliminary budget and a bill of materials. The second presentation will feature a simple physical prototype in addition to a CAD drawing of the mold. The third presentation will include the final design, a preliminary construction progress report, as well as at least one manufactured soundboard. The final presentation is expected to feature at least one complete, functioning carbon-fiber ukulele.

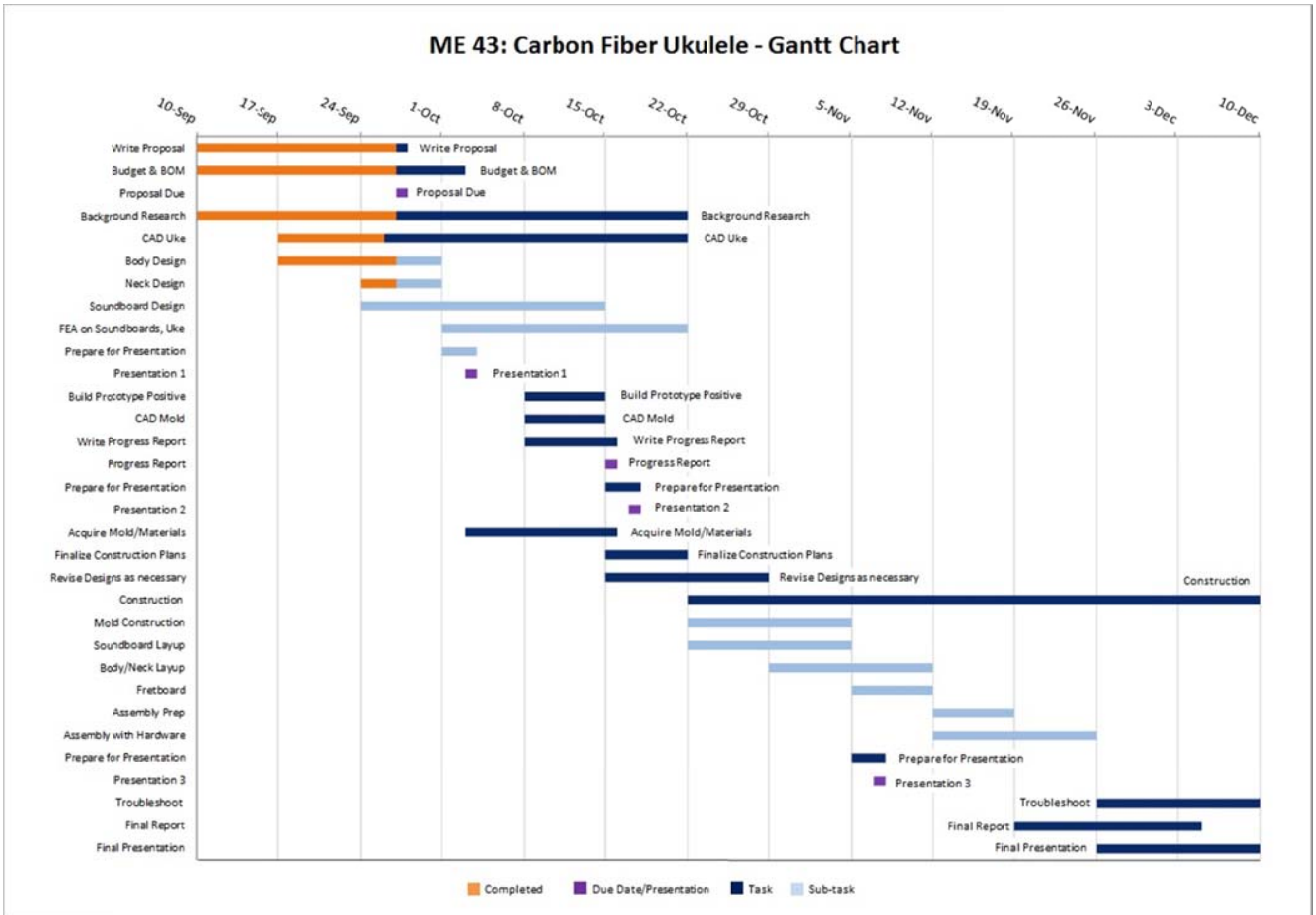
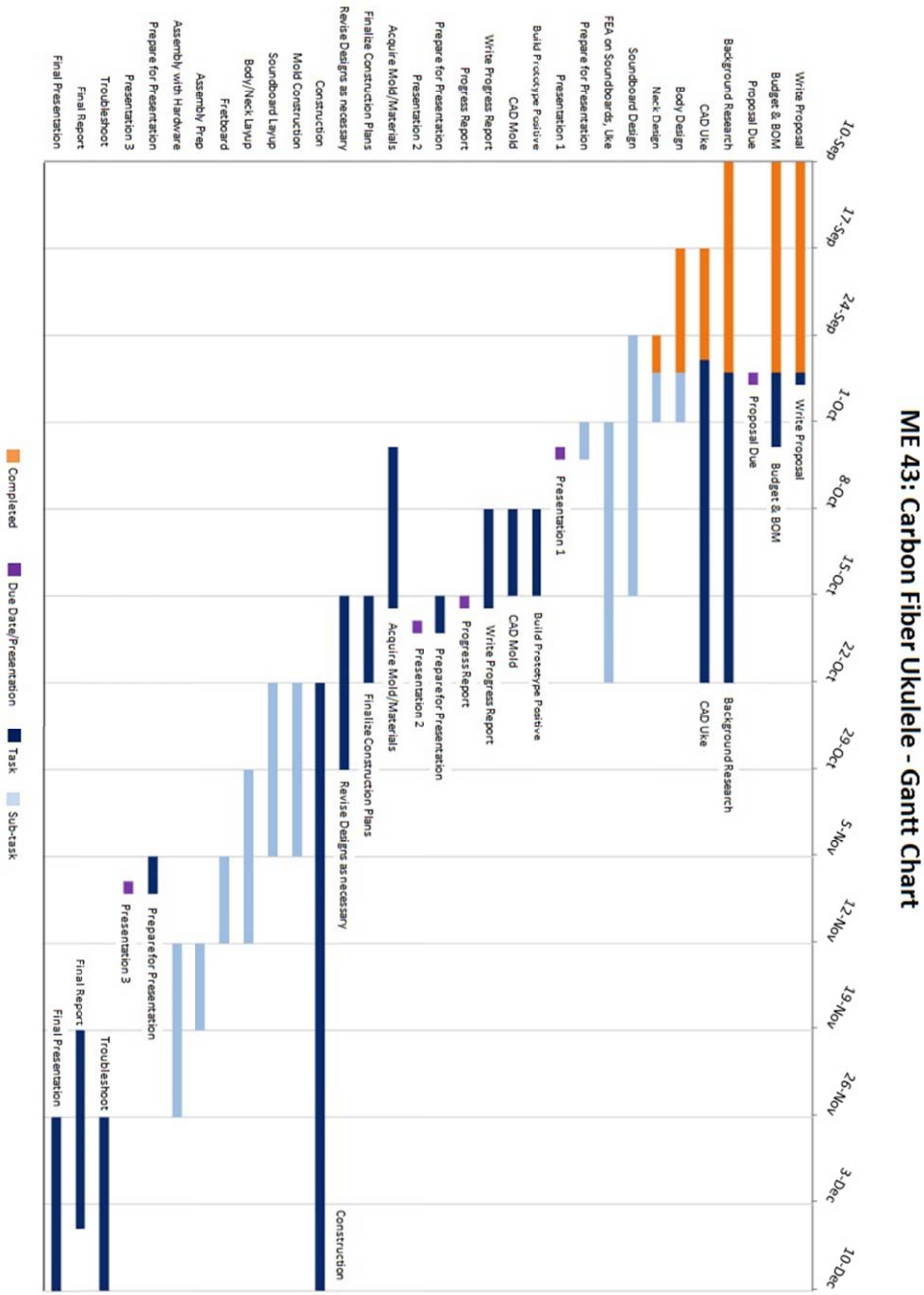



**Fig 1 - Gantt Chart for Project – A full size chart is also attached.**

# Responsibilities

Many of the tasks involved in this project will be completed through an ongoing collaborative process; however, there are a few specific responsibilities that have been assigned to particular members of the team. In this way, efficiency will maximized through division of labor and specialization. Alex Chan will be responsible for the budget, and resource and material procurement and logistics. Alex will also focus on the mold construction stage. Chris will be responsible for the design and analysis of the soundboard. Project scheduling will be handled by Emmanuel. Research, CAD work, and construction and assembly responsibilities will be shared between the team members through the use of cloud-based folders.


ME 43: Carbon Fiber Ukulele - Gantt Chart
10-Sep
17-Sep
24-Sep
1-Oct
8-Oct
15-Oct
22-Oct
29-Oct
5-Nov
12-Nov
19-Nov
26-Nov
3-Dec
10-Dec
Write Proposal
Budget & BOM
Proposal Due
Background Research
CAD Uke
Body Design
Neck Design
Soundboard Design
FEA on Soundboards, Uke
Prepare for Presentation
Presentation 1
Build Prototype Positive
CAD Mold
Write Progress Report
Progress Report
Prepare for Presentation
Presentation 2
Acquire Mold/Materials
Finalize Construction Plans
Revise Designs as necessary
Construction
Mold Construction
Soundboard Layup
Body/Neck Layup
Fretboard
Assembly Prep
Assembly with Hardware
Prepare for Presentation
Presentation 3
Troubleshoot
Final Report
Final Presentation
Completed
Due Date/Presentation
Task
Sub-task

# Appendix F – Progress Report

**ME 43: Senior Design Project**
FALL 2012

# Design and Manufacture of Carbon Fiber Ukulele
# Progress Report

Alex Chan
Emmanuel Runes
Chris Smith

Advisor: Chris Rogers

Submitted to: Gary Leisk, Paul Lehrman
October 28th, 2012

## Project Statement and Design Needs

String instruments such as the guitar and ukulele are traditionally made of wood, however, the use of wood presents a few challenges, such as the large amount of bracing required to strengthen the instrument, and wood's susceptibility to the detrimental effects of humidity and moisture. Because of such issues, there is a growing interest in designing and manufacturing instruments made of composites such as carbon fiber.

The goal of this project is to design and assemble a ukulele using carbon fiber. The concert ukulele's small size and relatively simple geometry made it a very feasible instrument choice given both the project's time and budget constraints, and the team's access to facilities with sufficient manufacturing capabilities.

The design goals of this project are listed below:

- Achieve comparable aesthetic and acoustic quality relative to a traditional wooden ukulele
- Utilize less bracing material than traditional wooden ukuleles
- Achieve a final overall weight lower than that of traditional wooden ukuleles
- Achieve increased resistance to moisture through appropriate choice of composites
- Incorporate industry-standard materials, composites, and processes

## Ukulele Specifications

The carbon fiber ukulele is designed to be concert-sized, which is a size class for the instrument family. Most of the major dimensions such as overall length, scale length and soundhole diameter, were adapted from dimensions of traditional wooden ukuleles, and altered to fit desired design features. Some dimensions, such as minimum radius and minimum draft angle, were determined based on manufacturing and assembly constraints. Important dimensions can be found below in Table 1, and Figure 1 shows additional detailed specifications. Details on materials and construction methods can be found in Table 2.  A schematic that illustrates the ukulele's different components can be found in Figure x in the Appendix.

| | |
|---|---|
| Overall Length | 58.0 cm |
| Scale Length | 38.0 cm |
| Body Width (at top) | 21.7 cm |
| Body Depth | 7.2 cm |
| Soundhole Diameter | 5.0 cm |
| Neck Width (at head) | 3.5 cm |
| Minimum Radius | 6.35 mm |
| Headstock Angle | 15° |
| Minimum Draft Angle | 1° |
| Number of Frets | 19 |

**Table 1 – Ukulele Dimensions and Specifications**

| Part | Material | Method of Construction/Source |
|---|---|---|
| Body, Neck and Headstock | Carbon Fiber | Layup on custom mold/tool, Vacuum Infusion Process (VIP) |
| Soundboard | Carbon Fiber | Layup on Flat Tool, VIP |
| Fretboard | Carbon Fiber | Layup on Flat Tool |
| Mold/Tool | RenShape (Foam) | CNC Machined, Epoxy Finish |
| Fretwire | 18% Nickel Silver | Off-the-shelf |
| Bridge | Wood/Plastic | Off-the-shelf |
| Saddle and Nut | Bone | Off-the-shelf |
| Tuning Pegs | Stainless Steel | Off-the-shelf |

**Table 2 – Materials and Construction Specifications**

## Design Considerations

There were a number of design features and manufacturing options that were considered for the ukulele. In the initial design phase, one of the preliminary design options that were considered was the use and type of soundboard bracing. Most ukuleles have bracing on the soundboard to prevent warping from the tension in the strings. Since carbon fiber is a much stronger material than wood, the design would ideally not need any bracing as it dampens the vibrations of the soundboard and adds weight to the instrument. Various types of bracing methods are used in wooden ukuleles, and the most common type is a radial bracing. An FEA analysis was performed on both braced and unbraced soundboards to evaluate the effect of bracing on the stress and displacement of the soundboard.

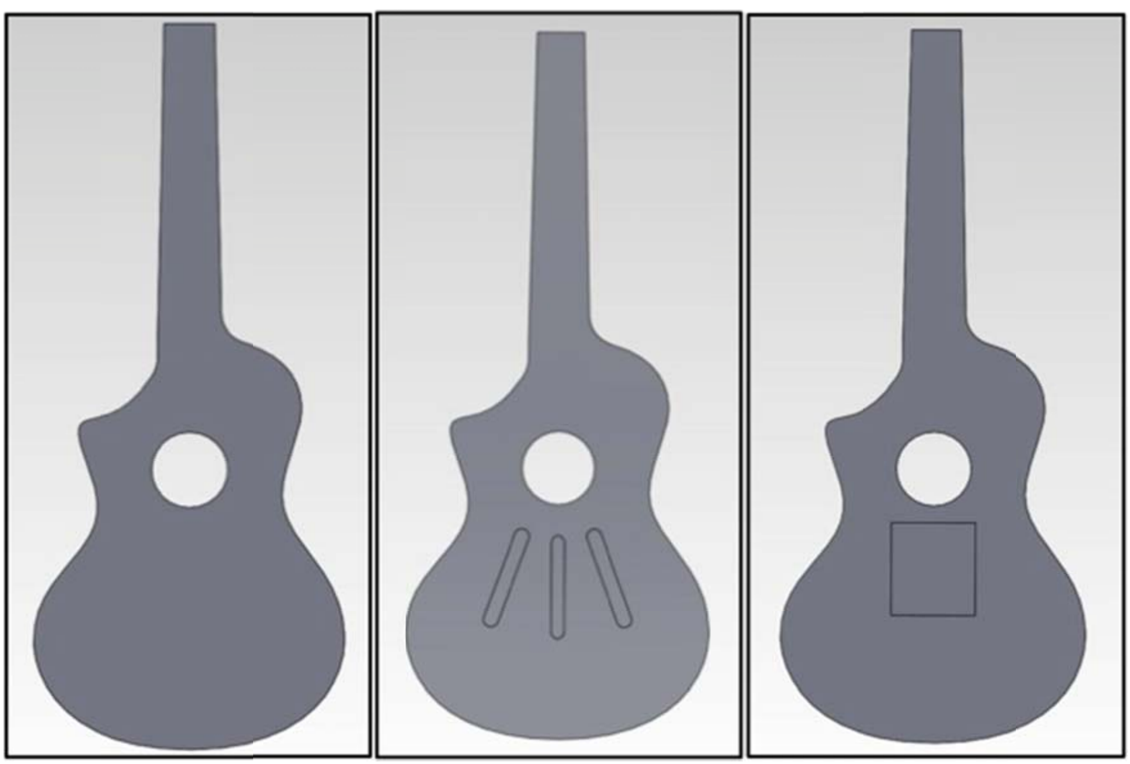


**Figure 2 – Types of Bracing (None, Radial, Square, respectively)**

Several high-end ukuleles also have a curved back or arched top. The curved back makes it slightly more comfortable for playing and also helps mellow the tone of the instrument while an arched top helps alleviate the need for bracing.

The constraints of the layup process for the ukulele also introduced a design feature conflict. Most traditional wooden ukuleles have a well-rounded corner where the neck of the ukulele meets the body, however, this design feature impedes the user from playing notes located higher up on the fretboard. The best option to combat this is to add a cutout to the design (see Figure 2), however, this feature may also lengthen and complicate the layup process, as it is difficult to lay carbon fiber around sharp corners. This requirement for rounded edges had to be taken into account for all the ukulele's features.

There are also a few different methods that were considered for the construction of carbon fiber. The first involves spreading resin between individual layers of carbon fiber as they are placed. After the last layer is applied, some padding is added and the mold is sealed in a vacuum bag. This setup is then allowed to cure at room temperature. The second method, a vacuum infusion process, (VIP) involves laying the carbon fiber sheets in the mold without any resin. The mold is then vacuum bagged, but with a tube coming into the center of the mold through the vacuum bag. This tube connects to a supply of resin. Running around the mold is a channel where the vacuum bag is attached. There is another tube connected to this channel that runs to a resin trap and then to the vacuum pump. In this method, the epoxy is sucked into the mold and through the carbon fiber, spreading from the middle of the mold outwards. After everything has been wet by the resin, the setup is disconnected and the mold is cured at room temperature.

## Final Concept

For this project, a radially braced soundboard was chosen for the final design. The design will also incorporate a flat back and soundboard. The test layup will feature a cutout, however, it is possible that the cutout's geometry will have a negative impact on the quality of the molded part, and so a final decision on whether or not to include a cutout will be made after the test layup has been completed. The construction will be done with a vacuum infusion process and conventional vacuum bagging.

## Justification

The decision to have a flat soundboard instead of an arched one was made due to constraints on time and budget. An arched top would require the design and construction of another mold while a flat top can be constructed on a flat surface. In addition, it was decided to have a flat back because of the large increase in time, and subsequently cost, to manufacture the mold for the body if the back were arched.

The decision to use radial bracing on the soundboard was largely based off of the FEA analysis shown in the appendix. The analysis compared a soundboard with no bracing, with radial bracing, and with square bracing. Both types of bracing decreased deflection in the soundboard by close to 35% and decreased stress in the soundboard by around 50%. Radial bracing was then chosen over square bracing because it produced a marginally higher decrease in deflection, and because it uses less material. Using less material both reduces the cost to produce the soundboard and causes less vibrational damping, which improves the acoustic quality of the instrument. Although adding bracing requires more construction time, hence decreasing manufacturability, it was decided that the increase in performance was substantial enough to merit the use of bracing.

It was also decided that if layup is possible, a design that featured a cutout, which would facilitate access to notes further up the neck, was desirable. However, a final decision on this will not be made until a test layup has been completed and the feasibility of the feature is confirmed.

Table 3 below shows a decision matrix of the different design features and manufacturing options for the ukulele. Scores were based on six weighted categories as shown below; however, because of the specific nature of each of the design options, not all of the criteria apply to each of the design options. The decision to use a flat back over a curved back is clearly indicated by the score differential in the matrix, with initial cost as a significant factor. Similarly, the use of conventional vacuum bagging is shown to be the more feasible option compared to using a custom vacuum bag, with cost again playing a major role. The scores for the bracing decision are relatively close, and the ultimate decision was based on the FEA analysis shown in the appendix. The matrix scores for the cutout option were also relatively close, and as mentioned above, a final decision on this will not be made until a test layup has been completed and the feasibility of the feature is confirmed.

| | **Weight Factor** | Curved Back | Flat Back | Custom Vacuum Bagging | Conventional Vacuum Bagging | Bracing | No Bracing | Cutout | No Cutout |
|---|---|---|---|---|---|---|---|---|---|
| Instrument Aesthetics | **.1** | 1 | -1 | 0 | 0 | 0 | 0 | 1 | 0 |
| Instrument Performance | **.2** | 0 | 0 | 0 | 0 | 1 | -1 | 1 | 0 |
| Development Time | **.1** | -1 | 1 | -1 | 0 | -1 | 0 | -1 | 1 |
| Manufacturability | **.2** | -1 | 1 | 1 | 0 | -1 | 1 | -1 | 1 |
| Initial Cost | **.3** | -2 | 1 | -2 | 1 | 0 | 0 | 0 | 0 |
| Running Cost | **.1** | 0 | 0 | 1 | -1 | 1 | 1 | 0 | 0 |
| **Total** | **1** | **-0.8** | **0.5** | **-0.4** | **0.2** | **-0.2** | **0.1** | **0** | **0.3** |

**Table 3 – Design Option Decision Matrix**

## APPENDIX

### I. Ukulele Schematic


**Figure 3 – Ukulele Components**

### II. Soundboard FEA Analysis

**Figure 3 – Soundboard**

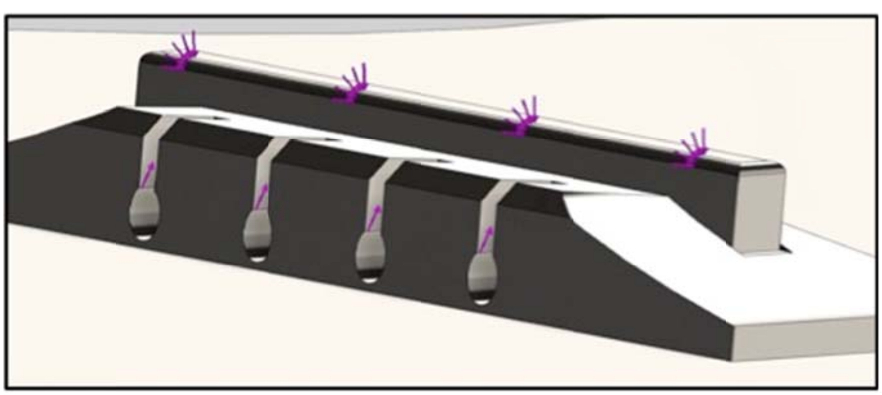


**Figure 3 – Force Vectors on Bridge**

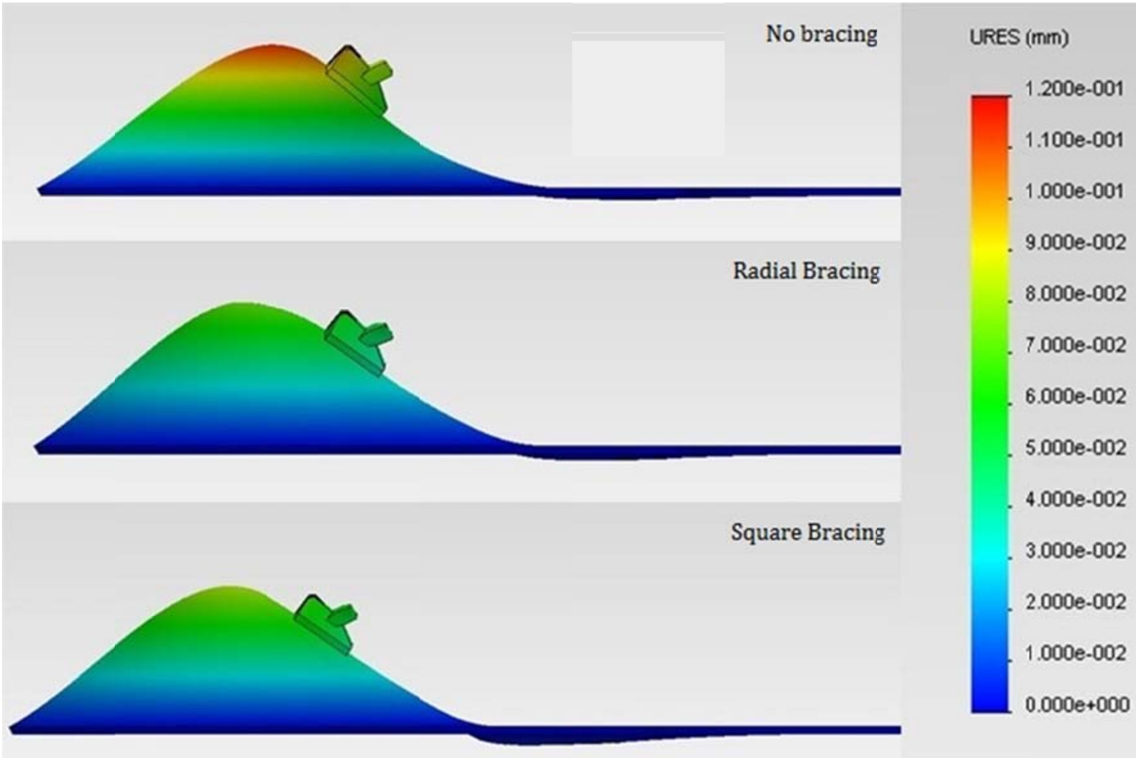



**Figure 3 – FEA Displacement Analysis**

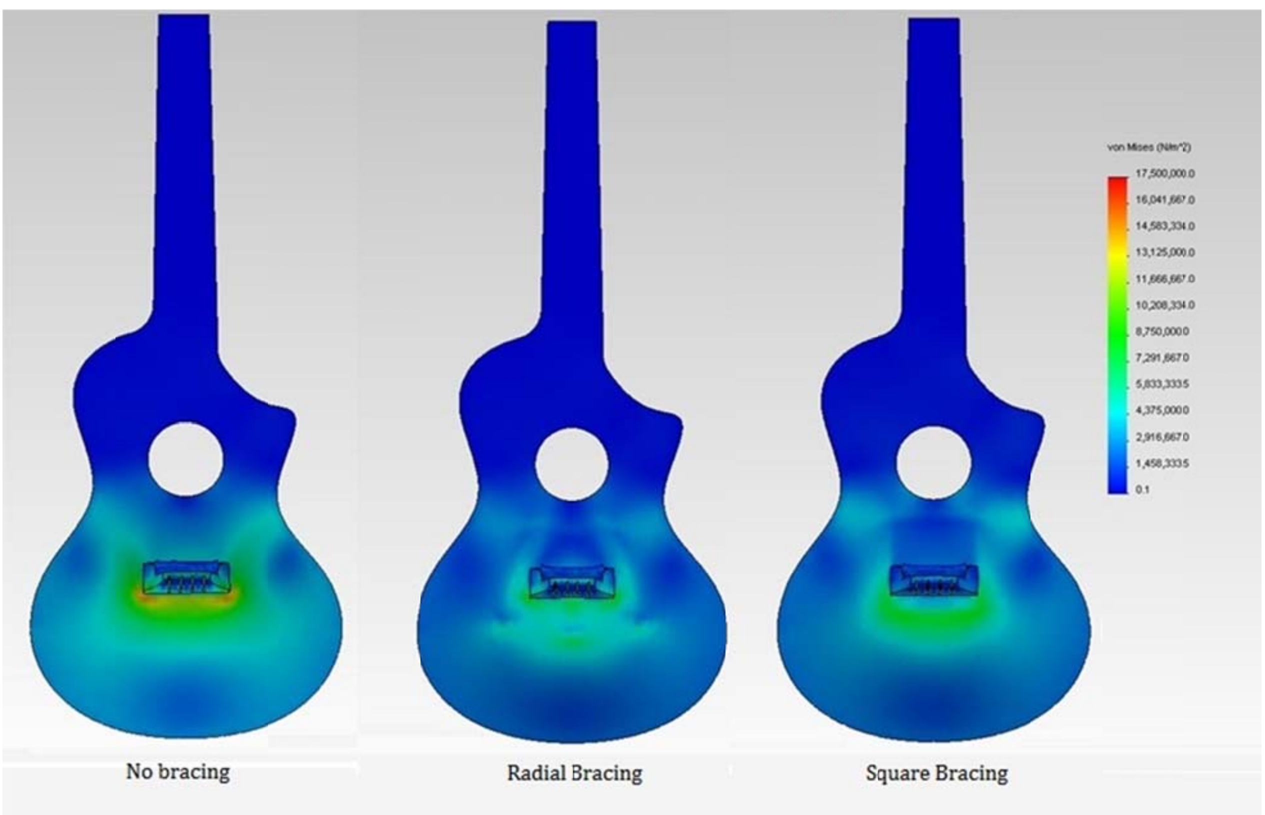



**Figure 3- FEA Stress Analysis**