Carbon Fiber Electric Guitar

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2006

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Abstract

Hardwood materials such as alder, ash, or maple might not be the best building materials for electric guitar bodies. This project investigates the use of carbon-fiber/epoxy composite materials as a suitable substitute to hardwoods. A hollow, carbon-fiber/epoxy electric guitar was designed and constructed, and an experiment was run to determine its natural frequencies and mode shapes. This data was then compared to modal data taken from a Fender Stratocaster, a commercially available, solid hardwood guitar. It was observed that the carbon-fiber guitar exhibited much higher natural frequencies and had significantly more stiffness than the hardwood guitar. Sound properties were comparable, if not an improvement, over the hardwood guitar as well.

Chapter 1: Introduction

Background and Theory

History of the Electric Guitar

The invention of the electric guitar is credited to Adolph Rickenbacker in the early 1930's. The first models were essentially the standard hollow, archtop, acoustic guitars to which electromagnetic transducers had been attached. In 1934, Rickenbacker and his business associates, George Beauchamp and Paul Barth, founded the Electro String Instrument Corporation and for 5 years they would go on to produce over 2,700 of their "Frying Pan" or "Pancake" lap steel electric guitars.

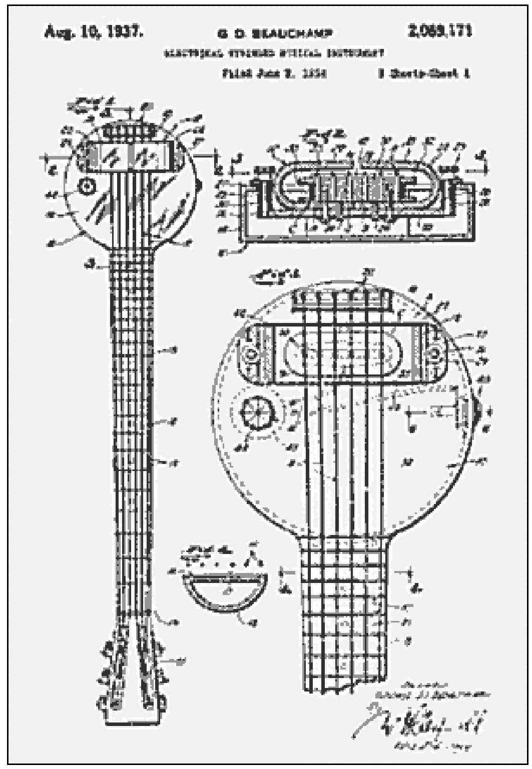


Figure 1. The Rickenbacker Electric Guitar

Over the years the electric guitar grew in popularity. During the Big band era, amplified instruments were necessary to be heard over the louder brass instruments. By this time other musicians and guitar makers were busy producing their own versions of the solid bodied electric guitar: In 1951, Fender Musical Instruments Corporation produced the first commercially successful solid body guitars, the single pickup "Esquire", and the double pickup version, the "Telecaster". In 1952, the Gibson Guitar Corporation countered with their "Les Paul" model. In 1954 Fender produced the

“Stratocaster”, which was offered many improvements over the “Telecaster”, and in 1957 Gibson released their innovative “humbucker” pickup, which was essentially two single-coil pickups wired together to reduce ambient electromagnetic noise that single-coil pickups often produced. Aside from a few changes in electronics and body construction, the basic design of most solid-body electric guitars available today are derived from those original designs.

Figure 2. The Fender Telecaster, the Fender Stratocaster, and the Gibson Les Paul

Today electric guitar is used extensively in many popular styles of music, including almost all genres of rock and roll, country music, pop music, jazz, blues, and even contemporary classical music. Its distinctive sound and intimate association with many legendary, internationally famous musicians has made it the signature instrument of late twentieth-century music.

<u>How Electric Guitars Work</u>

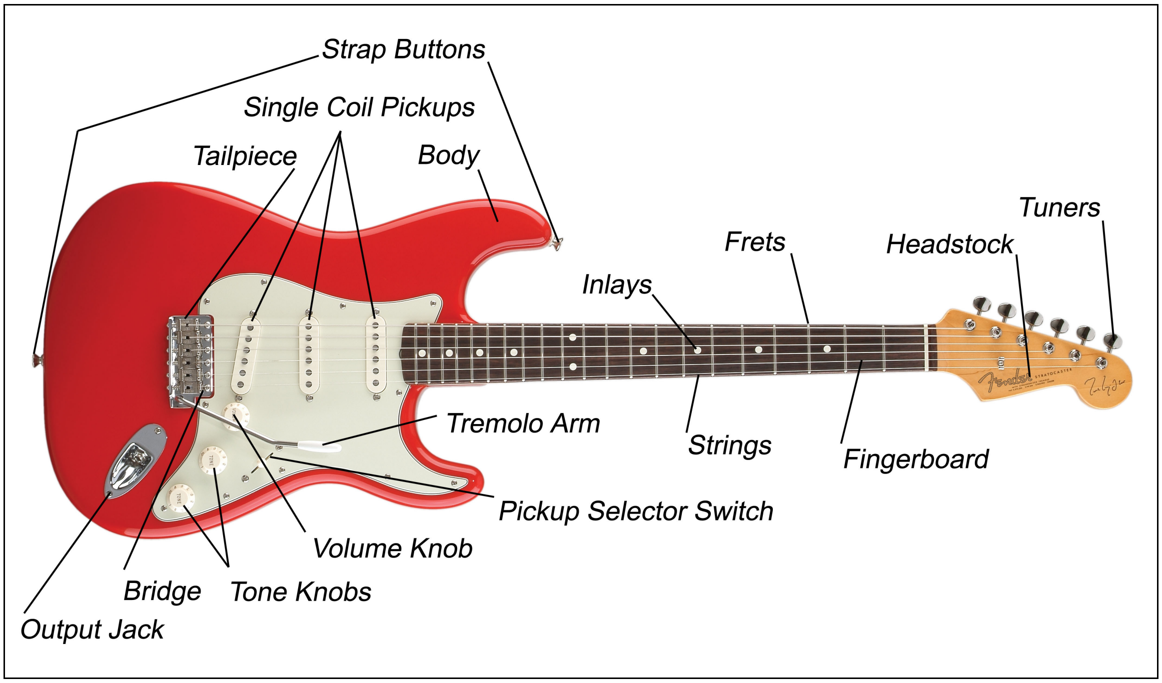


Figure 3. Basic Components The Electric Guitar

Unlike their acoustic counter parts, electric guitars have solid or semi-hollow bodies and don't rely on a soundboard and a chamber of air to amplify their sounds. Instead, electric guitars work on the principle of induced currents and circuits. The pickups on the guitar are made of one or more magnets wrapped with electromagnetic coils, or solenoids. The strings are made of ferromagnetic materials like steel and nickel, and because they run so close to the pickups they become magnetized as well, and produce a magnetic field that surrounds the string at all times. When a string is plucked, it oscillates at a certain frequency, as does its magnetic field. The electromagnetic coils in the pickups "sense" the string's oscillating magnetic field and produce an induced alternating current at the same frequency. This current travels through several potentiometers in the body that are used to control the tone and volume of the sound, and then through the output jack to the amplifier which amplifies the signal and produces a sound at the exact same pitch as the string.

Two properties that qualify a well-made electric guitar are: long *sustain* and good *tone quality*. The sustain of a guitar is the period of time during which a string can sustain its sound before it becomes inaudible. Tone quality refers to the continuity and clarity of pitch of any given string or note, the more continuous and clear, the better.

Although the body of the electric guitar isn't used to amplify the sound, it still affects the acoustics of the guitar a great deal. When you pluck a string, the string vibrates. How much and how long it vibrates depends not only on the properties of the string, but on the properties of the body and neck as well. The stiffer the guitar is, that is, the more the guitar is resistant to deflection or deformation under an applied load (i.e. the strings), the longer the sustain and the better tone quality will be.

The basic equation for the stiffness of an object is:

$$k = \frac{F}{\delta} , \tag{1}$$

where k is the stiffness (force per unit length), F is the force acting on the object, and δ is the deflection of the object in the direction of F. The stiffness (also known as the *spring constant* or *spring rate*) can also be calculated independent of F and δ for several different scenarios. The actual formulas vary greatly depending on the boundary and loading conditions of the object, but in general, an object's stiffness is directly related to its physical shape, and the material it is made of. A few of the basic deflection and spring rate formulas are given in Table 4 of Appendix C. From these general equations it is clear that if the physical dimensions of a guitar were held constant, the only way to increase the stiffness would be to use a material with a higher *modulus of elasticity*, or *E*.

Elasticity is that property of a material which enables it to regain its original shape and dimensions when a load that is acting on it is removed. The modulus of elasticity is the proportionality constant that relates the stress to the strain and, in general, is defined as:

$$E = \frac{\sigma}{\varepsilon} \quad , \tag{2}$$

where σ is the stress in the material (force per unit area), and ε is the strain of the material (deformation per unit length) in the direction of the stress. So a material with a high modulus of elasticity deflects a relatively small amount for a given load.

Stiffness also has a direct effect on the *natural frequencies* of an object. The natural frequency of a system is a frequency at which it oscillates if left alone after an initial disturbance. For any given system there are as many natural frequencies as there are *degrees of freedom*. The first natural frequency is also called the *fundamental frequency*. If the stiffness and mass of the system are known, the fundamental frequency can be calculated using the equation:

$$\omega_n = \sqrt{\frac{k}{m}} \quad , \qquad (3)$$ [1]

where ω is the fundamental frequency, k is the stiffness, and m is the mass. For multi-degree of freedom systems for which the stiffness is sought but is too complicated to calculate directly, one possible solution is to find the mass, test for the fundamental frequency, and solve for k using equation (3).

Electric guitar bodies are usually made from hardwoods such as alder, ash, and maple, to name a few. These hardwoods are desirable because they have relatively high stiffness (in the direction of the grain) for their weight, but are they really the best material for making electric guitars? The table below has the mechanical properties of these hardwoods and of a few other select materials.

Table 1. Typical Mechanical Properties of Selected Materials

Material	Modulus of Elasticity, E (GPa)	Modulus of Rigidity, G (GPa)	Density, ρ (Mg/m^3)	Specific Stiffness, E/ρ	Ultimate Strength, S_u (MPa)[a]
Alder, Red[bc]	9.5	--	0.41	23.17	--
Ash, White[bc]	12	1.308	0.55	21.81	--
Maple, Sugar[bc]	12.6	1.399	0.57	22.10	108
Aluminum Alloys	72	27	2.8	25.7	83-590
Steel Alloys	207	79	7.7	26.8	290-1100
Titanium Alloys	114	43	4.4	25.9	241-1200
E-Glass/Epoxy Composites	39	3.8	2.1	18.57	1080
Carbon-Fiber/Epoxy Composites	142-177	7.2-7.6	~1.6	~88.75-110.63	~2200-2800
Kevlar/Epoxy Composites	87	2.2	1.38	63.04	1280

[a]Ultimate Strength varies widely depending on the alloy and the heat treatment used.
[b]Properties based on 12% moisture content
[c]Values given are in the direction of the grain/fibers.

From the data in Table 1 it is clear why hardwoods are normally used for building guitars, they have basically the same specific stiffness as metals, but they are much less dense and therefore lighter. What also becomes evident from the table is that composite materials may be a better alternative to hardwoods. The carbon-fiber/epoxy composite material is about three to four times denser than the hardwoods, but it is about five times stiffer per weight, meaning the amount of material needed would be less, and the overall weight of the guitar would be less. This would no doubt change the vibration characteristics of the body, but in what way? How would a composite guitar behave? How would it sound? This project investigates that answer.

Problem Definition

Hardwood materials such as alder, ash, or maple might not be the best building materials for electric guitar bodies. Carbon-fiber composites have a much higher specific stiffness and could be used to make an electric guitar with a longer sustain and better tone quality.

Objective

The goal of this project is to determine if carbon-fiber/epoxy composite materials are more effective than hardwoods for building electric guitars. This will be done by designing, building, and testing a playable prototype and comparing its vibration characteristics to that of a standard, hardwood guitar. This project aims to show that this prototype guitar will be lighter, stiffer, and will exhibit comparable, if not better, sustain and tonal quality than a commercial hardwood electric guitar.

Chapter 2: Survey of State of the Art

Extensive research was performed to find literature related to this project. Searches were performed in the library as well as on the Internet for research papers, projects, patents, and other commercial undertakings involving composite materials being used as building materials for stringed instruments. A great deal of information was also needed on the subjects of making electric guitars and using composite materials.

There were no research papers or projects found that were directly related to this project, but a few papers did contain some relevant information that was used in later sections of this paper, those sources are listed in the References section at the end of this report. A few patents and commercial products were found that are related to this project, and a summary of each is given below.

Patents

One Piece Composite Guitar Body

Patent Number	Issue Date	Inventors	U.S. Classification	International Classification
6683236	January 27, 2004	S. Davis, R. Janes, C. Bash, P. Chou	84291; 84290; 84261	G10D 300
Abstract				
A body for a stringed instrument comprising a front face and a back face and a continuous side face there around; and an exterior laminate, the exterior laminate being formed of a plurality of composite layers including an interior layer, the composite layers of the laminate also including at least one supplemental layer, each layer including strands enveloped in an associated polymeric binder, with each subsequent layer being in intimate contact with the next adjacent layer.				

Composite Stringed Musical Instrument, and Method of Making the Same

Patent Number	Issue Date	Inventors	U.S. Classification	International Classification
6538183	March 25, 2003	F. Verd	84291; 84290	G10D 300
Abstract				
Methods of construction for acoustic and electrically amplified stringed musical instruments. The invention further relates to acoustic and electrically amplified stringed musical instruments comprising fiber-reinforced resin composite materials, where the instruments are provided with a sound-damping interior coating.				

Commercial Products

There are several composite electric guitars on the market today, each offering its own unique twist on the idea of increased stiffness to weight.

Figure 4. The Harmos MATRAX

Harmos Music, Ltd., noted for their innovative lap steel guitars, also makes an electric guitar called the MATRAX that utilizes a framework of carbon-fiber struts and wooden joints to create a strong, lightweight body. The MATRAX's neck is made of Rock Maple enveloping a core of carbon fiber rods, which make the neck too stiff for a truss rod. According to Harmos, "All of the previous electric guitars have fundamental resonance frequencies of 50 to 80 hertz. 50 to 80 hertz is very low and causes the overtones of the guitar to be attenuated (absorbed). The fundamental resonance of the Harmos guitar (body and neck) is above 400 Hertz and this helps amplify the overtones and therefore the life and timber of the guitar. You can physically hear this difference in Harmos' clear and lively tone."

Another company, Gus Guitars, makes several electric instruments that also employ composites as a building material. Their G1 series guitar and G3 series bass bodies are made of a solid Cedar core covered with a carbon-fiber/epoxy laminate skin. Gus Guitars also claim that the carbon fiber design allows for better sustain and tonal characteristics.

Figure 5. The Gus Guitars G1 Hardtail

Chapter 3: Design Development

Design Requirements

Before any design or analysis can be done, the scope of the project must first be fully defined; what is it that the final design must accomplish? Earlier it was decided that the prototype guitar must be playable. It should also be lighter, stiffer, and have better sustain and tonal quality than a standard electric guitar. Playable means that it must be a fully functional electric guitar, that is, it should be capable of producing sound and being played like a standard guitar. Lighter and stiffer will most likely be a result of using carbon-fiber/epoxy, but it is too early yet to quantify these requirements. It should also be robust. The neck must be able to support the load of the strings along with an appropriate factor of safety. Sustain can be measured from both guitars for comparison, and tone quality is more of a factor of personal preference, but should still be considered in the final testing.

In order to examine the different vibration characteristics of the two guitars, modal vibration data must be acquired for each. This data can also be used to calculate the stiffness of the each guitar using equation (3).

Development Testing

Modal frequency data was acquired for a Fender Stratocaster using the Dactron LDS Focus II dynamic signal analyzer and modal software. Lines were drawn on the guitar to form a grid of 95 measurement nodes. A test stand was then constructed from which the guitar was made to hang freely from the strap buttons. Two accelerometers were then placed at expected anti-nodes: the smaller “wing” and the neck.

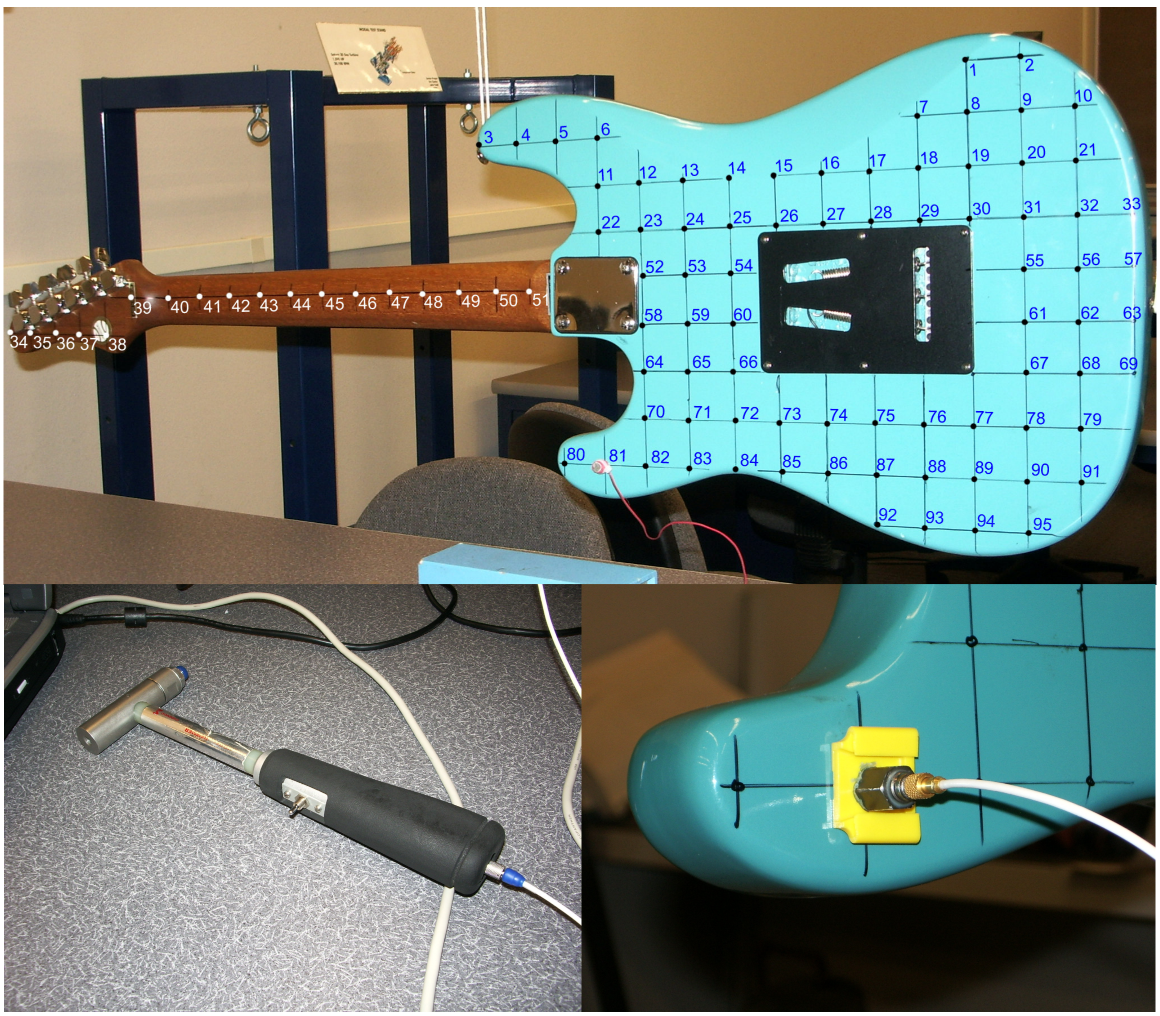


Figure 6. Modal Vibration Testing of a Commercial Electric Guitar

The Dactron modal software was then configured to measure magnitude and coherence date for frequencies 0 to 800 Hz from the two accelerometers. The instrumented hammer was then used to strike each of the 95 measurement nodes three times while the software averaged and cataloged the accelerometers’ outputs.

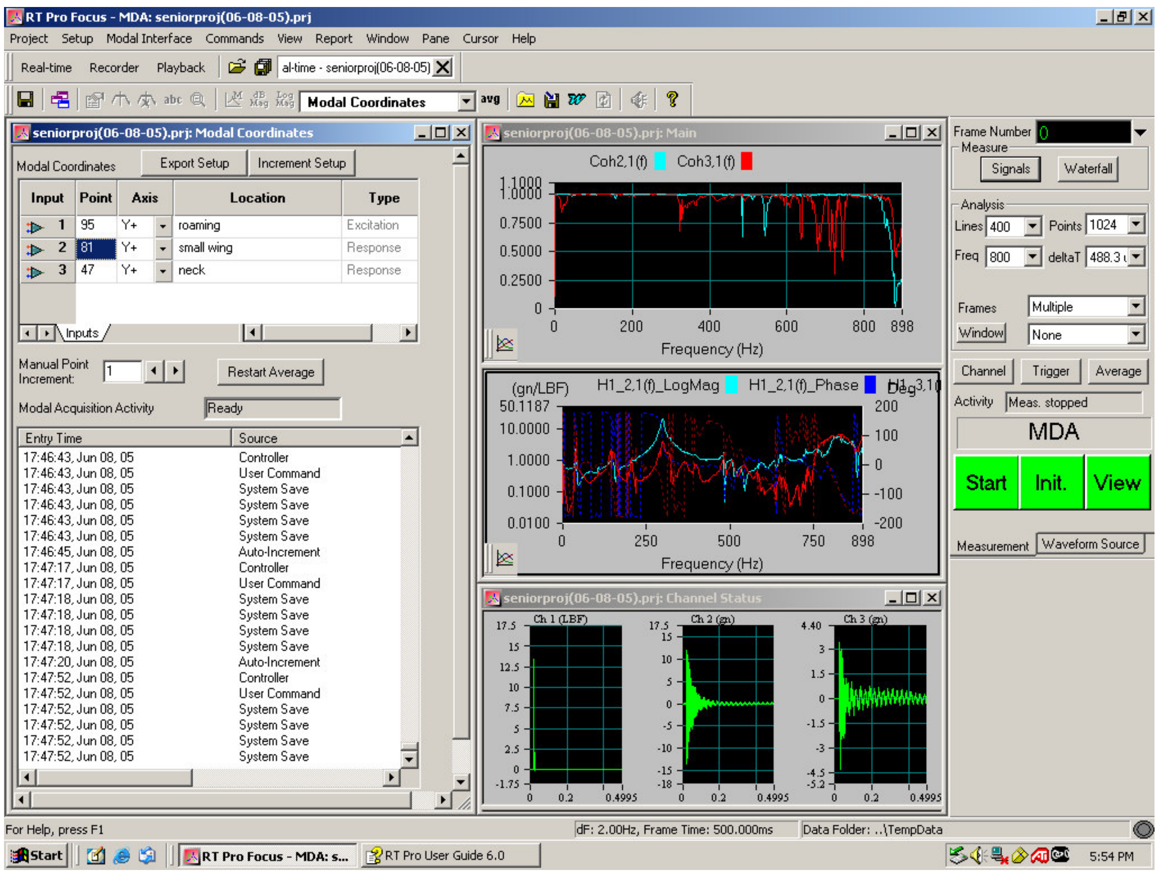


Figure 7. Dactron’s Modal Frequency Software

Once the vibration data was collected, a program called STAR Modal was used to identify the natural frequencies and plot the mode shapes. These plots are shown in Figure 8.

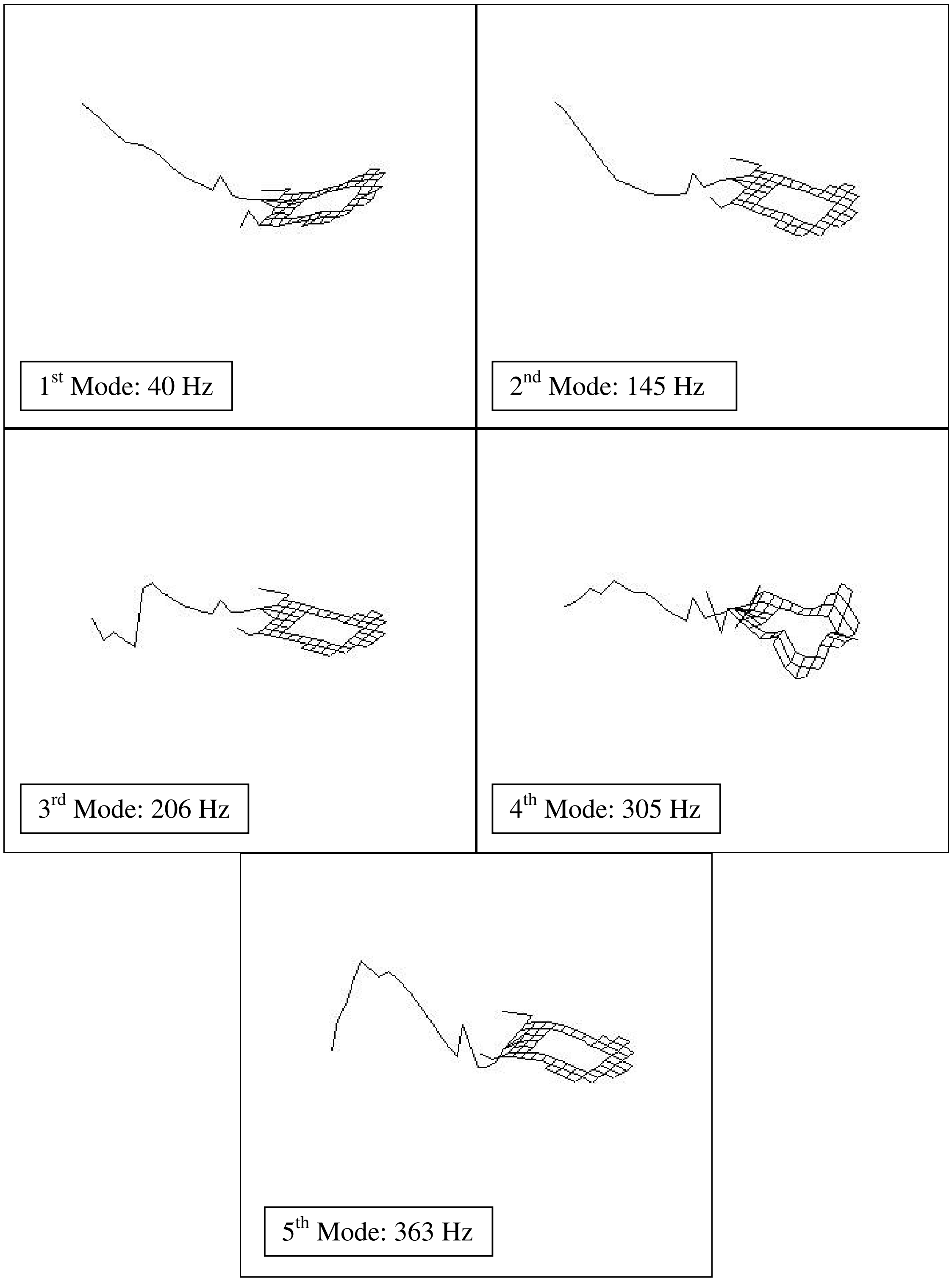


Figure 8. Experimental Bending Modes of a Fender Stratocaster

The first mode shape for the Stratocaster seems to be a simple bending mode with two antinodes at both ends. The second mode shape is also a bending mode, but with three antinodes, the third being roughly centered on the neck-to-body joint. The third mode is a bit unclear but seems to involve a great deal of movement in the headstock area. The forth mode shape is clearly a torsion mode, with a slight amount of bending in the neck. The fifth mode seems to be four-antinode bending mode. These shapes will be used later in this paper to compare with the prototype guitar's vibration characteristics.

Chapter 4: Design and Analysis

Design Background

The body shape chosen for the prototype is based off of a 1960's Montgomery Airline. This shape was chosen for two main reasons: the first being that it is a visually interesting, fresh, and unique design and the second because it has long straight sections that facilitate working with carbon-fiber fabrics (which can be difficult to mold against extremely curvy and/or complex shapes). The name "Carboncaster" was chosen partly to designate the building material and partly as a tribute to Fender's popular series. Solidworks was used to create the three-dimensional model and two-dimensional schematics used during this project (See Appendix A for complete design drawings of the prototype body and headstock).

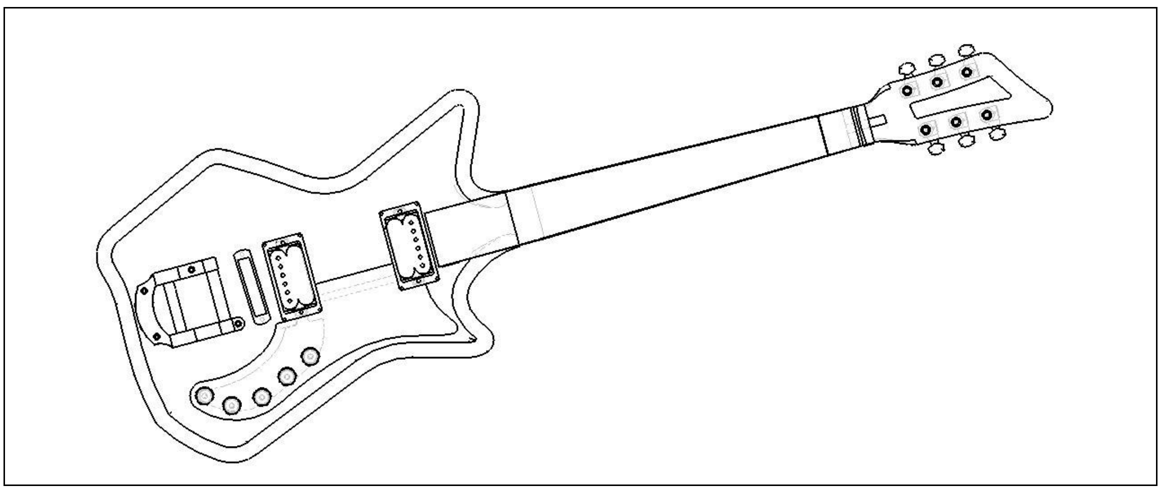


Figure 9. The "Carboncaster" Prototype Design

Because of the already large scope of this project, it was decided early on that aside from the body and the headstock, the majority of the other components should be purchased to help avoid as many complications as possible. For this reason the bridge, tailpiece, pickups, electronics, fingerboard, fret wire, strings, tuners, and strap buttons were all selected from a commercial vendor.

Another design consideration was whether or not to make the Carboncaster hollow or filled with a rigid, polyurethane core. A decision on this wasn't reached until most of the build phase was completed and so it is discussed in greater detail later in this paper.

Material Considerations

Another consideration that must be taken when building with carbon-fiber is what type of fabric to use. Carbon-fiber and other fiber-reinforcing materials come in many different patterns and configurations to best suit many applications. Unidirectional fabrics are made with the fibers all oriented in the same direction; these are also called the warp fibers. Simple weaves are made up of fill fibers woven under and over the warp fibers in a cross-hatched pattern, providing stiffness in two different directions. A twill weave is made with the fill and warp fibers woven together in an NxN pattern, where N is the number of fibers skipped with each weave. That is, for a 2x2 twill weave, the fibers are woven in a 2 over, 2 under pattern. Twill weaves tend to drape, or follow the shapes of a mold, much better than standard weaves. Another configuration is the harness, or HS satin weave. The HS satin weave comes with a single number designation. A 4 HS satin weave then means that the fill threads float over three warp threads, then under one warp thread. In general, the higher the number designation for twill and harness weave, the better it will drape.

For making the Carboncaster, since the majority of the loading occurs in the neck, it was decided that a unidirectional fabric should be used for the inner layers of the guitar, with a 2x2 twill weave on the outside, oriented in a ±45° direction to the neck centerline. This twill provides a double purpose: it provides stiffness in a direction other than the unidirectional fibers, and also is quite visually pleasing.

Strength Analysis

One of the design requirements for the Carboncaster is that the neck must support the loads caused by the strings, and it must be robust. Because of this some strength calculations were done to determine the thickness of carbon-fiber material required to support the strings with a safety factor of three. String load values were taken from Analysis of Stress Concentrations in an Electric Guitar Neck Joint, a thesis paper by John Collen, and are given in Table 2.

Table 2. Loads Produced by Individual Strings[6]

Average Force in Tuned Strings (lbs), String Label (note, string diameter in inches)					
1 (E, 0.010)	2 (B, 0.013)	3 (G, 0.017)	4 (D, 0.026)	5 (A, 0.036)	6 (E, 0.046)
15.8	15.2	16.1	18.7	19.4	17.4

The strings then provide a total average of 102.6 lbs on the neck and body of the guitar. With a safety factor of three, that's a design load of 307.8 lbs, or 4924.8 N. This load and the equations for buckling in beams will determine the thickness of the carbon-fiber in the neck.

For a relatively long, slender beam loaded in compression, the critical force P_{cr} that results in *elastic instability*, or *buckling*, is defined by Euler as:

$$P_{cr} = \frac{\pi^2 EI}{L_e^2} \quad , \qquad (4)^2$$

where E is the elastic modulus, I is the moment of inertia of the smallest section with respect to the buckling-bending axis, and L_e is the equivalent length of the beam based on its end conditions. For a cantilever beam with one fixed end and one free end,

$$L_e = 2L \quad . \qquad (5)^2$$

For this calculation, material properties will be used for an AS4/3501-6, carbon-fiber/epoxy material. The moment of inertia is calculated for the smallest cross-section in the neck and the bending axis will be located at the strings. In order to find the moment of inertia about the strings, the parallel axis theorem must be used. The parallel axis theorem states that the moment of inertia through any axis parallel to the axis of the objects centroid can be found with:

$$I_x = I_{xc} + Ad^2 \quad , \qquad (6)^2$$

where I_x is the moment of inertia about the strings axis, $\bar{I}_x$ is the moment of inertia about the centroid of the neck, A is the cross-sectional area of the neck, and d is the distance from the centroid of the neck to the strings. The moment of inertia about the centroid of a half-ellipse is:

$$I_{xc} = ab^3\left(\frac{\pi}{8} - \frac{8}{9\pi}\right) \quad , \tag{7}$$

where *a* and *b* are defined below in Figure 10.

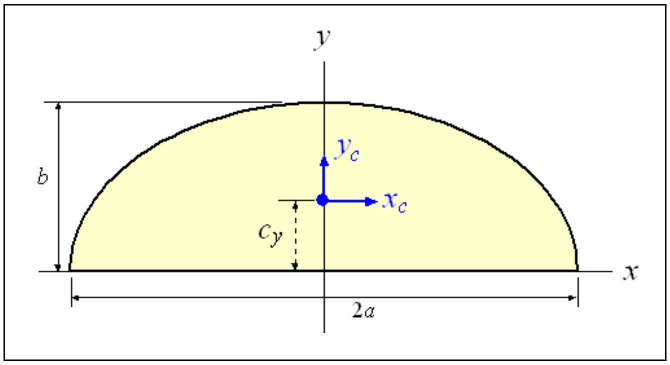


Figure 10. Location of Centroid of a Half-Ellipse

For a hollow half-ellipse of unknown thickness, the moment of inertia changes to:

$$I_{xc} = \left(ab^3 - a'b'^3\right)\cdot\left(\frac{\pi}{8} - \frac{8}{9\pi}\right) \quad , \tag{8}$$

where

$$a' = a - t \quad \text{and} \quad b' = b - t \quad . \tag{9,10}$$

Substituting equations (9) and (10) into (8), and then (8) into (6), the equation for the moment of inertia about the strings becomes:

$$I_x = \left[ab^3 - (a-t)(b-t)^3\right]\cdot\left(\frac{\pi}{8} - \frac{8}{9\pi}\right) + Ad^2 \quad . \tag{11}$$

For this problem,

$$A = \frac{\pi ab}{2} - \frac{\pi a'b'}{2} \quad \text{and} \quad d = \left(C_y + s\right) = \left(\frac{4b}{3\pi} + s\right) \quad . \tag{12,13}$$

where C_y is the distance to the centroid of the half-ellipse, and *s* is the distance from the flat surface of the neck to the strings.

Now substituting equations (12) and (13) into (11), and combining (11) with equation (4) we can solve for the thickness. Microsoft Excel's solver addin was used to accomplish this. For:

P_{cr} = 4924.8N, E = 142GPa, L = 0.327m, a = 0.021m, b = 0.018m, and s = 0.009m, the minimum thickness of AS4/3501-6 needed to support the load of the strings with a safety factor of 3 is:

***t* = 768 nanometers** .

This is ridiculously small, since the thickness of just one ply of carbon-fiber is about 198 times as thick. It seems, then, that three layers of unidirectional carbon-fiber and 1 layer of twill weave should easily be able to support the strings without buckling. Yielding, however, is another matter.

The longitudinal compressive strength of AS4/3506-1 is about 1440 MPa. The area calculated from the Excel spreadsheet is about $4.68\text{x}10^{-8}$ m^2. This means that a load of about 67.36 N will cause a carbon-fiber/epoxy neck of this thickness to yield in compression. A new calculation now finds that thickness of material needed to support the compressive force of the strings is:

***t'*= 56.2 micrometers** ,

or a little less than half the thickness of one ply of carbon-fiber. So four layers should still be fine.

Theoretical Modal Analysis

In addition to creating the drawings and models, Solidworks was used to perform some simple vibration analysis on the Carboncaster. Using the COSMOSWorks addin software, two frequency studies were performed on the guitar. The first study analyzed the guitar body as if it was solid and made of wood, Sugar Maple to be exact, and second analyzed a hollow carbon-fiber/epoxy (AS4/3601-5) body of approximately 4mm in thickness. Mechanical properties for Sugar Maple were obtained from The Wood Handbook[5] and the properties for the AS4/3601-5 were obtained from Engineering Mechanics of Composite Materials[3]. Both sets of data were entered into the Solidworks materials database prior to analysis, and both orthogonal materials were aligned with their fibers running parallel with the centerline of the neck. The model was also restrained so that it could only hinge about the locations of the strap buttons. This analysis is not considered to be incredibly accurate, but is used more for observing the differences materials have on the vibration characteristics of the body. Figure 11 shows the first five mode shapes for the solid wooded body.

This figure shows the second, third, forth, and fifth modes calculated by COSMOSWorks. The first mode was simply the guitar swinging from the guitar strap buttons. The second and third modes are bending modes about the neck. The forth is a torsion mode and the fifth is a combination of bending and torsion. These shapes are somewhat similar to the mode shapes seen in the Stratocaster tested earlier, even though the frequencies are quite different.

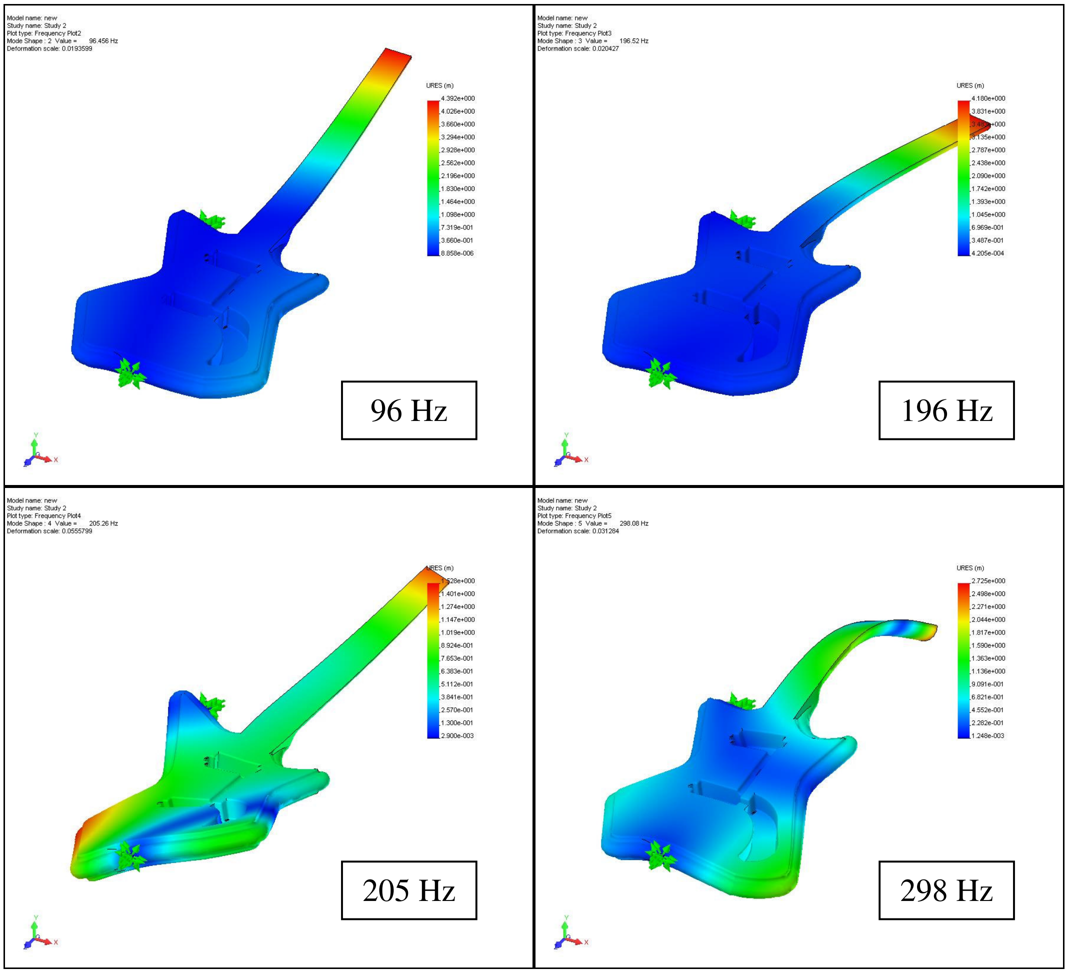


Figure 11. Theoretical Wooden Guitar Modes

Figure 12 shows the first five theoretical mode shapes for the carbon-fiber body. The first mode for the carbon guitar was also from swinging about the strap buttons. The second and third mode shapes for this guitar are similar to the wooden guitar, but the frequencies are much higher. The forth mode shape is quite different, however, as the neck stays relatively stationary while the body oscillates vertically. For the fifth mode the neck and face of the guitar remain stationary while the back face oscillates vertically.

From these figures it is clear that, for the computer solution, the carbon-fiber guitar is either much stiffer or much lighter than the wooden guitar, or perhaps both. Each of the modes occurs at higher frequencies and there is much less movement in the neck than in the wooden guitar. This further supports the idea that a hollow, carbon-fiber guitar will be much stiffer than the wooden guitar.

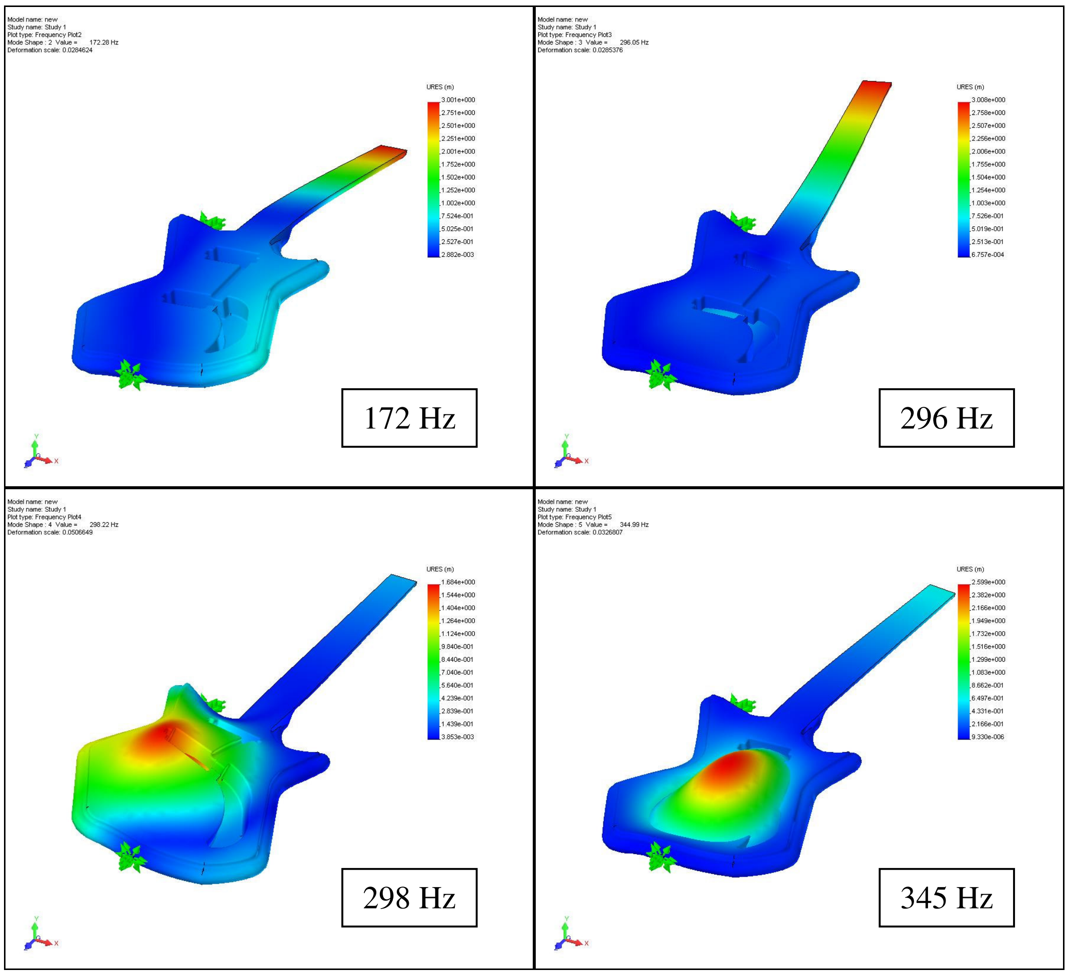


Figure 12. Theoretical Carbon-Fiber Guitar Modes

Chapter 5: Construction

With the design complete, the next step was to actually build the Carboncaster. To build a complex shape out of carbon-fiber or other fiber reinforcing composites, it is usually necessary to first build a plug or mold of that same shape. A plug is basically a positive mold of the final shape onto which the composite lay-up is cured. The plug can then either best discarded or used as a core material for the part. A mold is a negative of the final shape into which the composite lay-up is cured. Molds are generally used for when making multiple parts or when high surface finish is desired. A general rule for composites is that the best surface finish exists at the contact side of the lay-up. For these reasons it was decided to use fiberglass molds to make the Carboncaster body. A complete description of the building process is given below.

Figure 13. Building Materials

Table 3. Parts and Material Quantities

Item Number	Description	Quantity
1	1.5-ounce fiberglass matte, 50 inch wide	4 yards
2	0.75-ounce fiberglass matte, 50 inch wide	1 yard
3	Carbon-fiber twill, 50 inch wide	2 feet
4	9-ounce unidirectional carbon-fiber, 12-inch wide	2 yards
5	Electric guitar components[a]	1
6	6061-T6 aluminum sheet, 12-inch by 12-inch, 0.08 inch thick	1
7	6061-T6 aluminum block, 1.5-inch by 4-inch by 12-inch	1
8	6061-T6 aluminum block, 4 inch by 4 inch by 0.5 inch	1
9	Two-part expandable pour foam, part A	2 quarts
10	Two-part expandable pour foam, part B	2 quarts
11	MEKP epoxy/resin catalyst	20 ounces
12	Polyester gel coat	2 quarts
13	Duratec clear hi-Gloss additive	2 quarts
14	Duratec Tooling Gel Coat	2 quarts
15	Mirror-glaze release wax	1
16	Clear, polyester laminating resin	4 quarts
17	Bucket, measuring cup, paintbrushes, roller, and squeegee	1
18	Non-clear, polyester laminating resin	4 quarts
19	Acetone	2 quarts
20	Bondo Body Filler	2 quarts

[a]bridge, fingerboard, fret wire, output jack, knobs, potentiometers, strap buttons, 3-way switch, tailpiece, tuners, and wood glue.

The cost of the parts and materials used in this project, including the materials needed to make the plugs and molds, was approximately $700. The cost to produce a second guitar should be around $400, depending on the availability of carbon-fiber.

Building Process

Making the Plugs

The first step of the building process was to fabricate the foam plugs over which the molds will be made. The final product will have the same shape, size, and surface texture of the plug, so this step was somewhat critical, but as it is made of polyurethane foam and not carbon fiber, it is a lot easier to work with. Cutting the foam into the design of the guitar was accomplished by importing the Solidworks model of the guitar into a CNC code generating program, and then running that code on the “Shop-Bot” in the Student Projects Machine Shop.

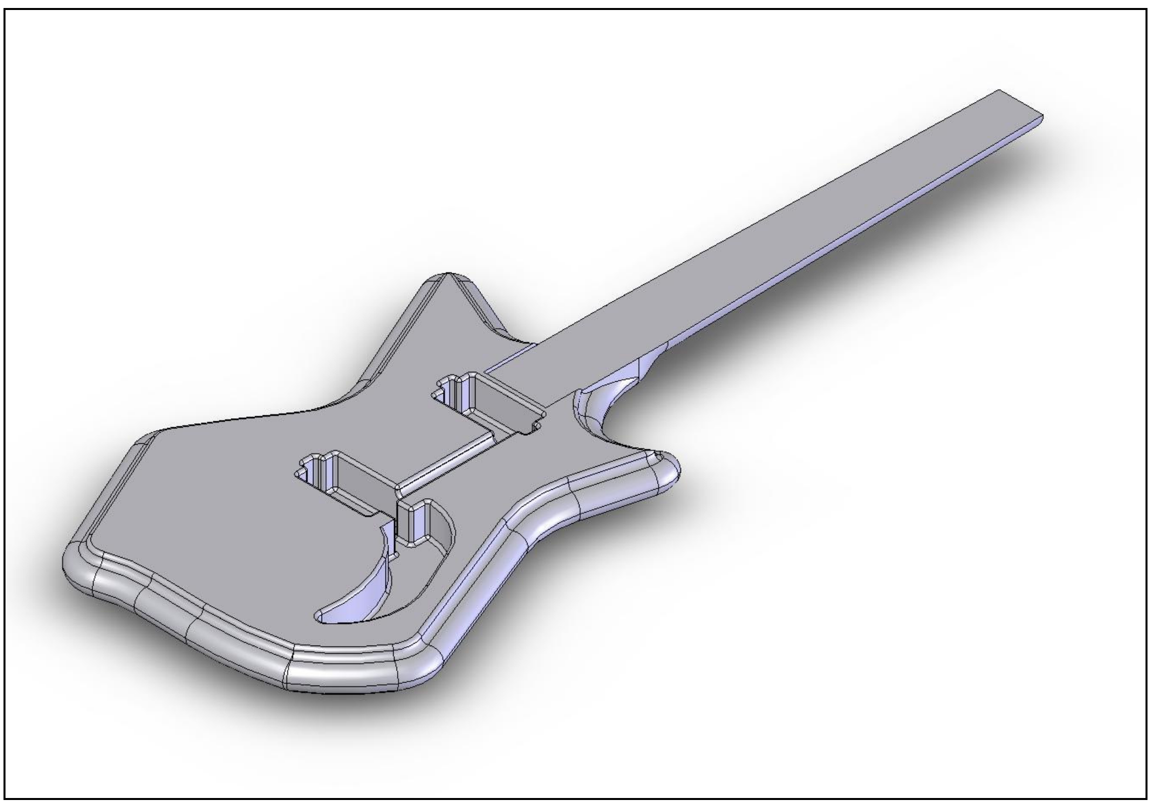


Figure 14. Prototype SolidWorks Model

When cutting a truly three-dimensional shape (a shape that has unique features on at least three planes and can't be formed from a two-dimensional sketch and extrusion) it is usually necessary to cut the shape in two or more pieces and glue them together afterwards. This is exactly what had to be done with the plug. Because the guitar has no true mid-plane (the neck being offset from the body) the plug had to be cut in three pieces: the front, the back, and the neck.

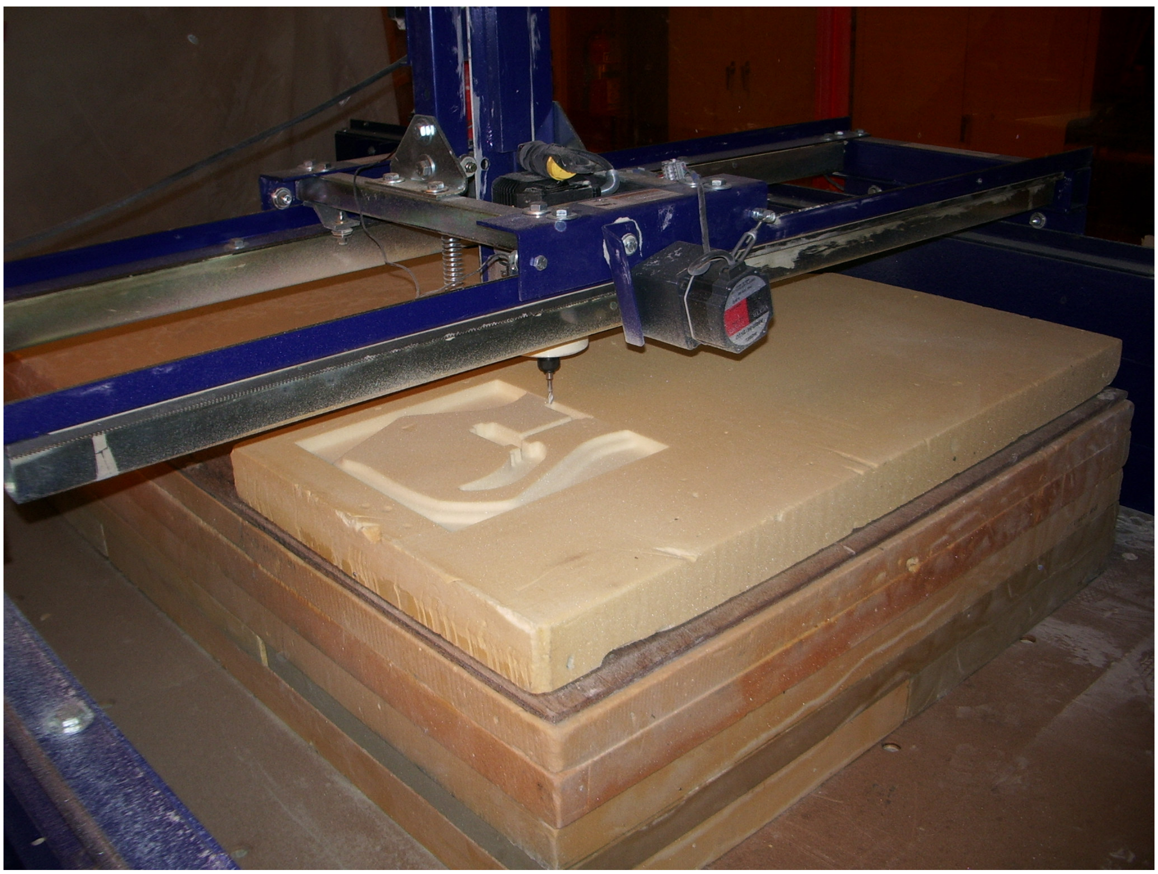


Figure 15. Cutting the Foam with the Shop-Bot

In this figure we see the foam plugs being cut by the "Shop Bot". The code used to run the "Shop Bot" was generated from the Solidworks model using the CAMWorks software addin. This was a very long (and loud) step in the building process because the linear velocity was reduced in order to prevent the mill from tearing the foam rather than cutting it. Also two complete passes were needed to reach the depth required for the design.

Figure 16. Neck, Front, and Back Plugs

After the three plugs had been cut, hand tools were used to separate the pieces and remove any excess foam from around the parts. The plugs were then coated with laminating epoxy and left to dry overnight. This layer of epoxy served both to harden the plugs as well as provide a foundation for spraying a several coats of the Duratec Tooling Gel Coat surfacing primer (item 14). Even after this surfacing primer was applied, the surfaces of the plugs were still somewhat porous and rough and so Bondo (item 20) was used to help fill in the gaps. Many hours were spent applying the Bondo, waiting for it to dry, sanding it down, and repeating until the plugs were as smooth as possible.

Figure 17. First Layer of Duratec Surfacing Primer and Bondo

. In order to get the smoothest surface possible on the final carbon-fiber lay-up, the mold would have to be as smooth as possible, which in turn meant that the plug would have to be as smooth as possible, hence the importance of this step in the building process. Figure 17 shows the plugs after the Duratec primer and all of the layers of Bondo had been applied. The guitar is now ready for another layer the Duratec primer.

Figure 18. Second Layer of Duratec Surfacing Primer

A different color primer was chosen for this application to contrast with the previous so that if any sanding had to be done the first layer would be easy to identify.

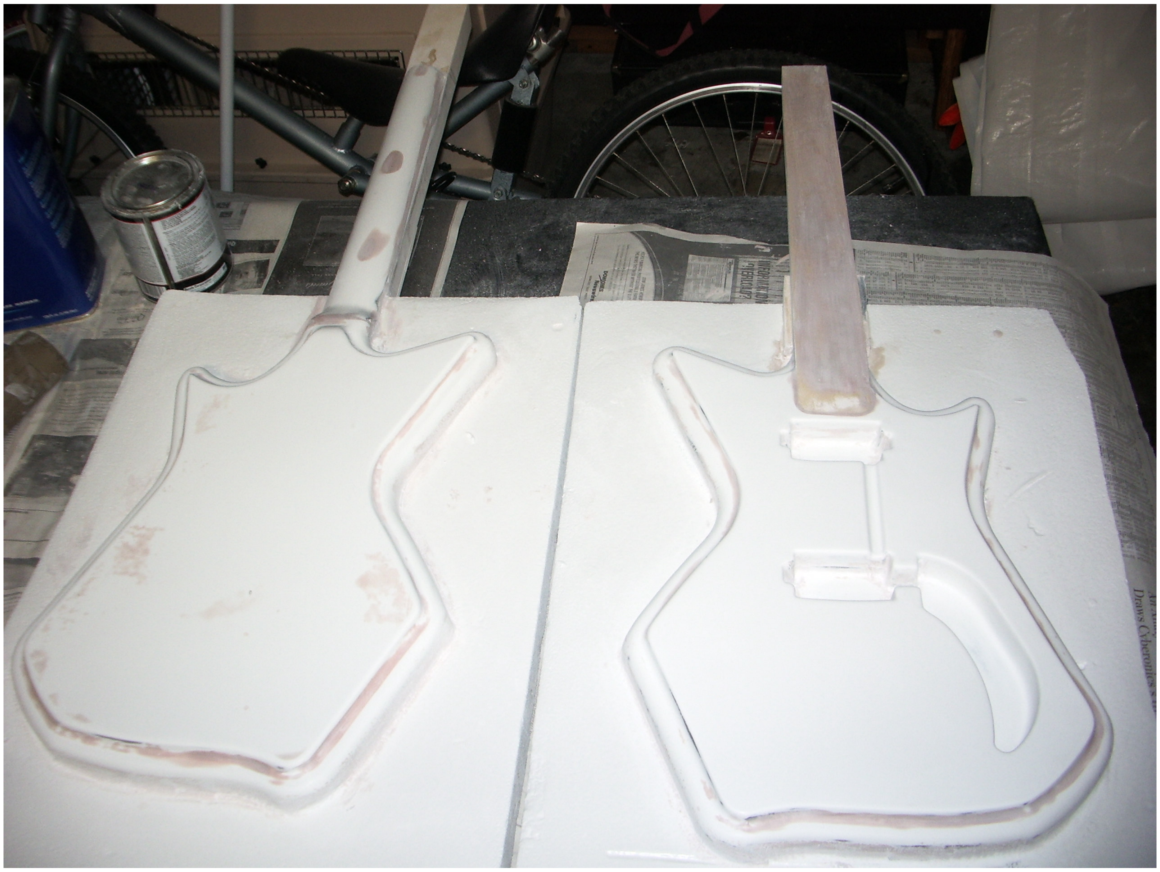


Figure 19. Completed Plugs

After a couple of touch-ups the neck pieces were glued to the bodies. Several more applications of Bondo were then needed to fill in the gaps between the neck and body parts. At this point the plug was almost ready for the fiberglass lay-up; the only thing left to do was apply the release wax (item 15) to the mold to keep it from bonding to the fiberglass. For new molds it is recommended to apply between 3 and 5 coats of wax with a soft terry cloth, and to buff each layer before drying. Once this was done the plugs were ready to be molded.

Figure 20. Making the Fiberglass Molds

<u>Making the Molds</u>

Two kinds of fiberglass matte were used to make the molds: a 1.5-ounce (item 1) and a 0.75-ounce (item 2). This weight refers to the estimated ounces per square yard of material. The first layer of the mold is the most important, so the 0.75-ounce matte was the first to be applied, wetted with laminating resin (item 18), and rolled down. Careful attention must be paid when rolling down the matte so as not to trap air bubbles. After this layer was dry, several layers of the heavier 1.5-ounce matte were applied until the molds were approximately 0.25 inches thick. The molds were then removed from the plugs and cleaned.

Figure 21. Front and Back Molds

After the molds were complete several preparations were made to insure that the carbon-fiber halves would join easily in the middle. A couple layers of 10 mil thick tape were run along the top edge of the back mold. This extra edge thickness would allow for an offset bonding surface between the two carbon-fiber halves, as shown in Figure 22.

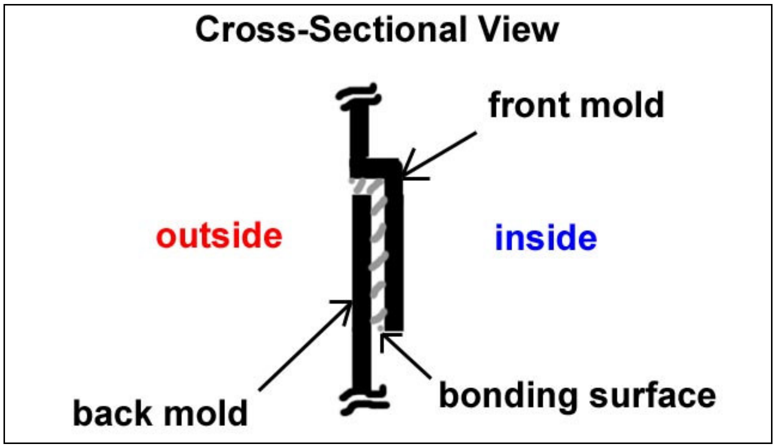


Figure 22. Offset Carbon-Fiber Bonding Surface

With this done, printouts of the Carboncaster shape were used to cut the carbon-fiber unidirectional and twill fabrics (items 3 and 4). When cutting carbon-fiber it is helpful to put tape on the cut edges, this prevents the fabric from unraveling.

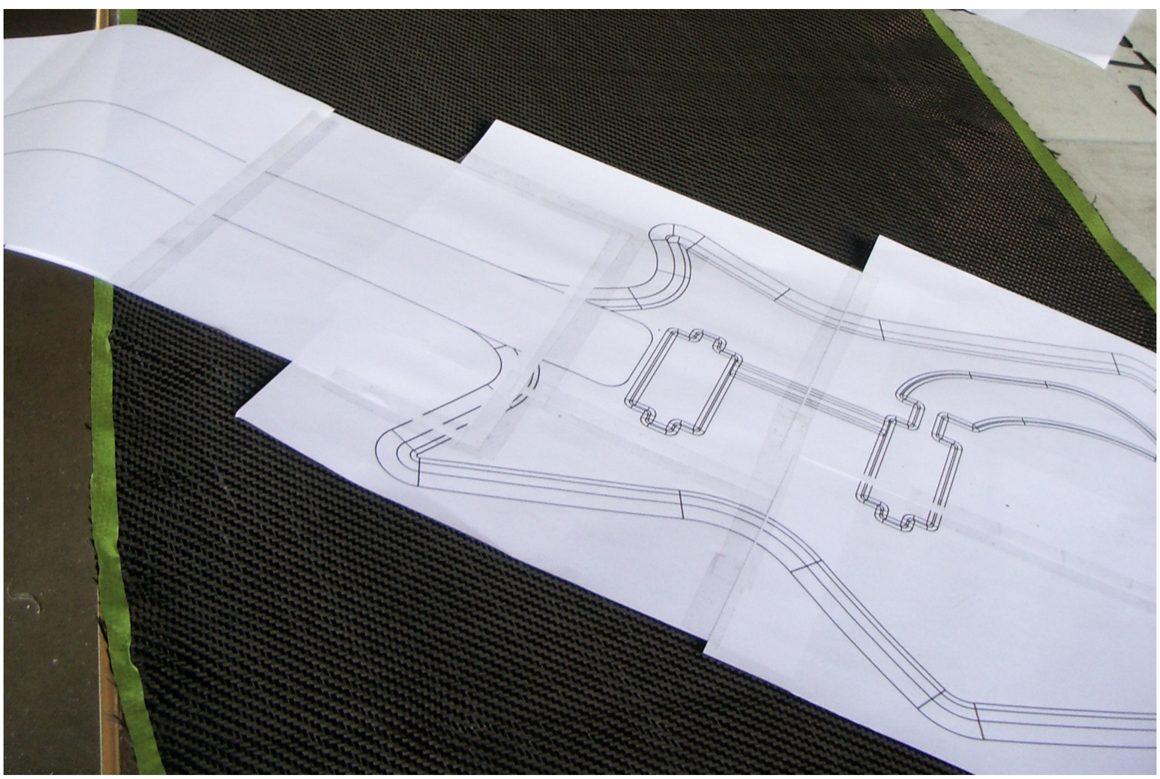


Figure 23. Patterns for Cutting the Carbon-Fiber

Laying Up The Carbon-Fiber

The first thing to do before laying up the carbon fiber inside the two molds was to make sure that the molds' surfaces were free of imperfections. Next, the inside of the molds were coated with the polyester gel coat (item 12). It is recommended to dilute the gel coat and spray it on with a spray gun; this is supposed to provide the best coverage. The polyester gel coat has a very tacky surface and so it easily accepts additional layers. Around 4 layers of gel coat were applied provide a strong, protective surface on the guitar. Because the gel coat is very tacky, the last layer was mixed with about 20% of the Duratec Clear High-Gloss Additive (item 13), so that it formed a non-tacky surface and allowed the carbon fiber to be easily moved around inside the mold before wetting it with the clear laminating resin (item 16).

Because the resin used was polyester based, the amount of time available to work with the lay-ups was only about 20 minutes, so everything had to be prepared ahead of time. The Cal Poly HPV (Human Powered Vehicle) team generously donated all of the vacuum bag, release cloth, breather cloth, and tacky tape used for this project. Release wax was again applied to the molds and it was time to lay up the carbon-fiber. The first layer wetted and rolled into the mold was the 2x2 twill weave, followed by several layers of unidirectional fabric. The mold was then covered with release cloth, and then breather cloth, and finally placed inside the vacuum bag. A pump was then used to remove the air from the bags and compress the carbon-fiber lay-ups against the molds until they were cured.

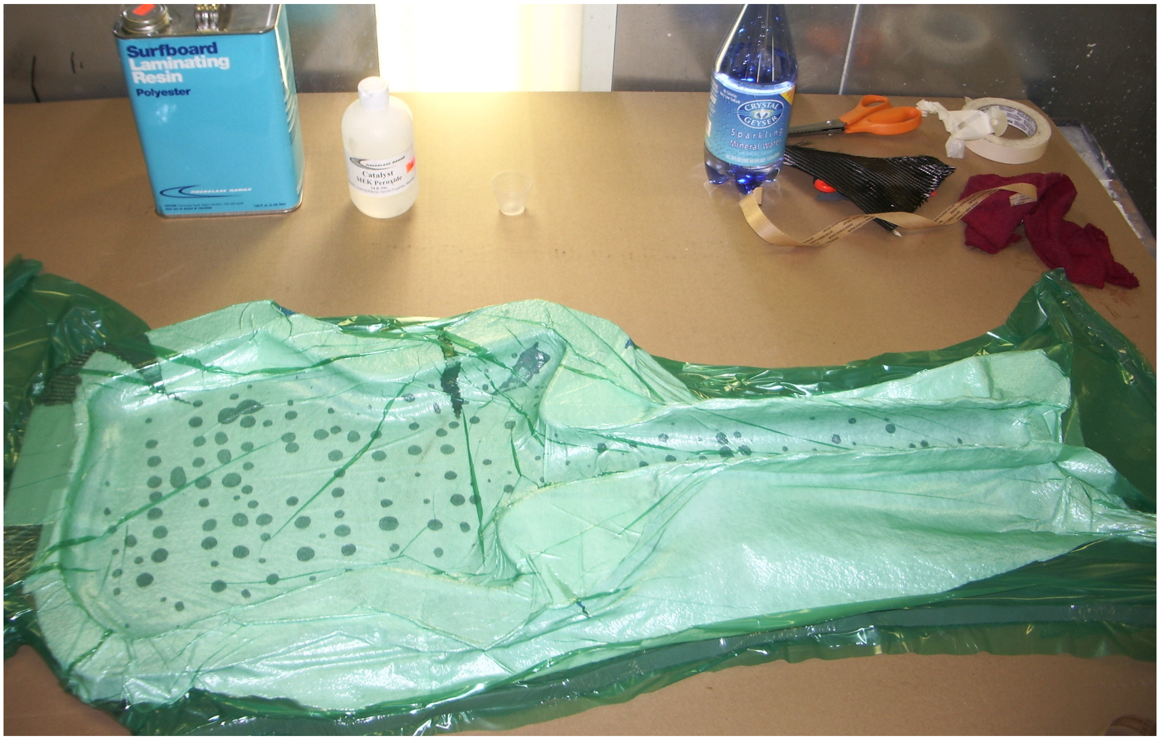


Figure 24. Vacuuming the Carbon-Fiber Lay-ups

Figure 25. The Completed Carbon-Fiber Halves

With both halves of the carbon-fiber skin finished, it was then time to work on the aluminum inserts and headstock. The purpose of the aluminum inserts was to provide a material other than carbon-fiber for all of the guitar components to thread into. In hindsight these inserts did not have to be as large as they are and a good deal of weight could have been reduced. Regardless, the holes for the components were measured off and drilled so that these inserts could be cut to size, drilled, tapped, and glued to the inside of the front half.

Figure 26. Aluminum Headstock, U-Channel, and Inserts

The headstock was made from the 1.5-inch by 4-inch by 12-inch aluminum block (item 7). First the rough shape was cut using a vertical band saw. A milling machine was then used to cut the final shape and drill the holes for the tuners. Files and heavy-grit sand paper were used to create the fillets. An aluminum U-channel of 0.25 inches x 0.25 inches was then cut to the length of the neck. The headstock was then glued and riveted to one end. The U-channel was then glued and riveted to the inside of the front half's neck, as shown in Figure 27.

Figure 27. Aluminum U-Channel Riveted to Neck and Headstock

Once the headstock was securely fastened to the front half, it was time to glue the halves together. Resin was mixed and c-clamps were used to hold the two halves together as strips of carbon-fiber weave were wetted and placed over the seam. This was all done by hand, without pulling a vacuum on the part, so when the resin had cured the edges needed some extensive clean-up work. This was definitely a process that should be considered for improvement when making the next guitar. Once the two halves were joined it was time to attach the fingerboard. The pre-cut fingerboard blank that was purchased earlier was measured, cut to length, stained black, and planed so that it matched the profile of the neck. The individual frets were then measured and cut. These were then inserted into the fingerboard with a small hammer and the ends shaped using a file. The fingerboard was then glued to the neck and allowed to dry.

Figure 28. Attaching the Fretted Fingerboard

At this point it was time to write up the electronics. For the Carboncaster's electronics I decided to use Jimmy Page's Les Paul wiring configuration. This was because it seemed to offer the most versatility of control and sound. This configuration uses two humbucker pickups, four push/pull potentiometers, and a 3-way switch. The four potentiometers provide a tone and volume knob for each of the humbuckers and also act as a switch if pushed or pulled. For instance, pulling the tone knobs for each of the pickups switches the internal wiring of the two electromagnetic coils in the humbucker from parallel to series (and visa versa), while pulling the bridge pickups volume knob switches the wiring between the two pickups from parallel to series (also visa versa). Pulling the neck pickup's volume knob switches the outputs of the two humbuckers from in phase to out of phase. The 3-way switch is used to select which pickup's output will be sent to the amplifier. Forward selects the neck pickup, backward selects the bridge, and middle selects both. This setup was a bit complicated to put together but was definitely worth the effort. A schematic for the Jimmy Page wiring configuration is given below.

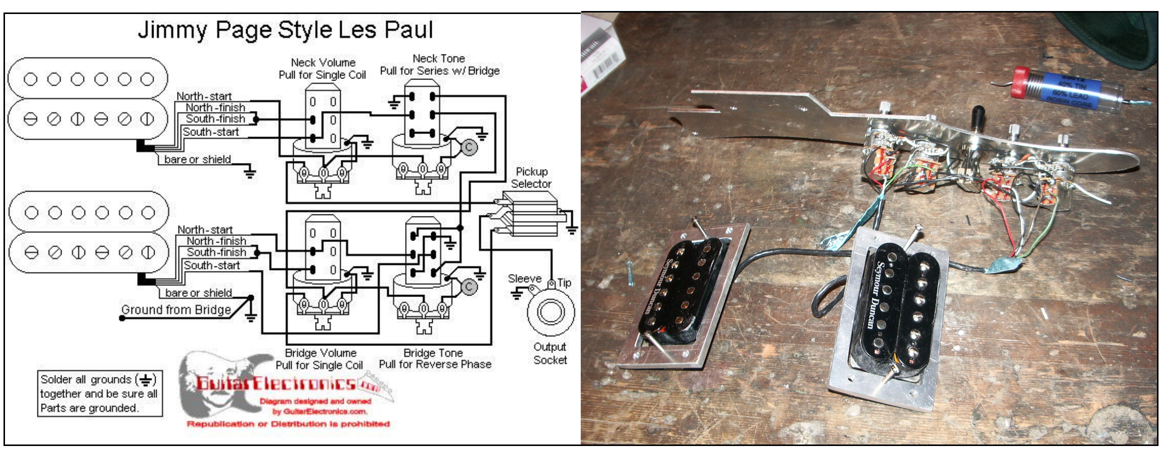


Figure 29. Electrical Wiring Schematic

With the electronics complete, all that was left to do was put everything together.

Figure 30. The Carboncaster

Chapter 6: Testing

With the Carboncaster finished, vibration testing was needed to determine the differences between its hollow, carbon-fiber guitar body and the solid, wooden body of the Stratocaster that was tested earlier. The same experiment was done one the Carboncaster using the exact same hardware as before.

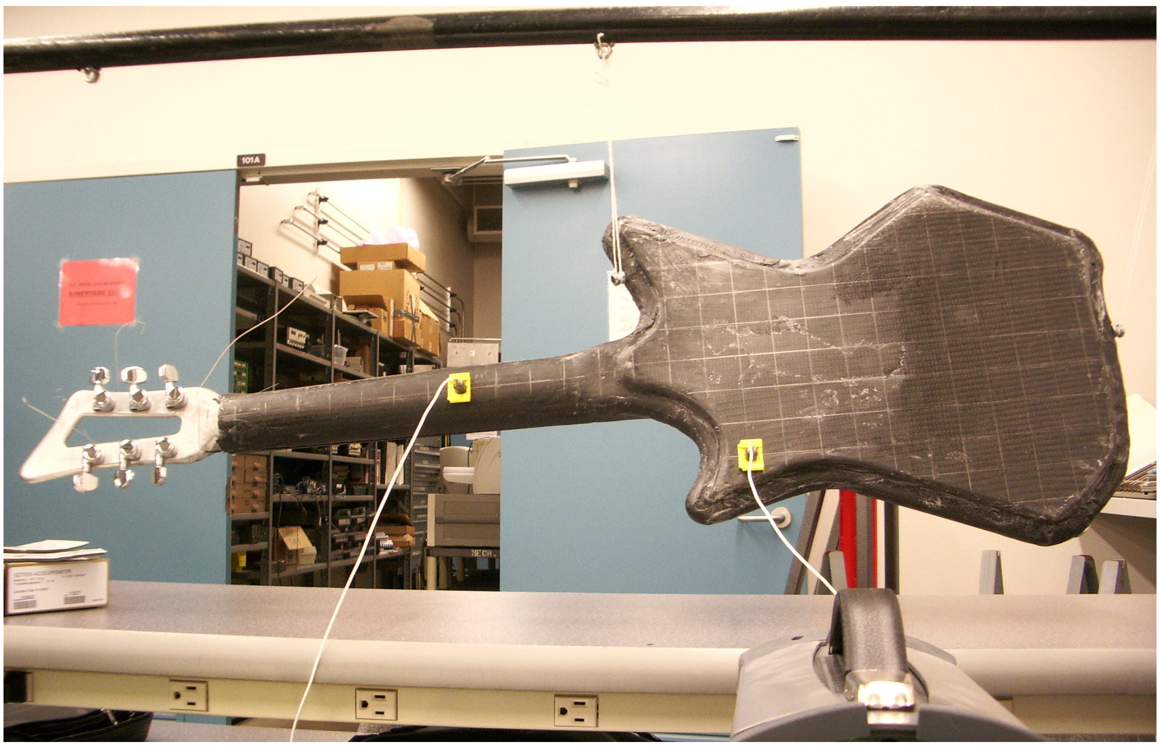


Figure 31. Modal Vibration Test Setup

The guitar was instrumented with the same accelerometers in roughly the same places and hit three times with the hammer on 113 measurement nodes. The magnitude and coherence data from the accelerometers was again transferred to the STAR Modal program to determine the natural frequencies and bending modes of the instrument. The results of this experiment are given in the following section.

Chapter 7: Results

The results of the vibration testing of the Carboncaster are quite promising. The next five figures show the first five mode shapes and frequencies of the guitar as identified by STAR Modal.

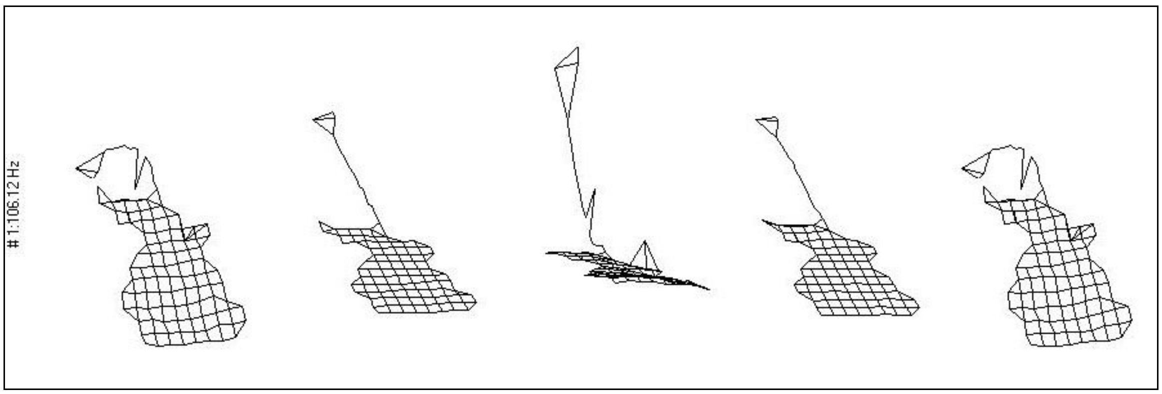


Figure 32. Prototype First Mode: 106 Hz

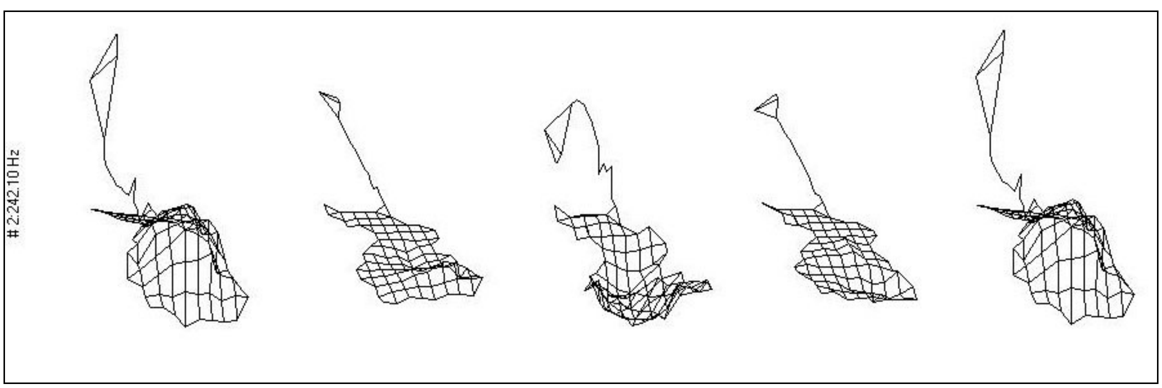


Figure 33. Prototype Second Mode: 242 Hz

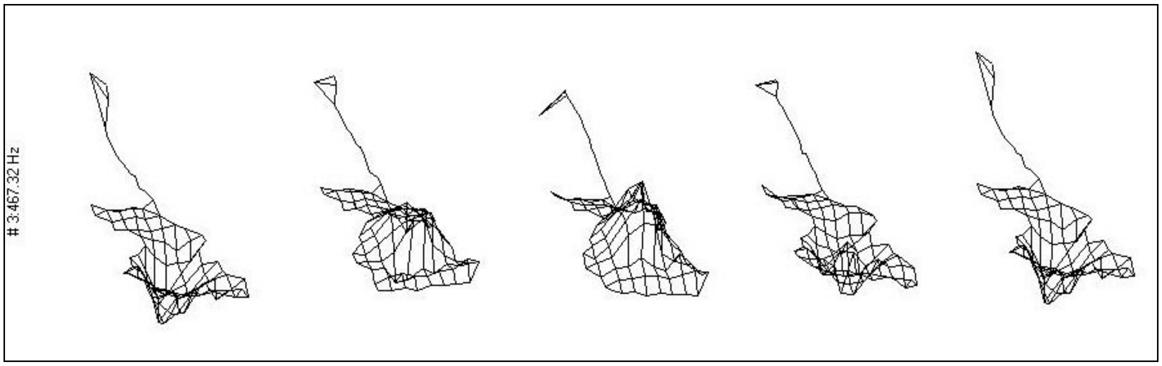


Figure 34. Prototype Third Mode: 467 Hz

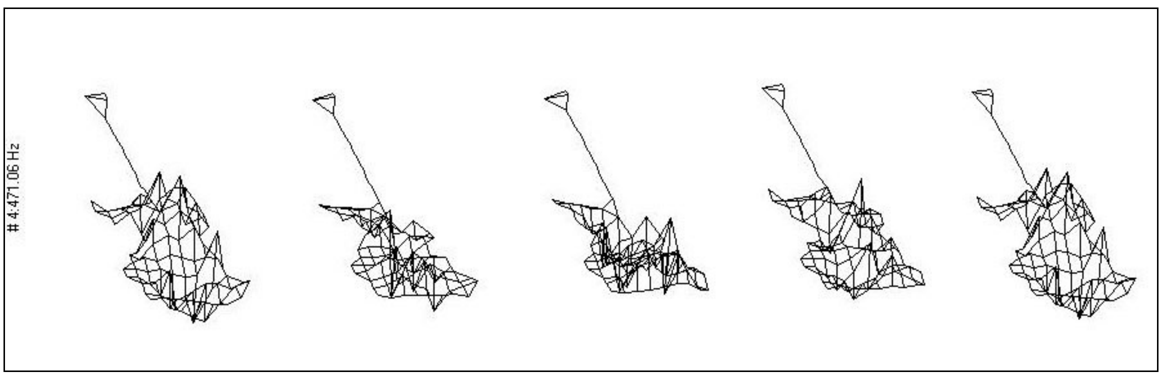


Figure 35. Prototype Fourth Mode: 471 Hz

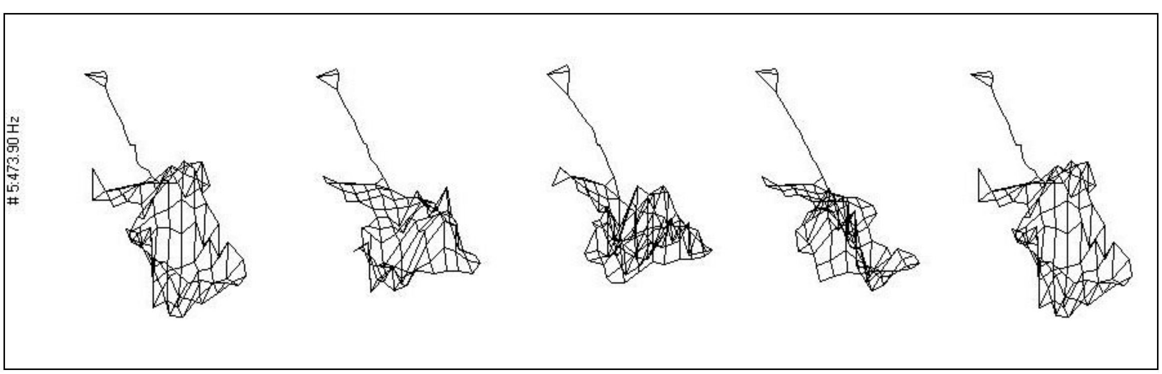


Figure 36. Prototype Fifth Mode: 474 Hz

The first mode, like that of the Stratocaster, is a bending mode, but while the Stratocaster's first natural frequency occurred at 40 Hz, the Carboncaster's occurs at 106 Hz. The same can be said for the second mode; it is similar to the Stratocaster in the fact that it appears to be a three-antinode bending mode, but it occurs at a much higher frequency. The third, forth, and fifth modes are unlike any of the ones seen for the Stratocaster. They all involve vertical oscillations in the body with little or no neck movement, and they all occur in a very small frequency range.

From just those five figures it should be clear that the Carboncaster is much stiffer than the Stratocaster. Solving equation (3) for both should show this as well. The measured weight of the Stratocaster is about 7 lbs, or about 31 N. The Carboncaster weighs in at about 9 lbs, or 40 N. This extra weight could be due to the fact, as was mentioned before, that the aluminum inserts inside the guitar were oversized, or also because the headstock is a solid block of aluminum. Either way, these weights translate into about 3.16 kg for the Stratocaster, and about 4.07 kg for the Carboncaster. Using these values, the values of the measured fundamental frequencies of both guitars, and equation (3) the stiffness of the two guitars can be calculated:

$$\omega_n = \sqrt{\frac{k}{m}} \quad \Rightarrow \quad k = \omega_n^2 m ,$$

k_{Strat} = (40 Hz)^2(3.16 kg) = **5,056 N/m**

k_{Carbon} = (106 Hz)^2(4.07 kg) = **45,730 N/m**

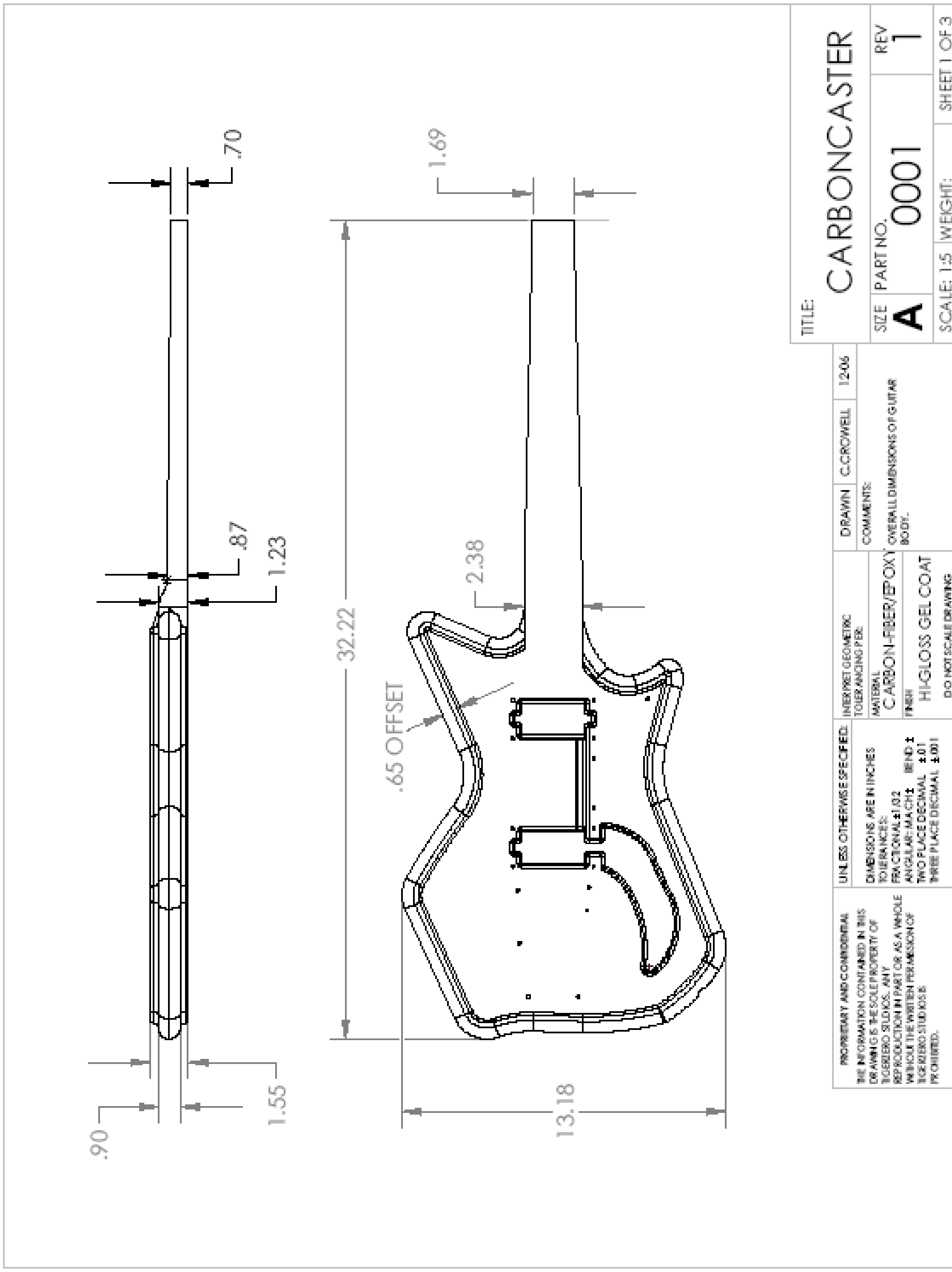
As this shows, the Carboncaster is approximately *nine times stiffer* than a commercial Stratocaster.

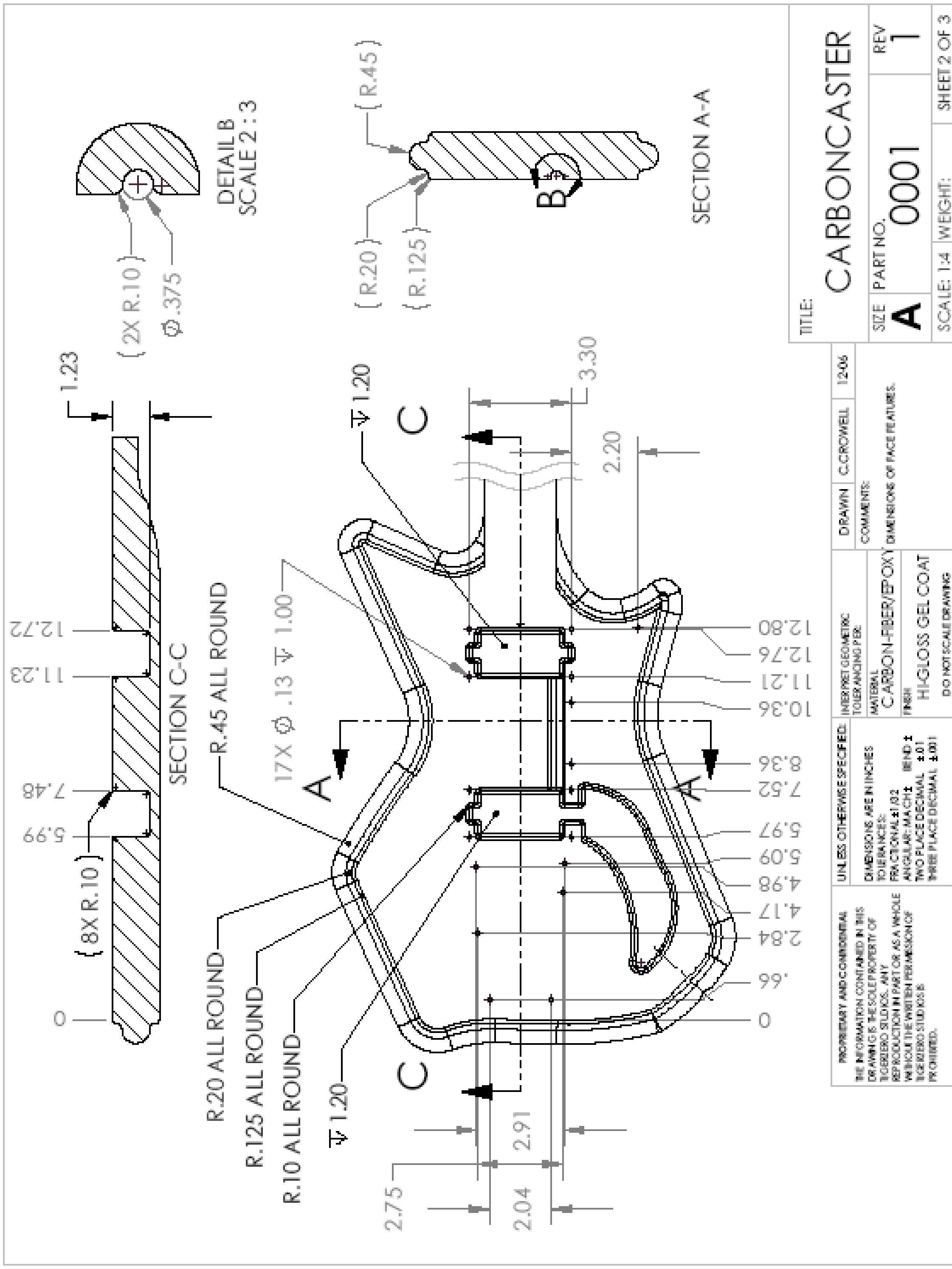
Chapter 8: Conclusions and Recommendations

From the test results it is clear that the Carboncaster is in fact stiffer than a commercial hardwood guitar. It is also playable; the electronics work and it can be played just as a normal guitar would be. It is robust; the thickness of the carbon-fiber laminate skin should more than keep the neck from buckling or yielding in compression. The sustain is comparable to a standard guitar, and the tone quality is excellent. It is a little heavier than intended, but most likely for reasons previously mentioned. Based on these criteria it would seem that the project was almost a complete success!

There are improvements to be made on the design, to be sure, but as a novice in both the areas of making guitars and using composite materials, I feel this guitar serves as an excellent proof-of-concept. I feel that for the next guitar, now that the construction process has been somewhat established, a little more time should be spent on design. I also think that more testing should be done on other commercial hardwood guitars. What are the characteristics of other guitar models? What are the differences between guitars of the same model? What about other materials or other design alternatives? Fiberglass or Kevlar? Wood or foam core? There are many aspects of this project that could use further investigation. But for this project, for this guitar, I believe that I've accomplished everything that I set out to do. And I wouldn't be surprised that if in the coming years more and more people are making electric guitars from composite materials.

Appendix A. Detailed Schematics




CARBONCASTER
TITLE:
SIZE
A
PART NO.
0001
REV
1
SCALE: 1:4
WEIGHT:
SHEET 2 OF 3
DRAWN
C.CROWELL
12-06
COMMENTS:
DIMENSIONS OF FACE FEATURES.
MATERIAL
CARBON-FIBER/EPOXY
FINISH
HI-GLOSS GEL COAT
DO NOT SCALE DRAWING
SECTION A-A
DETAIL B
SCALE 2 : 3
SECTION C-C
(2X R.10)
⌀.375
(R.45)
(R.20)
(R.125)
1.23
(8X R.10)
R.45 ALL ROUND
R.20 ALL ROUND
R.125 ALL ROUND
R.10 ALL ROUND
17X ⌀ .13 ↧ 1.00
↧ 1.20
↧ 1.20
3.30
2.20
2.91
2.75
2.04
0
5.99
7.48
11.23
12.72
12.80
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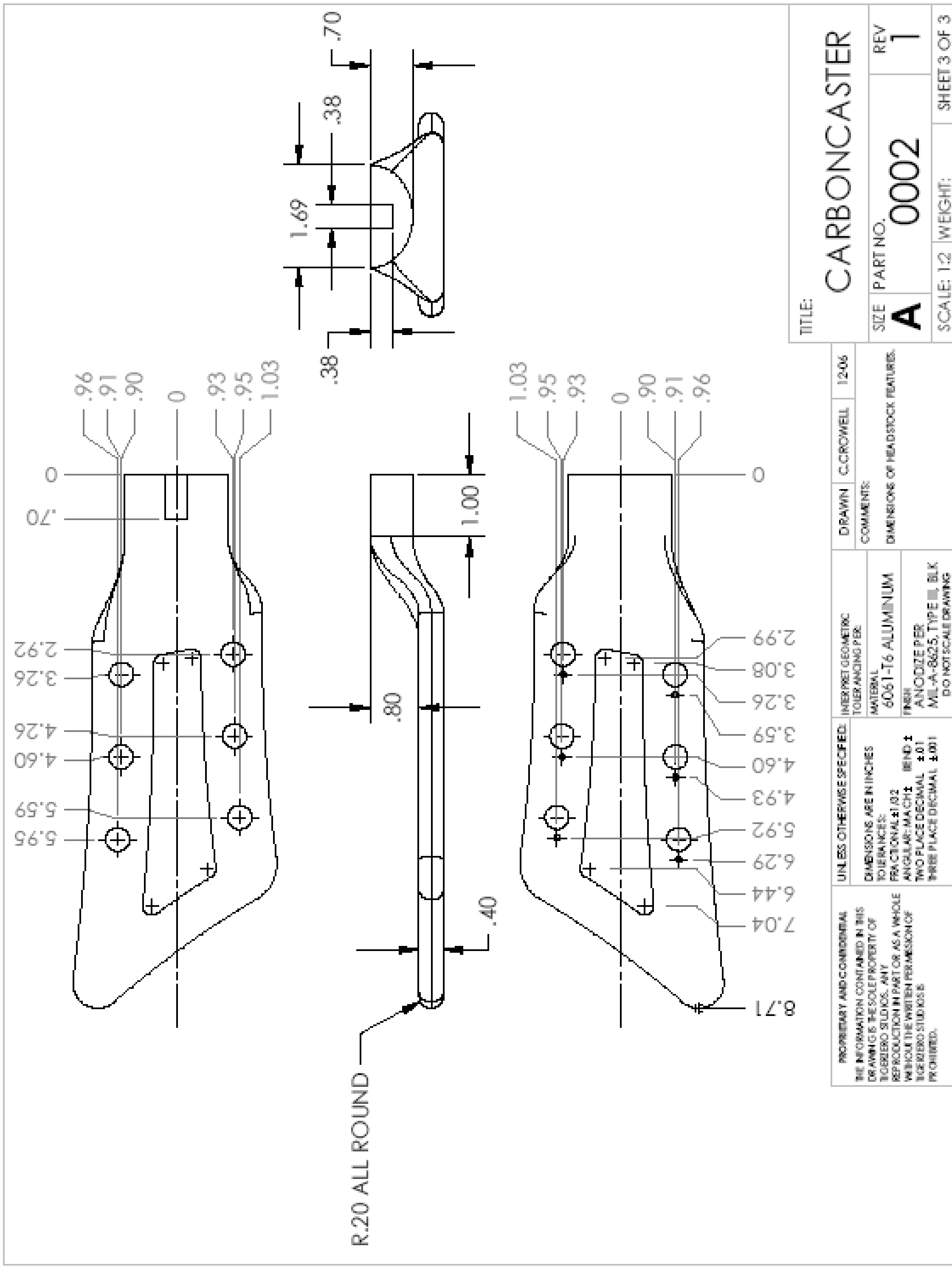

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.70
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3.26
4.26
4.60
5.59
5.95
1.00
.80
.40
R.20 ALL ROUND
2.99
3.08
3.26
3.59
4.60
4.93
5.92
6.29
6.44
7.04
8.71
TITLE:
CARBONCASTER
SIZE
A
PART NO.
0002
REV
1
SCALE: 1:2
WEIGHT:
SHEET 3 OF 3
DRAWN
C.CROWELL
12-06
COMMENTS:
DIMENSIONS OF HEADSTOCK FEATURES.
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061-T6 ALUMINUM
FINISH
ANODIZE PER MIL-A-8625, TYPE III, BLK
DO NOT SCALE DRAWING
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001
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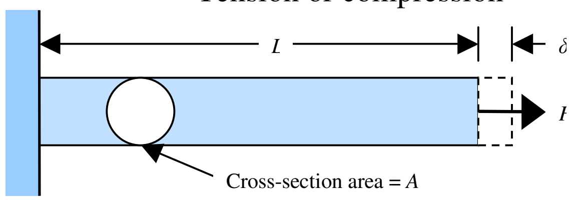
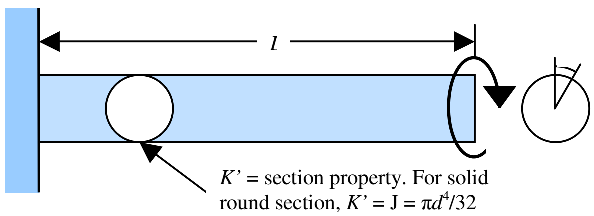
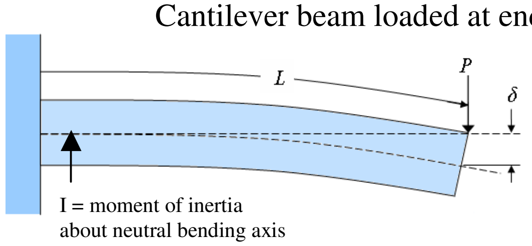
Appendix B. Supporting Material

Table 4. Deflection and Stiffness Formulas for Straight Bars of Uniform Sections[2]

Number	Case	Deflection	Spring Rate
1.	Tension or compression 	$\delta = \frac{PL}{AE}$	$k = \frac{P}{\delta} = \frac{AE}{L}$
2.	Torsion 	$\theta = \frac{TL}{K'G}$	$k = \frac{T}{\theta} = \frac{K'G}{L}$
3.	Cantilever beam loaded at end 	$\delta = \frac{PL^3}{3EI}$	$k = \frac{P}{\delta} = \frac{3EI}{L^3}$

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3. John Collen, Analysis of Stress Concentrations in an Electric Guitar Neck Joint, Thesis Paper (California State Polytechnic University, 2004) pg. 11.
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5. I. M. Daniel, O. Ishai, Engineering Mechanics of Composite Materials, 2^{nd} Edition (New York: Oxford University Press, 1994) Chapter 2.

Special thanks to: Andrew Davol, George Leone, Charles Birdsong, Larry Coolidge, Lee Josephs, Jim Meagher, Nicholas Keleshian, the HPV team, the hangar shop techs, and everyone else who provided insight and support for this project.