Design, Manufacture and Analysis of a Carbon Fiber Epoxy Composite Acoustic Guitar

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

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1 Introduction

1.1 Origins of the Classical and Steel String Guitar

Richardson [1] chronicles the evolution of the guitar quite well, beginning with the a description of what the earliest stringed instruments looked like and then continuing with the earliest guitar-like instruments:

> Following the death of Mohammed in 632, Arab Moslems became a major political force, overtaking lands to the west along the Mediterranean coast of Africa and north into Spain…they took with them a group of instruments known as *al' ud*, literally meaning "of wood," a word which was later transformed into "lute." *Al' ud* was the successor to much earlier pear-shaped Egyptian and Persian instruments, which were carved from solid wood and incorporated a sound-board made from stretched animal skin. By contrast, *al' ud* was made entirely from wood.

He continues to describe this early four-fretted, four-stringed instrument which could only produce 20 notes, and how it changed into the very artful renaissance lute. While the Moors were in power in southern Spain for 600 years, more guitar-like instruments had come into existence:

> These were known collectively as *guitarra*. They differed from *al' ud* in that they were of box construction, with their soundboards and back plated separated by pairs of ribs (sides). By the fifteenth century, two forms of *guitarra* were in common use: the six-course *vihuela de péñola*, and a smaller, less refined four-course "guitar." Courses refer to pairs of strings tuned either in unison or octaves…

The *vihuela de péñola* was quite similar to the modern guitar in that it had the incurving waist, flat back and angled peg-head. This instrument was played with a plectrum (pick) but changed to the *vihuela de mano* which was played by plucking with the fingers and thumb (Figure 1.1). The four-course guitar was considered of lower status, Richardson hypothesizes, because it was less difficult to play.

Figure 1.1. Orpheus, from Greek mythology, playing a vihuela de mano. Frontpiece from the famous vihuela tablature book by Luis de Milán [2].

By the end of the sixteenth century the vihuela was no longer in style, having been replaced by the five-course guitar with the courses tuned the same as the upper five strings of the modern guitar. At the end of the eighteenth century a sixth string was added and double strings were no longer in use (today's mandolin, tuned the same as the violin, is a four-course instrument). During the beginning of the nineteenth century many more changes were happening to refine the guitar:

> A longer, raised fingerboard with the twelfth fret at the body joint facilitated playing in the upper range. As a consequence, the bridge was raised to a more central position and the use of a bridge saddle created a cleaner sound. The carved rose and most of the excessive ornamentation was abandoned to produce guitars of beautiful simplicity. But there

> were more subtle changes occurring inside the instrument. Influential makers such as Josef Pages of Cadiz and Louis Panormo of London were beginning to develop a rudimentary system of fan-struts to support the bridge in its new, more vulnerable position. These replaced the simple lateral bars used in the lute, vihuela and early guitars.

The final tweaks to the now established design of the classical guitar were made by Antonio de Torres Jurado (1817-1892) who increased the size of the sound box and improved the bracing system. Part of the success of Torres is due to his partnership with Tárrega who composed, played, and taught guitar music. Tárrega's music played by him and his pupils has helped the guitar reach the heights of popularity that it has attained today.

Around the same time Torres was improving the classical guitar, the steel string guitar was being developed in the United States. Christian Fredrich Martin, with fourteen years of training under the Viennese maker of guitars and other instruments (Stauffer) immigrated to New York and opened a shop in 1833 [3,4]. Eventually he moved out of the city to Nazareth, Pennsylvania (where a large number of German immigrants settled) and spent the rest of his life there. The X-bracing system which is a standard feature on steel string guitars today is accredited to Martin. Initially the X-brace may have been developed in order to save wood over the fan bracing system, but when guitars began to be strung with steel strings (around 1900) the X-brace was able to handle the higher tension with slight modification. Steel strings were used to enable the guitar to hold its own against louder instruments such as the banjo, mandolin and fiddle. By 1920, the X-brace was an industry standard. Martin Guitar Company is also accredited with increasing the length of the neck such that it met the body at the 14th fret as opposed to the 12th for the purpose of making it more versatile. The classical guitar still has a 12 fret neck. Martin developed the Dreadnought guitar, which had a larger body, to be a better accompaniment for singers. This body style is characteristic of a standard steel string guitar.

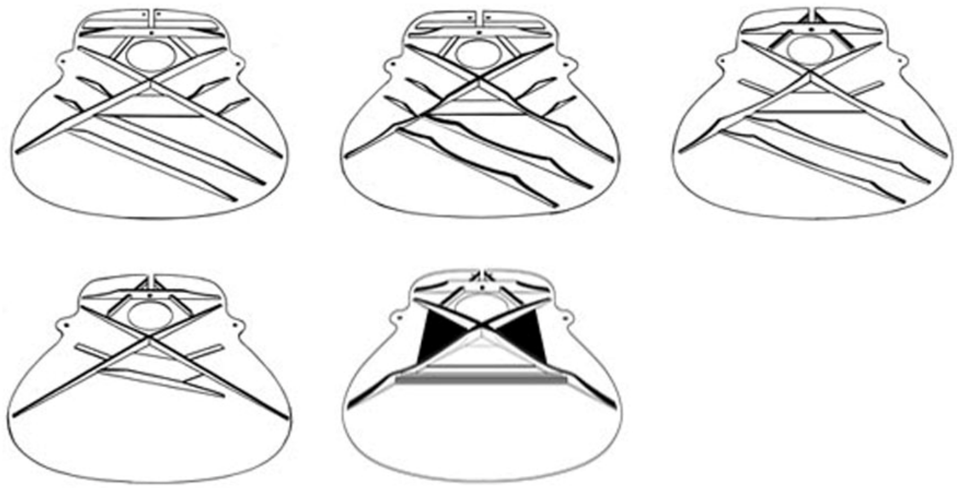

Figure 1.2. Guitar tops with various forms of X-bracing used by Martin Guitar Co. [4].

Since Martin and Torres' innovations, many guitarmakers, called luthiers, have tried their hand at the craft. This has lead to many different guitars using different woods and body shapes. Some common body styles are concert guitars which have a smaller body and a tighter waist, and jumbo guitars which have a larger body for deeper sounds. Other design innovations have occurred such as the NT neck design of Taylor Guitars which allows for easier adjustability of the neck and also the bridge truss system developed by Breedlove Guitars to relieve some of the string tension from the top allowing for thinner, more responsive tops. Many one-off luthier experiment with many additional designs in an effort to improve the sound quality of their guitars.

1.2 The Anatomy of a Guitar

In order to better understand the following chapters, a common lexicon will be helpful. Figure 1.3 shows the basic anatomy of an acoustic guitar using the CAD geometry created in the design process. Missing from this diagram are some of the interior features of the guitar which are shown instead in Figure 1.4 which shows a cutaway of the guitar along the centerline. Near the heel of the guitar inside the sound box (i.e. body) is a block of wood called the neck block which is where the neck is attached to the body of the guitar. There is also a block of wood called the tailpiece which secures the sides of the guitar together. Seated in the tailpiece is an endpin, used to attach a strap to the guitar and may also have an electric "jack" for amplifying the guitar.

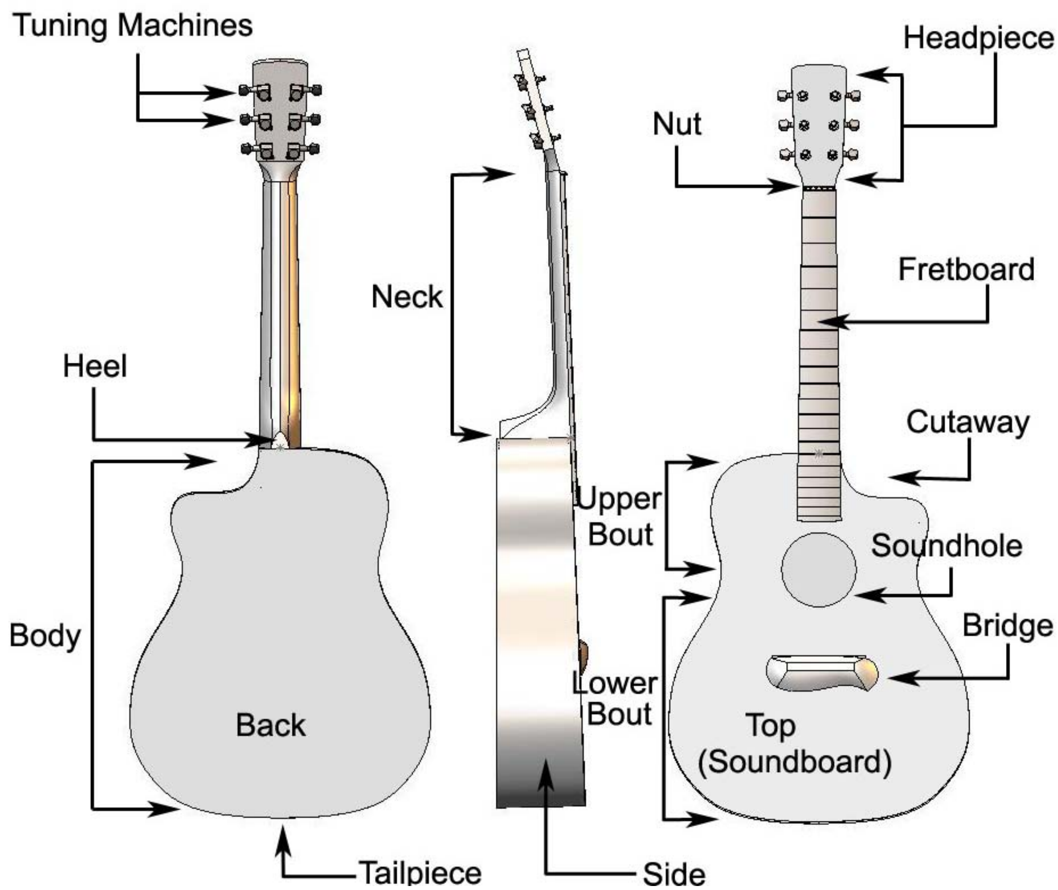

Figure 1.3. Anatomy of an acoustic guitar.

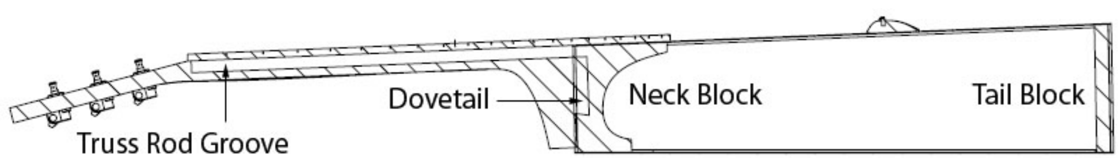

Figure 1.4. Cutaway view down the center of the guitar revealing the truss rod groove, the dovetail joint and the blocks.

Traditionally a truss rod is fit into a groove of varying depth carved into the neck beneath the fretboard; the curve of the rod acts against the string force and stiffens the neck. Instead of this traditional method, a double rod was used which was fit into a uniform groove. The ends of the rods are threaded into brass blocks and are adjustable so that one is in tension and the other in compression, which has the same effect as the curved truss rod. Recently guitarmakers have started using graphite-epoxy bars instead of rods, but these bars are not adjustable by a nut as the rods are. In traditional guitars light wooden beams are bonded to the underside of the soundboard to prevent it from collapsing under the tension of the strings. These braces are not necessary in a graphite guitar because the layup can be engineered with the appropriate amount of stiffness.

An explanation of the purpose of some of the components of the guitar might also be useful. Starting from the top of the diagram, the tuning machines are pinion-worm gear assemblies that are used to tension and relax the string. The nut of the guitar is a piece of bone or hard plastic and serves as one end of the scale length (also known as the speaking length) of the strings. The fretboard is slotted to receive metal frets which are used to discretely break the continuous range of notes that could be produced by the strings into select frequencies which can be made into pleasing combinations to the human ear. There are 20 frets on the guitar placed on a log scale. The neck is joined to the body of the guitar at the fourteenth fret. The heel of the guitar is alike to a butted joint which supports the bending moment caused by the strings.

The cutaway in the guitar is not primarily for sound purposes, but allows the guitarist facilitated access to the frets numbered higher than fourteen. The sound hole of the guitar is often mistaken to be the primary location where the sound waves emanate, which is not accurate. The sound hole, contrary to its name is a vent to allow the top of the guitar to vibrate up and down, much like a sub-woofer has a vent to allow the speaker to move. Though some sound does come from the sound hole, especially with air resonance modes and coupling to the structural modes, the majority of the acoustic power of the guitar comes from the center of the lower bout of the guitar where the bridge is. The oscillations of the strings couple with the top of the guitar and move this area like a speaker. The bridge is used as the link between the strings and the guitar top. Not shown in the cutaway view is a bridge plate which lies underneath the soundboard (behind the bridge) and gives added stiffness to the top, preventing it from deforming unduly. Fitted into the bridge is the saddle of the guitar which is the counterpart of the nut and defines the other end of the strings’ speaking lengths. A slight angle is applied to the saddle such that the length of the strings varies from one to the next; in addition the shape of the saddle where each string crosses is varied slightly. These alterations to the saddle shape and positioning are called compensation and as the name suggest, they compensate for the strings’ deviation from an ideal, “physics” string by altering the scale length. Bridge pins (not shown) are inserted into holes in the bridge and hold the end of the strings in place. The sides of the guitar provide for the air cavity and thus alter the fundamental frequencies of the guitar system by allowing coupling between the top and back. The sides of the guitar contribute negligible sound radiation. The back of the guitar does not contribute a great amount of sound especially since it rests against the chest of the guitarist and is thus damped considerably.

1.3 Luthiers Dilemma: Tradition and Innovation

The steel string guitar is in a state of transformation. This versatile instrument is used to create so many diverse forms of music each with different playing styles, rhythms and accompaniments. To bring out complimentary aspects of the instrument a host of differing methods of construction are used. The construction of similar instruments, such as the classical guitar, which is of the same genus, or the violin, which is of the same family, have long had the book closed on the proper way to construct the instrument. This is because the musical forms that accompany these instruments are strongly established. However, the music played on the steel string guitar is still being invented and is so far removed from its roots that only a skilled musicologist can hear the relation.

Furthermore, musical forms and styles are altered everyday due to the acceleration of cultural diffusion across the internet. Any small-time musician or musical group can share their music with the world via a website or an online social network. This diffusion adds doubt to the thought that "the book" on how the guitar might ever be closed. In addition, the hyper-interconnectivity of current society is causing musical communities to re-visit the norms of how music is created on the steel string guitar's older relatives.

The influence that the many evolving styles of making music have on the design and crafting of the steel string guitar is drastic. The result is that there is no "right way" to build a guitar. There are guidelines that change based on the style of music that is to be played, but these are open to interpretation and innovation. The construction processes and design components for wooden guitars are challenged repeatedly as luthiers[1] strive to improve and perfect. Additionally, the materials that are used to make guitars are tested and re-evaluated. As large amounts of rare wood are devoured by the furniture industry and others, the need to conserve what remains leads many luthiers to consider different wood sources. By the same influence, builders are turning to new materials such as composites and plastics for the critical radiating components of the guitar [5, 6, 7 and 8].

The tradition of building guitars incorporates a lot of artistry, know-how and empirical evidence, but no rigorous scientific process. In recent years, however, more builders have begun to use scientific methods to improve their product. It is said that anything that is changed with respect to the construction of an instrument changes how it sounds; the art of a good luthier is to know which changes have the largest effect. Thus the luthier's dilemma is the ability to modify and innovate the design of the guitar while remaining tied to the traditions that have worked. Acoustic research is beginning to facilitate innovation by revealing the various ways that the components of the guitar contribute to the overall sound.

[1] Luthiers are stringed instrument makers.

1.4 Acoustic Research

A great amount of work has already been done to characterize stringed musical instruments. The vast majority of this work has been in regards to the violin which is similar to the guitar in several respects. The guitar has been studied by several research groups, most of which has focused on the classical guitar. The extent to which a musical instrument has been studied is due to the degree of popular acceptance of the instrument, how long it has been in use, and the standardization of construction. These criteria lend motivation to the researcher because they show that the instrument is interesting to the general population and that research on a sample set of instruments is applicable to the entire population. This is the reason why folk or steel string guitars have been ignored for the most part in the research community. Although the steel string guitar is popular, probably more so than the classical guitar, the construction process is quite variable and the instrument has not been around as long (two factors which are obviously related).

1.4.1 Measurement Techniques

Many decades of research in musical acoustics along with even more research in related fields of vibration have brought forth a myriad of creative ways to measure quantities pertinent to the study of guitars. One of the most important measurements that is taken in musical acoustics is the mapping of the mode shapes of the vibrating cavity. The shapes of these modes influence how they couple to various structural components and affect how sound is radiated. One of the first ways that the mode shapes were measured was by Chladni or nodal line patterns. These were created by sprinkling fine granules of salt or sand on the relatively flat top and back plates, exciting the instrument at its modal frequencies, and then observing the nodal lines that collected the granules [9]. From the nodal lines the mode shapes are inferred. This method works best for guitar plates before they are assembled; they become curved once the guitar is constructed and cause the powder to slide off the edges.

So-called “modal analysis” is a more refined approach which provides more information about the amplitude of the modes. Modal analysis is performed by exciting the guitar by tapping it with a hammer and then measuring the impedance at locations across the surface in question [10, 11 and 12]. The hammer gives an approximate force impulse that excites all resonance frequencies which are superimposed since the guitar plate is a linear system. This is done primarily in two ways. The first is to tap the bridge or another location on the guitar with a hammer and then measure the response at an array of points on the surface with an accelerometer. This method has the disadvantage of adding mass to the system which slightly alters the frequencies observed. The second method which is called the “roving hammer” method is to measure the response at a single location (such as the bridge) and excite the guitar with the hammer at various points on the guitar surface. The magnitude of the response at the bridge indicates the amplitude of the mode shape at that point. Recent work has been done to use impulsive air impingement to excite the guitar rather than a hammer [13].

In order to eliminate the added mass of the accelerometer, touch free measurement systems such as a laser vibrometer are used to measure the response. The laser beam is split with a semi-transparent mirror into a measuring and reference beam. The measuring beam is reflected off the surface to be measured and the phase is compared with the reference at the sensor head. The frequency spectrum is calculated by fast Fourier transform methods. Scanning laser vibrometers are used to measure the whole surface very quickly, eliminating the need to take hundreds of measurements, thus increasing the accuracy of the result. They have also been used to measure the planar sound field in air [14]; the changing refractive index due to the varying density alters the phase of the laser enough to be sensed.

Instead of using an impulsive force to excite the guitar at all frequencies which leaves the need to deconstruct the superposition of the mode shaped, the guitar may be driven by a sinusoidal force in order to pinpoint resonance frequencies and mode shapes. This has been done by affixing a magnetic cylinder to the bridge and then actuating it using a sinusoidal current through a coil around it. Again, this method adds mass to the system. The guitar can also be driven by a force generated by an acoustic pressure wave from a speaker.

Various forms of holography are used to visualize the mode shapes of the guitar with the advent of the laser in 1960 and allowed better visualization of assembled instruments [9]. Unfortunately preliminary methods required clamping of the guitar which imposed inaccurate boundary conditions. Later development of speckle interferometry or electronic (TV) holography allowed for visualization of the modes in real time [15]. A diagram showing the basic hologram creation process can be seen in Figure 1.5.

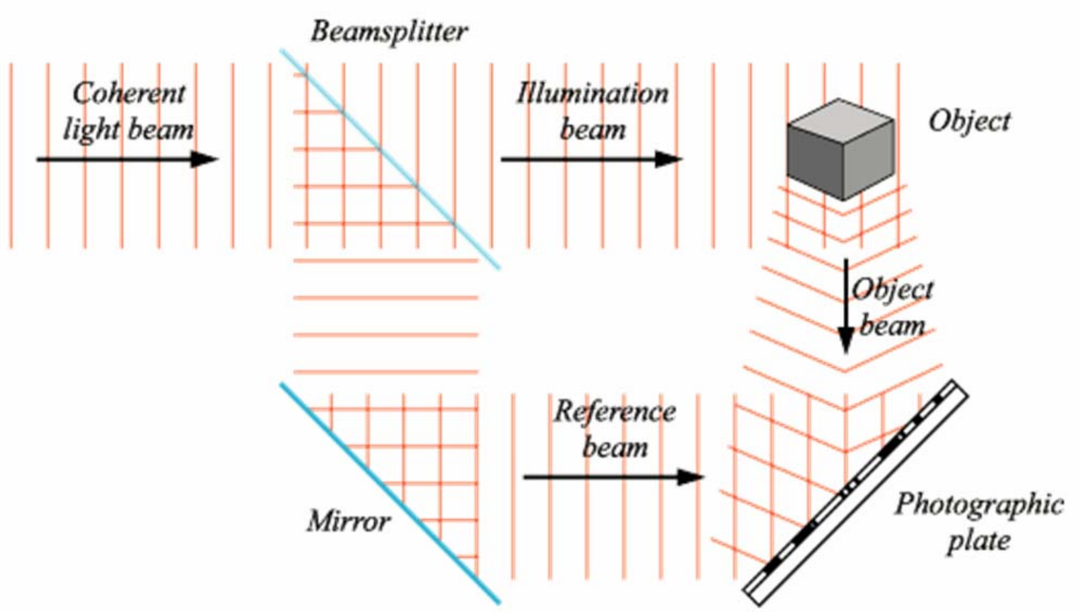

Figure 1.5. Creation of a hologram, the principle behind interferometry measurements [16].

The standard manner to capture the sound radiated from an instrument is to record the frequency spectrum a meter away from the center of the top plate. This frequency spectrum is often taken in addition to structural vibrations to correlate these two results. A more elaborate method to determine the directional sound field is to use a microphone torso. This method employs an array of microphones placed along a semi-circular fixture equidistant from the center of the sound board. The torso is able to rotate such that sound pressure levels can be recorded on a hemispherical surface around the instrument.

Ideally instruments are tested in an anechoic chamber so that reflections and environmental noise do not influence the measurements. It is also important to consider the fixturing of the instrument. Often it is suspended by elastic supports to give it free conditions. Free conditions are also imposed on top and back plates that are measured, although this does not simulate the conditions of the plate once mounted to the sides of the guitar. Plate measurement is important because the practice of luthiers is to listen to plates while selecting wood to determine its quality, as well as for tuning when the thickness of the plate is being adjusted [17]. In order to eliminate coupling of the top to the back and sides, guitars have been partially buried in sand while testing [18]. Little has been done to try to simulate the actual boundary conditions of the guitar while playing as these are difficult to simulate and are not very consistent between players.

1.4.2 Violin Research

A great deal of similarities exist between violins and guitars, thus researchers would be remiss if this information was not used to guide studies into the physics of the larger instrument. The most thorough work on the acoustics of violins has been done by Hutchins [19, 20, and 21] whose publications include several exhaustive reviews of the literature. As a researcher and luthier, her goal is to uncover the scientific backing for many of the traditions of violin making that seem to be on the level of superstition. One such example she gives has to do with sourcing wood for top plates:

> The lore of violin making tells us that a spruce tree growing on the north side of a mountain should be cut in the spring when the water is moving up in the wood cells, and that the first six or eight feet of the trunk should be discarded because the twisting and the weight of the big trunk cause increased density in the wood with a less even grain structure…When a flitch is properly cut and joined for a violin top, the annual-ring spacing, or grain, ideally should be narrow in the center of the violin top, gradually becoming wider toward the edges. Also the grain should be vertical to the bottom surface of the top plate. The more researchers study…the more the seemingly unsupported lore of violin making makes very good sense [21].

Hutchins and other researchers like her have avoided separating the validity of tradition and have used feedback from musicians and luthiers in order to guide research. Being an avid luthier herself, Hutchins has done work on building a family of instruments based around the violin that covers the range of classically composed music. An important factor that was discovered in her research is the issue of “sound-masking” which has to do with the power of certain radiating modes being hidden by more strongly perceived modes. This is an important aspect of psychoacoustics which will be discussed later. With regards to violin making, Hutchins has discovered several important aspects of design. For instance, the ratio of the along-grain elastic modulus to that of the cross-grain modulus should be 10:1 for the top plate (spruce) and 5:3 for the back (curly maple). Also, spruce trees grow more slowly later in life which causes densification of the outermost part of the tree. This is why the outer portion of the quartersawn wood that is used for the top plate should be in the center when the two pieces are joined. While investigating why wood for violin making is aged for such a long time (10-20 years for the top and 20-50 for the back), it was found that the ratio of crystalline to amorphous structure in the cell walls of the wood increases with time; this gives a brighter, clearer sound and reduces sensitivity to moisture.

Another question that Hutchins addressed was the concept of “playing in” instruments. Traditionally it is said that violins do not sound good if they are played infrequently, and violins that have not been played for a while should be played in. Evidence for this concept was found when a violin was excited by a classical music radio station for 1500 hours and the frequency response of the instrument was measured before and after. Significant shifts in the peaks of the main modes were observed [21]. The fundamental frequency was reduced by 25 Hz, and once the violin had rested for a while it increased again by 15 Hz.

Fundamental measurements of the violin have been performed which include the mode shapes of the sound box, frequency spectra of the sound field, and vibration of the neck. Dünnwald measured the sound quality (i.e. the frequency spectrum measured by microphone) of 700 violins and compared the quality as judged by five parameters to that of old Italian violins [22]. He found that 23% of the violins' spectra matched that of the standard according to his criteria. Though these results were not corroborated by listening studies, they do beg the question: why are older violins more cherished? Marshall conducted impact measurements on a violin on the range of 0-1300 Hz and measured vibrations in the neck at certain frequencies [10]. He hypothesized that perhaps these neck vibrations contribute to the "feel" of the older, master violins.

The findings and innovations of researches of the violin have results and techniques which can be directly or indirectly applied to the study of the guitar. From the literature it is clear that this has been done to a great extent and the two research communities are in close communication. Indeed, many researchers of the guitar are also researchers of the violin and other instruments as well.

1.4.3 Mode Labeling

Several methods are used for labeling the mode shapes of the guitar. This thesis will use the same convention used by Wright [23] as it is straightforward and seems consistent with most research. The modes are labeled by two numbers; the first being the number of antinodes across the width of the guitar (parallel to the bridge), and the second the number of antinodes along the length of the guitar. The components of interest for sound radiation are the top and back of the guitar, thus the modes numbers will be preceded by a "T" for the top modes and a "B" for the back modes. Due to the coupling of air to the plates of the guitar, some modes appear twice, the first when the plates are in antiphase and the second when they move together. A subscript after the mode numbers indicates the order of the same-shaped modes by frequency. Thus the first mode of the top plate with fluid coupling through the sound box, the plates moving in antiphase, is $T(1,1)_1$. If modes are referred to without a subscript but appear twice, then both modes are meant.

Some researchers discuss the modes of the air in the guitar separately from the structural modes. These "air modes" are often labeled by the letter "A" followed by the mode number which is just the frequency order in which the modes appear.

1.4.4 Guitar Research

Richardson notes that the guitar is a lightly damped structure, thus the admittance (velocity per unit force) is highly dependent on the frequency [1]. In other words, the character of the guitar sound is dependent on a system that is sensitive to the input. This is why small changes to the guitar which affect its normal vibration modes can change the sound of the guitar dramatically. One of the key aspects mentioned by Richardson as often being excluded from measurement and analysis is the effect of the strings [24]. Modeling of the guitar string was done by Wright and measurements were done [23]. In this case the string was mounted on a rigid bar which provided good results, but attaching a string to a guitar complicates the problem. Wright used a creative way to achieve consistent plucking force; a fine copper wire was bent around the string and pulled until it broke. A light sensor called an "opto-switch," was used to measure the string vibration.

Similar to Hutchins, Caldersmith has undertaken work to design a family of guitar-like instruments based around the guitar. He notes that it is unusual that the guitar did not evolve a family on its own the way the violin did with the cello, viola, and bass. The modal frequencies of these instruments are measured [25].

When measuring the response of guitars and evaluating the resonance modes, effort has been made to discover which modes are the most critical to sound radiation and the character of tone. In acoustics it is known that the net sound radiation of symmetric dipoles is zero. However, due to the guitar's asymmetry, dipole guitar modes are not necessarily non-radiating. Christensen notes that the T(1,1), T(1,2) and T(3,1) modes are the main radiators of sound [26]. All researchers are in agreement that the most sound radiation comes from the first mode. Little sound actually comes from the back of the guitar because it is not coupled to the strings and additionally, in a musical setting, the chest of the player and their clothes would dampen these modes.

In seeking to design guitars that produce a certain sound, researchers strive to be able to recreate what they measure. Hill et al. have developed and analyzed characteristics or parameters of the guitar modal frequencies which they deem to be most critical to determining the tone. These are the resonance frequencies, Q-values, effective masses and orthogonal radiation components [27]. To provide quick definitions for these parameters, the Q-value, otherwise known as the quality factor of the mode, compares the time constant of decay to its oscillating period. Thus it compares the frequency to the rate of energy dissipation. Higher Q-values indicate lower rates of energy dissipation. The effective mass is how much mass is "seen" by the strings at the bridge which takes into account the fluid loading. If a mode has a higher effective mass, then more energy must be transferred to oscillate the plate. The orthogonal radiation components refers to the monopole and dipole sources that model the guitar's response which are superimposed for each mode. The researchers were able to deconstruct these parameters from the guitar and then reconstruct them quite accurately with a model of dipole and monopole sources with the same parameters. The accuracy which they achieved shows that the acoustical parameters which affect the tone are well understood. The holography interferograms that were made are shown in Figure 1.6.

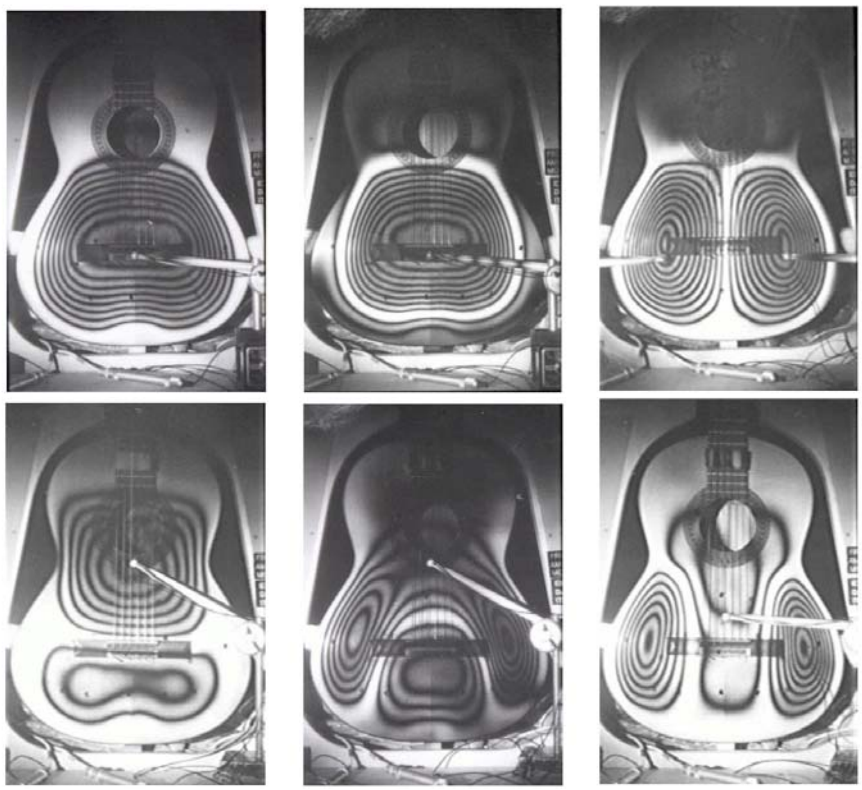

Figure 1.6. Holography interferograms of six guitar modes from Hill et al. [27]. The frequencies are (left to right, top to bottom): 94.5, 182.5, 218.0, 353.5, 417.0 and 458.0 Hz.

Therefore even with an understanding of the significant acoustic parameters which build guitar tone, it is still necessary to know what changes to the guitar construction alter the tone in what way. Elejabarrieta et al. conducted a study where they measured a guitar top plate that was under construction by a skilled luthier [28]. Measurements of the modal and dynamic response were made at various construction steps. This type of experiment demonstrates how the tone is “built” along with the guitar, which by analogy can guide future construction efforts. One of the interesting observations from their work is that as the top was thinned, the sound hole cut, and the edges trimmed, the natural frequencies decreased which showed that stiffness was a greater contributor than the mass. This remained true when the various pars and braces were added which raised the natural frequencies. The change in natural frequencies that they discovered are displayed in Figure 1.7.

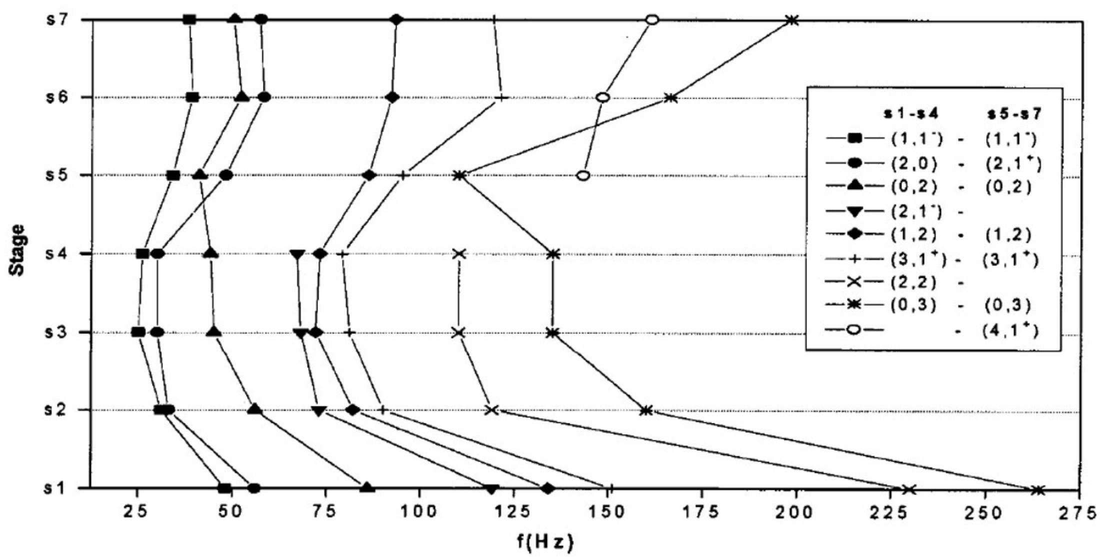

Figure 1.7. Modal frequencies of a classical guitar top plate during construction from Elejabarrieta et al. [28]. The top is thinned, trimmed and the soundhole cut in steps s1 through s4 and braces and bars are added between s5 and s7. The mode numbering schema in the legend is different from this thesis.

1.4.5 Numerical Analysis of Guitars

In addition to mathematical models, numerical models have proven to be useful tools in modeling guitar behavior. Elejabarrieta and his fellow researchers have published a series of papers that have developed understanding of the guitar through a finite element model (FEM) [11, 29, 30 and **Error! Reference source not found.**]. In [29], the researchers modeled only the air inside the guitar and found its modes of vibration, discovering that the modes were sensitive to the bracing pattern. The results that were found for the air modes were then applied in a coupled analysis [11]. First the top and back plates were analyzed on their own (in a vacuum), then they were attached to the sides of the guitar, still without air. Finally the model was coupled to the air model that was created previously. ABAQUS and SYSNOISE software were both used.

ABAQUS was able to perform coupled analysis between an acoustic medium and a structure, and the SYSNOISE was able to use more complicated elements as well as accommodate for the orthotropic nature of wood. The researchers were able to transfer the appropriate matrices between the programs in order to obtain their results. The conditions used were fixed ribs (sides) and the plates had hinged boundary conditions. Adding the sides to the two plates increased the back modes by 15% and the top modes by 7%. They found that the air acts as an added mass and lowers the modal frequencies with its influence being greatest on the lower modes. Their experimental measurements done with roving hammer method. The numerical results were off by 9-40 Hz with the larger errors coming from the higher modal frequencies.

The same numerical model was also used to evaluate what effect the density of the gas in the sound box has on the frequencies [30]. The properties of Helium, Krypton and Air were applied to the previous numerical model and a guitar box was measured while filled with these actual gasses. It was found that the type of fluid in the sound box had a great influence on the air mode frequencies and thus the way that coupling occurred with the guitar. They also found that the mode shapes (structural and fluid, with the exception of the Helmholtz) were not changed with different gasses.

Again these researchers applied their model to a different task which was to observe the effect of wood properties on the modal frequencies of the top plate [31]. Poisson’s ratio, density, elastic moduli and shear moduli were all altered. Poisson’s ratio was found to change the eigenfrequencies almost imperceptibly, but they were decreased according to the inverse square root of density. The frequencies depended most on the in-plane Young’s moduli and the shear modulus. The greatest contributors were the Young’s moduli which caused reordering of some of the modal frequencies as the longitudinal modulus was varied from 7 to 15 GPa and the transverse from 1 to 4 GPa. The first three modes were not affected by Young’s modulus in the direction of the grain, but all were affected by Young’s modulus across the grain. The shear modulus altered the modes a bit, but not as much as Young's moduli although the shear modulus is the only parameter that really affected T(2,2). The results are replicated in Figure 1.8.

The advantage of using numerical models is made clear through the examples presented by this research group. They show that properties of materials and environment as well as slight alterations to construction steps can be simulated without having to construct many instruments. It is not possible to repeatedly un-glue, alter and re-glue a guitar top as the braces are thinned down (for example), but once a numerical model is proven by experiment to match the guitar it models then it is reasonable to assume that small changes to the model will also have accurate results.

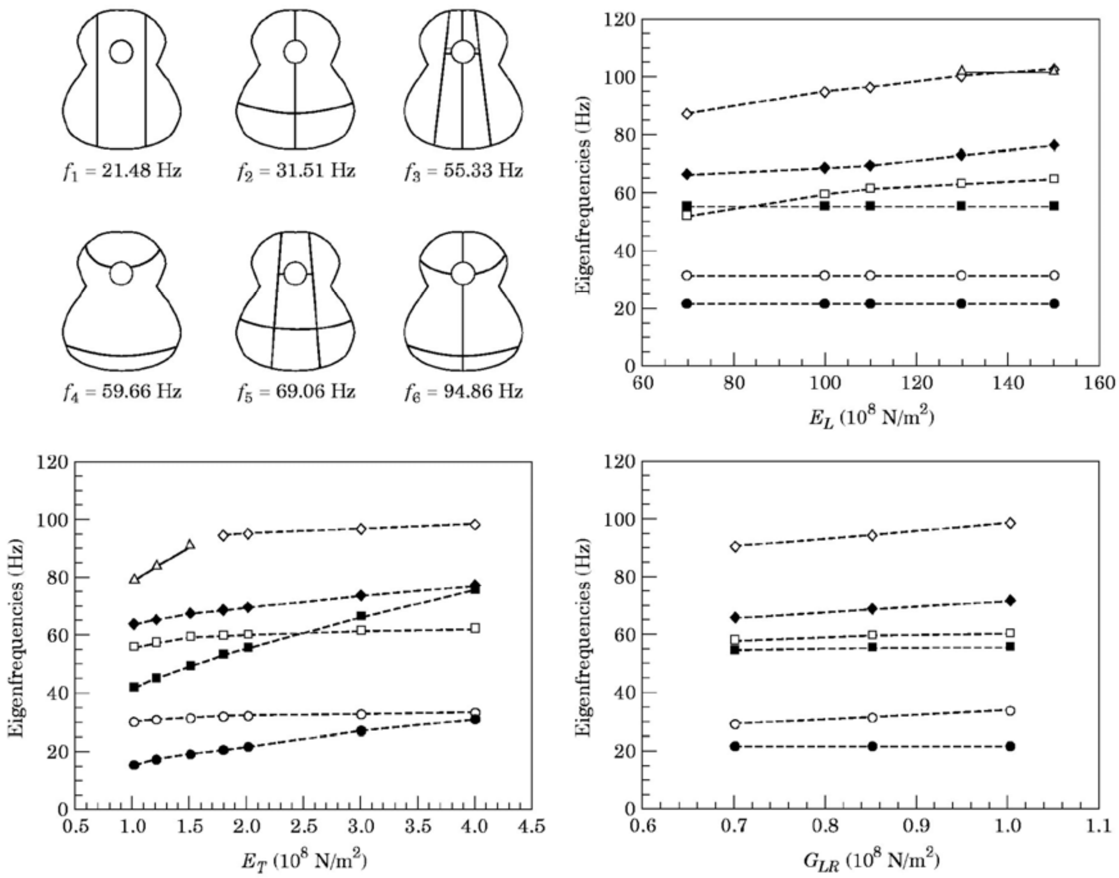

Figure 1.8. Modal frequencies of a classical guitar FEM with changing E_L (elastic modulus along the grain), E_T (elastic modulus transverse to grain) and G_{LR} (shear modulus in-line with the grain with respect to the radial direction). The mode shapes are shown in the upper left by approximate nodal lines. The data is reproduced from [31].

1.4.6 Psychoacoustic Analysis

Even with perfect numerical or mathematical analysis and precision measurement tools, research is not of use unless it is guided and influenced by musicians and luthiers whose ears have been trained to hear the fineness of musical instruments. As Wright quotes from Yehudi Menuhin, the American violinist and conductor: “There is no such thing as music divorced from the listener. Music, as such, is unfulfilled until it has penetrated our ears.” Thus many researchers have used studies of the human perception of sound (psychoacoustics) to determine what makes music pleasing. A very small subset of this field is related to guitar and other stringed instrument research.

An important aspect of this research is to accurately analyze how humans perceive sound and use the resulting knowledge to design ways to get meaningful feedback. This is difficult to do since beauty is truly in the ear of the hearer. The task then is to be able to create a lexicon of agreed-upon musical descriptors that allow less subjective grading of instruments and music. Once this is accomplished, the grades that are given must be found consistent. Then a scientific analysis must be correlated to the results.

An early example of psychoacoustics in practice comes from Rohloff who found that the transients in the 4-8 kHz range were to a large extent responsible for the perceived quality of tone as opposed to the steady state region [32]. This work is complimented by Jaroszewski et al. who found the following.

> Sounds characterized by a very rapid initial transient were often defined as 'hard,' 'flat' or 'noisy' and were scored low. On the contrary, high scores were mainly assigned to sounds rising slowly in loudness and usually defined as 'soft' or 'pleasant' [33].

Thirteen well-differentiated guitars were used in the study. It was found that the higher quality guitars had long onset times (time to 90% maximum loudness) and a short decay afterwards. The lower quality guitars were the opposite. Three musicians rated the guitar in 0.5 to 1.5 hour sessions over a 6 month period. As found by Wright [23], the transient times of many tones across the scale of the guitar must be measured since they will differ dramatically on the same instrument depending on how the string couples to a structural mode of the guitar.

The importance of a blind study for musical acoustics has been understood as early as 1941 when a study was done in which Stradivarius violins were played alongside modern violins [34]. If a listener can see that a guitar or violin is a master class instrument, then they are liable by their nature to adjust their opinions and hear it as a better instrument, especially if they are already of the opinion that these sorts of instruments are better. Caldersmith makes similar observations in his violin pilot study [35]. He compared two “named” violins with two recently made violins in a blind study. He concluded that the audience (of trained musicians) could not tell the difference between the two categories. He notes that perhaps the perception of old instruments being better came about because of a flood of cheaply made instruments during Europe industrialization in the 19th century. Other researchers found that a variety of guitars of different quality were ranked the same by a blind listening study and also inspection by guitar teachers and students [36].

Šali and Kopač interpreted the pleasance of a guitar tone as the relative combination of consonant and dissonant tone pairs [37]. The higher number and power of consonant tone pairs as opposed to dissonant would indicate a higher quality instrument.

1.5 Carbon Fiber and Composites

Carbon fiber composites have been put to use in many applications for decades and musical instruments have not been exempt. Inherently having a high stiffness to mass ratio and the manufacturing process lending itself well to shell structures, graphite composites are an obvious choice for an alternative to wood in stringed instruments. A selection of graphite composite stringed instruments is shown in Figure 1.9.

Figure 1.9. Carbon fiber instruments. From left to right, a violin, cello, folk guitar and mandolin. The violin and cello are by Luis and Clark and the guitar by RainSong.

Not only are composites a good substitute for wood, but they have advantages as well. Many researchers and luthiers have noted the need to find wood with particular elastic and shear moduli [21, 38 and 39]; carbon fiber allows the part to be designed with specific properties such that repeatable, ideal properties can be obtained every time. In addition, the bracing patterns that are used to strengthen the sound board are not necessary for a carbon fiber guitar, but can be added for traditional tone. It is clear that bracing is not used to enhance the tone of an instrument, but it is necessary so that the sound board does not fail. Therefore, eliminating the bracing system allows for a more resonant top plate which can be made less resonant by choice if necessary [38].

RainSong is the first company to mass produce carbon fiber guitars (about 10 a month). Initially their technology included adding “acoustically dead” material into the layup to dampen some of the bright graphite tone, but they found that musicians appreciated the very bright yet full tone of the composite without extra damping. According to Decker, the inventor of RainSong guitars, wooden guitars damp out frequencies above 1000 Hz, but the composite guitars made by RainSong continue to be linear in their response way past this point giving them a brighter sound. Other advantages of composite guitars is that they are not subject to dimensional variation from changing temperature and humidity which causes damage to wood guitars and makes them go out of tune. RainSong used an image of one of their guitars being used to paddle a canoe to emphasize the point that composite guitars are more robust regarding sensitivity to moisture than wooden guitar (see Figure 1.10). A wooden guitar used in this way could probably never be played again. Also, the guitars are lighter and stronger, making them easier to transport and they are much less likely to be damaged during shipping. Finally, composite guitars avoid using endangered species of wood that are becoming more difficult to find [38].

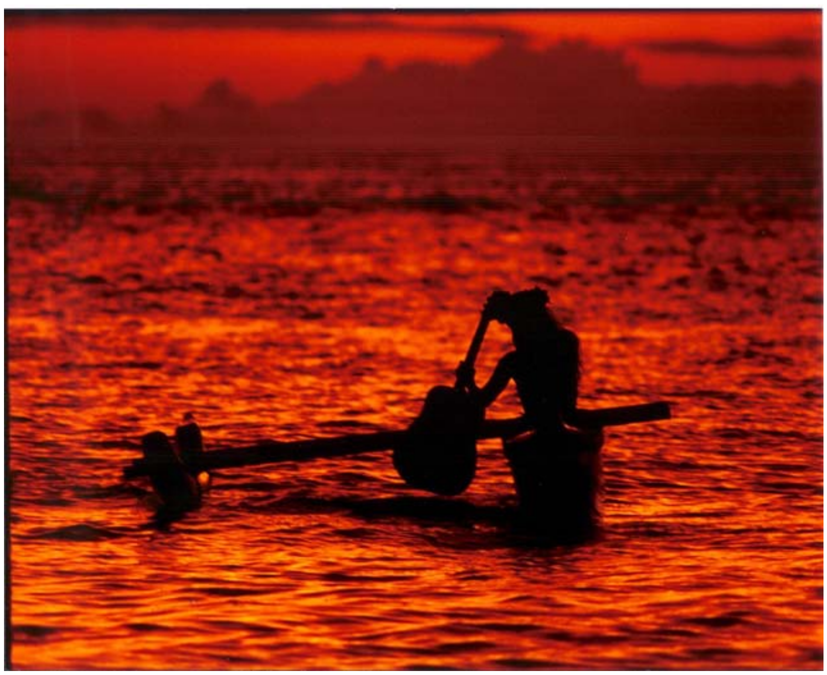

Figure 1.10. A RainSong dreadnaught graphite guitar being used as a paddle illustrates the point that composite guitars do not succumb to moisture. Image copyright RainSong Graphite Guitars, used by permission.

Besnainou evaluated the properties of wooden and composite panels with a trained luthier in order to discover the properties that were desired [39]. Apparently plucked stringed instruments (like guitars) need a higher ratio of along-grain to across-grain stiffness than bowed instruments. Guitar luthiers want ratios around 20 and violin makers want ratios around 10. Guitar makers look for a specific gravity around 0.42 while violin makers want the lowest density wood possible. Lutes were made in this study with composite soundboards with a wood veneer so that they did not appear to be made from composites. The Q factor was measured for the composites and for wood, and good results were obtained.

2 Design of the Guitars

2.1 Cost Analysis and Sponsors

A cost analysis was performed for the construction of the guitar (materials and tooling) in order to determine what funds were needed to accomplish it. Two main resources for standard guitar materials were used: Steward MacDonald and Luthiers Mercantile International (LMI). It was discovered the LMI generally had the more inexpensive materials.

Sponsors were sought to donate materials, funds, and insight for the guitar construction. Several guitar companies were approached to sponsor the project but with limited success. The most helpful interactions with guitar makers was with Breedlove guitars in Tumalo, Oregon and Dr. John Decker who hand-makes guitars in Hawaii. Neither provided funds or materials for the project (though Dr. Decker was not actually approached for this reason), but both gave very interesting insight and conversation around the topic of how to use engineering knowledge to improve the manufacture of guitars.

Though sponsors in the guitar industry were not to be found, sponsors in other industries were. Janicki Industries, a tool maker for aerospace, marine, and transportation applications donated more than sufficient carbon fiber fabric for the project as well as all necessary layup materials. Engineers at Janicki also provided valuable technical help on how to best prepare the molding surfaces to release the components of the guitar. 3M donated a lot of abrasives, tapes, and safety equipment which were necessary for finishing the guitars. High density polyurethane foam for making the side molds was donate by the UW Formula SAE team and foam sheet for the core of the sandwich structure was donated by the UW Human Powered Submarine team.

The remaining costs from the guitar construction were covered by the Mary Gates Undergraduate Scholarship which was awarded to Jon Hiller. Jon applied for this scholarship with the intention of using the funds for the guitar project. After the completion of the guitar construction, further funds for purchasing testing equipment was provided by general funding of the Microcellular Plastics Lab under Professor Vipin Kumar.

2.2 Analyzing a Wood Guitar

Though the advantages and versatility of carbon fiber to improve the design of an acoustic guitar were considered, the intention of the design was to mimic the tones of a wooden guitar. This was the goal because the desirable qualities of the acoustics guitar are somewhat well established and trying to mimic the tones of wood gives opportunity to compare the two when construction is finished.

The main metric which was used to characterize vibration properties of an instrument is the modal frequencies of the top plate of the guitar. The vibration of the strings of the guitar excite the top of the guitar at the bridge, which is in the center of the lower bout of the guitar and this causes the guitar top to oscillate, propagating sound waves at a variety of frequencies corresponding to the superposition of various normal modes of vibration. The back of the guitar also had modal frequencies, but these are mostly damped by the person who is playing the instrument. Likewise the sides and neck of the guitar contribute little to any radiated sound.

Initial measurements of a wood guitar were done using a Polytek OFV 2600 laser interferometer. Measurements were done on both a Yamaha FG401 and a Taylor Big Baby. The first of these guitars has a very similar profile to the designed guitar and the second guitar has a smaller air cavity and a soundboard with a smaller area. In addition, data for the fundamental modes of vibration from guitars in literature was tabulated, though many of the guitars analyzed in previous studies are classical guitars.

The measured and existing modal frequencies were used as a design standard in order to tune the composite layup to simulate a wood guitar.

2.3 Guitar Geometry—Developing a CAD model

The overall shape of the guitar was influenced by several factors. First was the book by Cumpiano and Natelson [40] which is probably the most comprehensive and most used book on the entire process of building a guitar by traditional methods. In addition, measurements of existing guitars were used such as the profile shape of a Yamaha FG401 guitar (Figure 2.1) and the neck dimensions of a Tacoma DM9 guitar (Figure 2.2). The shape of the Yamaha guitar was captured by placing an image of the guitar body into SolidWorks and fitting a spline to the profile. The cutaway in the guitar was added in without reference to another instrument. A standard scale length for the fretboard was used as recommended by Cumpiano. Almost every part of the guitar was modeled in SolidWorks, including pieces that would be purchased, such as the tuning machines, though these were not modeled in full detail. Figure 2.3 shows the entire guitar CAD assembly with the exception of the nut, frets, strings and headpiece inlay. For stylistic reasons, unique headpiece profiles, bridge profiles and inlays were used between the two guitars.

Figure 2.1. Yamaha FG401 guitar. The body profile from this guitar was used as a template for the shape of the graphite guitar.

Figure 2.2. Tacoma DM9 guitar. Aspects of the neck shape from this guitar were used as guidelines for the graphite guitar. The bridge design was also influenced by the DM9.

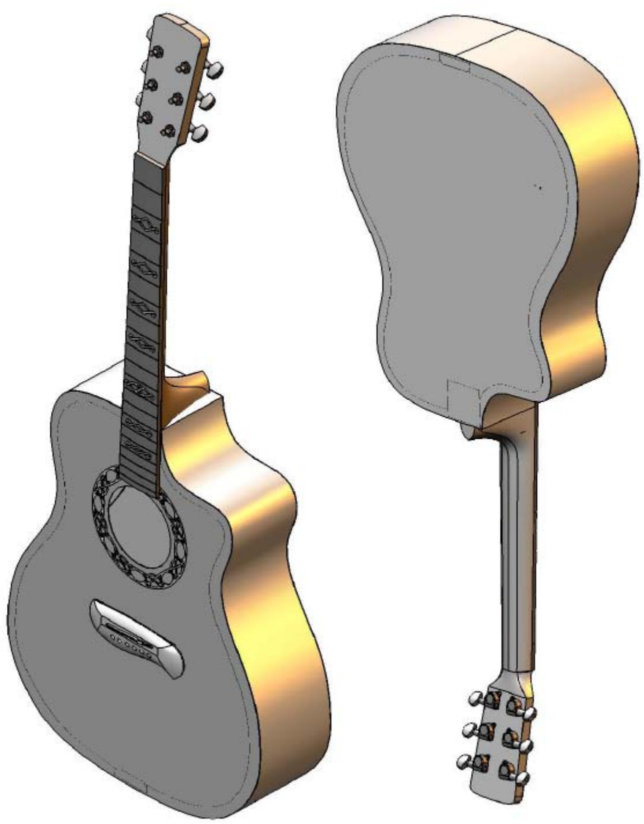

Figure 2.3. CAD assembly of guitar with almost every component. The nut and headpiece inlays are missing as well as the frets and strings.

2.4 Preliminary Material Testing

Carbon fiber varies greatly in its properties depending on its manufacturing and the size of the bundles and the type of weave. The fabric used in this layup is a plain weave with a count of about 12-13 “pics” per inch in both the warp and the fill directions and 3000 strands per tow. In addition to fiber differences, the epoxy that was used differs from one manufacturer to another. The epoxy used was West Systems 105 resin with the 206 hardener. Due to insufficient existing material data, material tests were necessary in order to get reasonable results from the finite element model (FEM). For the initial FEM, an 8-noded shell element with isotropic properties was used to model the carbon fiber structure. The assumption of isotropic properties is legitimate in this plane-stress situation since the layup varied the orientation of the fabric several times across the cross-section. Thus the material layup was considered as a single material and specimens were prepared from the full layup including the foam core. Specimens with two different layered structures were used. The first is a [0/core/S] layup, and the second, [45/0/core/S]. The notation for the layup gives the orientation of the one of the principle fiber directions relative to a stationary axis. The “S” indicated where the symmetry of the layup is. Strain gauges were not used, and thus Poisson’s ratio was not determined, however, by varying Poisson’s ratio in the FEM it was seen that it did not have a large effect on the results. Values for Poisson’s ratio from classical lamination theory were used. Later on, material tests done following ASTM standards for testing composites were conducted to give more accurate properties for the individual layers of carbon fiber so that the guitar could be modeled with layered shell (SHELL99) elements in ANSYS. This will be discussed in Chapter 5.

The results of the [0/core/S] layup is shown in Figure 2.4; the results of the [45/0/core/S] layup is shown in Figure 2.5. Table 2.1 shows the elastic modulus calculated for the first layup for each test run and varying number of sample points of the initial portion of the curve. Table 2.2 shows the same for the second layup. It is seen that the calculated elastic modulus decreases as the number of points increases because the slope of the curve is decreasing. Also the standard deviation of the elastic modulus increases as the number of points used increases because as the specimens yield at different points and spread apart, the variance of the sample increases.

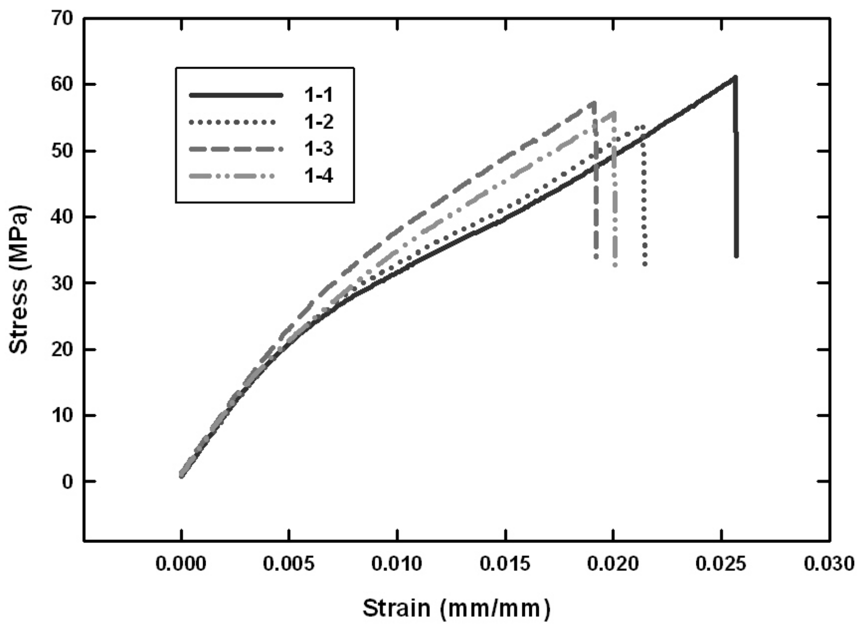

Figure 2.4: Stress-strain plot for first test layup with two total layers of carbon fabric.

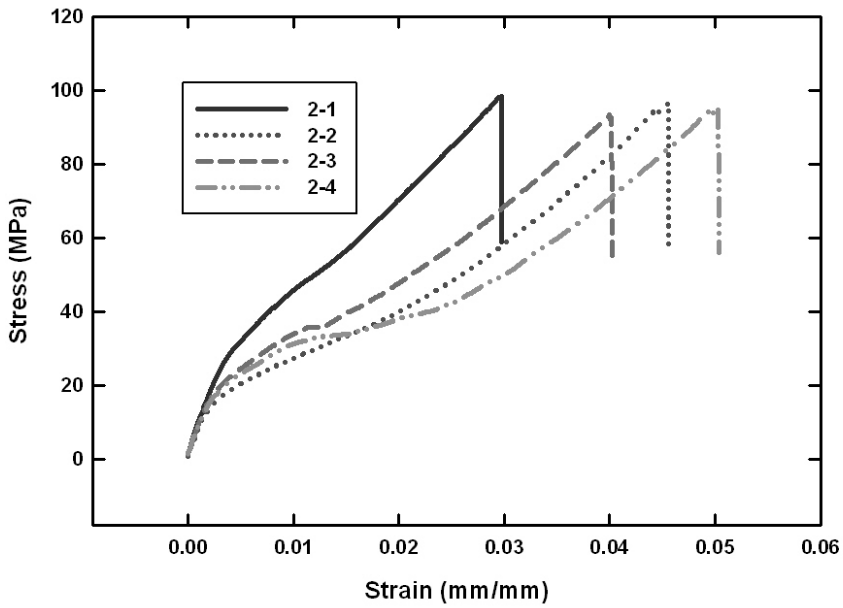

Figure 2.5: Stress-strain plot for the second test layup with four total layers of carbon fabric.

Table 2.1. Elastic modulus of [0/core/S] layup using 10, 20, 30 and 40 points. Values are given in MPa.

Data pts	"1-1"	"1-2"	"1-3"	"1-4"	Mean	Standard Deviation
10	4607.6	4604.1	4663.2	4762.4	4659.3	64.0
20	4588.0	4561.2	4649.4	4734.2	4633.2	66.5
30	4503.5	4477.7	4598.1	4647.8	4556.8	69.1
40	4348.9	4337.5	4531.8	4478.4	4424.2	83.2

Table 2.2. Elastic modulus of [45/0/core/S] layup using 10, 20, 30 and 40 points. Values are given in MPa.

Data pts	"2-1"	"2-2"	"2-3"	"2-4"	Mean	Standard Deviation
10	8604.6	7867.3	8604.6	7993.3	8267.4	340.1
20	8246.4	6984.8	8246.4	7007.4	7621.3	625.2
30	7785.5	5711.1	7785.5	5945.8	6807.0	982.0
40	7027.2	4449.6	7027.2	4839.4	5835.8	1199.3

2.5 Preliminary Finite Element Analysis

The material data that was obtained was used to guide the layup design by attempting to "tune" the modal frequencies obtained from finite element model to those measured on the wooden guitars and existing data in literature.

2.5.1 Square Panel Test

In order to get a feel for the accuracy of modeling graphite composites in ANSYS, a square panel (approximately 30 cm on a side) was simulated and also physical created and tested. Both cantilevered and free boundary conditions were modeled and tested, however it was found that creating actual cantilevered boundary conditions was difficult to do. After two fixtures intended for cantilevering the edges of the plate produced results nowhere near those given by the FEM, the cantilevered experiment was abandoned and free conditions were used exclusively. The frequency spectrum as measured by a laser vibrometer for the free plate tapped in the center with a hard object is shown in Figure 2.7. The plate was tapped in various locations where there were nodes and antinodes and the modal frequencies were deduced from the collective response. Some of the first modes of vibration are shown in Figure 2.6 along with the location at which the frequency spectrum was measured with the laser vibrometer.

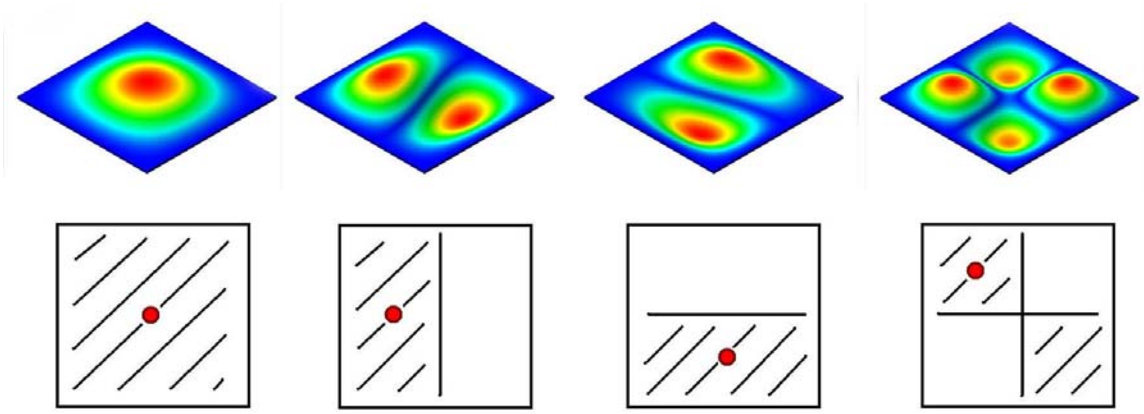

Figure 2.6. Modes of vibration of a square plate with fixed boundary conditions and measurement locations.

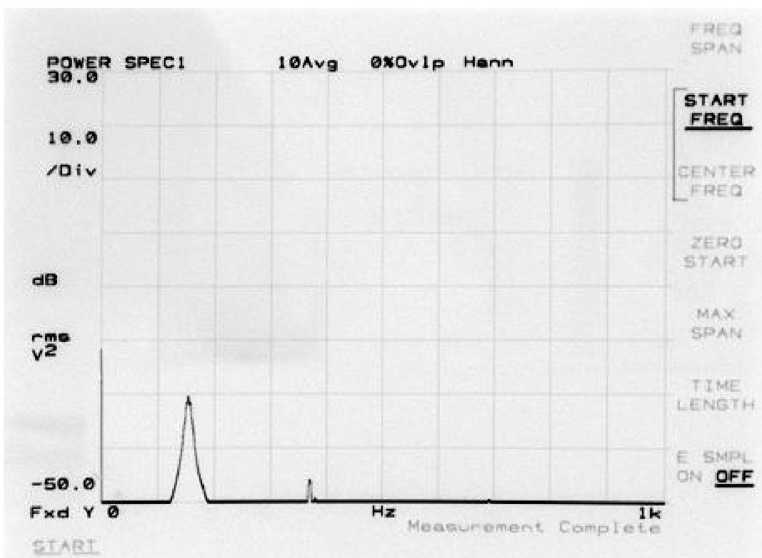

Figure 2.7. Frequency spectrum of free square panel. The panel was excited by tapping the center with a hard object.

The experimental and FE results are shown in Table 2.3. The results show agreement between the numerical and experimental data. The errors are calculated between 0.37 and 13.29 percent of the reading with no particular trend. Differences in measurement of the fourth and fifth and the fifth and sixth modes, which should be equal indicate that the layup suffers from inconsistencies which cause it to be un-symmetric. This could be due to fabric warp or shear or misalignment. The first four modes given by the FEA are shown in Figure 2.8.

Table 2.3. Comparison of experimental and FE results of the vibrating modes of a free square plate. Results are in Hz.

	Mode 1	2	3	4	5	6	7
FEA	135.5	195.7	232.7	346.4	346.4	594.8	594.8
TEST	145	195	260	335	350	525	545
Difference	9.5	0.7	27.3	11.4	5.6	69.8	49.8

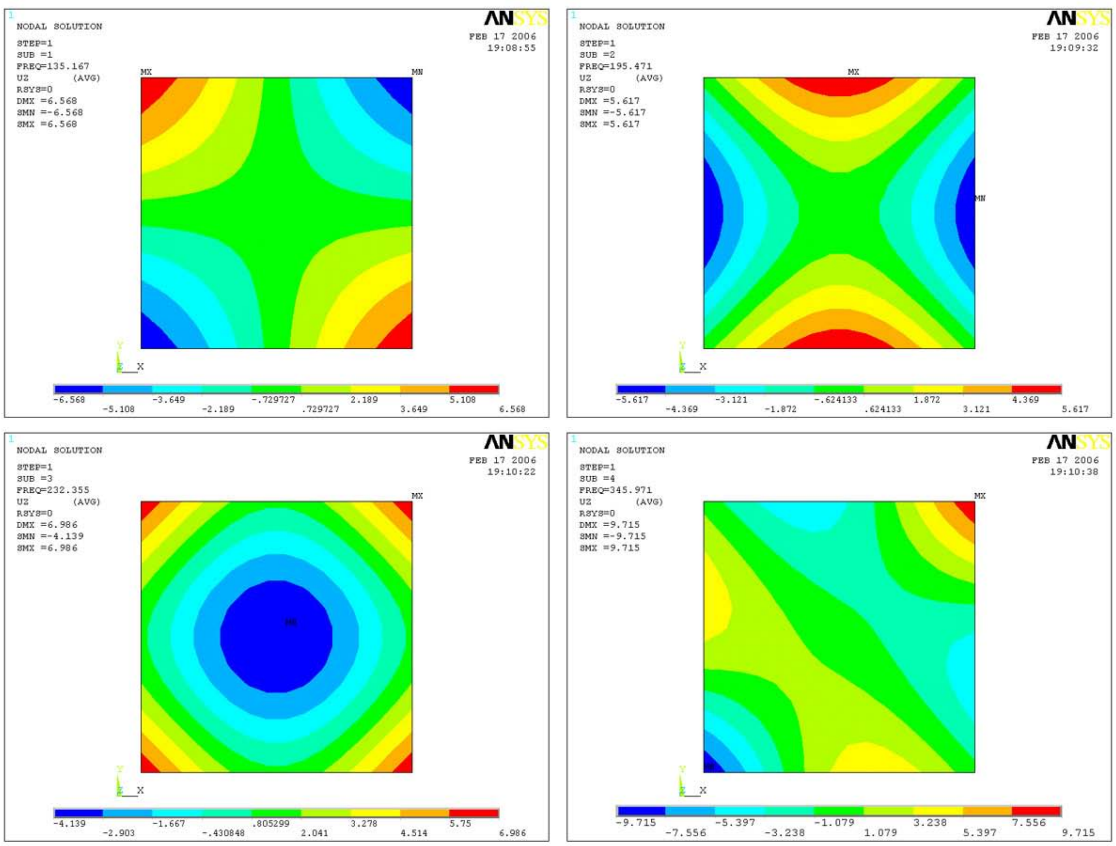

Figure 2.8. First four modes of a free square plate with averaged material properties.

2.5.2 Deflection Out-of-Plane

It was important to have a layup designed such that out-of-plane deflection of the guitar would not be significant in addition to matching the modal frequencies of the wood guitar. An out-of-plane deflection test insures that the force of the strings at the bridge will not cause enough deflection relative to the fingerboard that playing will be affected. If the strings deflect the soundboard too much, then high action[2] will result which will make the strings go out of tune when fretted. To get an initial understanding of the deflection for the layup, a test panel was deflection out of plane numerically and experimentally. The test panel was of the back of the guitar and had pinned boundary conditions imposed. Both the numerical and actual back plate had increasing load applied to the center of the lower bout of the back and deflection was recorded by a dial gauge in the case of the experiment. The deflection of the back plate should be a good approximation for the top plate deflection. The back plate was used because a top plate prototype had not been made at this point. The model in ANSYS was analyzed with a non-linear analysis using averaged properties of the [45/0/core/S] layup. The results showed agreement between FEA and experimental results up to one millimeter of deflection (Figure 2.9). Subsequent analysis showed that deflection of the top under normal string tension would be about 0.5 millimeters, thus the capabilities of the numerical tool are sufficient for static analysis of the guitar model.

[2] Action refers to the height of the strings above the fretboard.

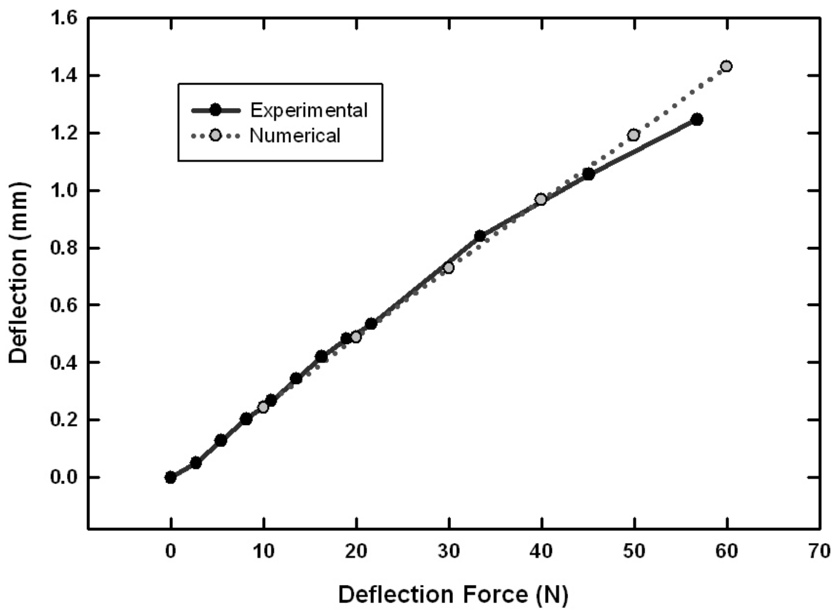

Figure 2.9. Deflection of the back plate of the guitar under increasing load by experiment and numerical analysis.

2.5.3 Deflection Due to String Tension

The deflection of the bridge under static loading was simulated in ANSYS. Cantilevered boundary conditions were applied at the edge of the top. And the appropriate string force was applied at the bridge. The total force of average guitar strings is 726 N. The results showed a hump beside the bridge in the lower bout and a dip in the top plate near the soundhole due to the moment at the interface of the bridge and soundboard. This shape is usually visible to the naked eye on wooden guitars. The maximum deflection was 0.4 mm, but the deflection at the bridge itself was less than 0.1 mm. This indicated that the string force will not deflect the guitar enough to alter the playability. It should be noted that the entire guitar structure will provide less stiffness than rigid boundary conditions so the absolute deflection of the saddle relative to its unstrung position will be greater than the numerical solution indicates. The mesh, boundary conditions and results are shown in Figure 2.10.

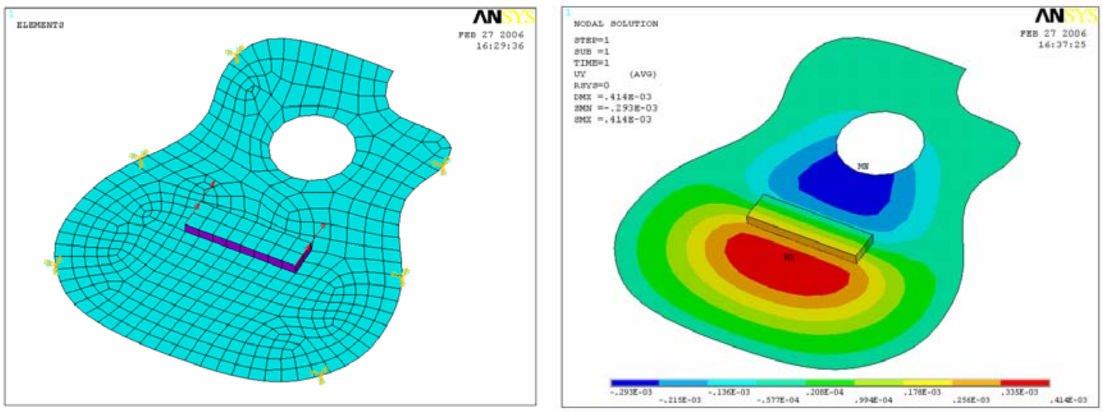

Figure 2.10. Deflection of the top plate due to string tension. The mesh and boundary conditions are shown on the left and the results on the right. The maximum deflection is 0.4 mm and the deflection at the bridge is less than 0.1 mm.

2.5.4 Modal Analysis

Initial modal analysis of the top plate was done in ANSYS using shell elements with properties that were averaged across the thickness. This model did not take into account the foam core dropping at the edges of the plate or the double thickness of the bonded portion of the edge of the plate. The bridge was included in the analysis as well as the string tension, although forces do not affect the modal analysis. Analysis was done with the top plate edges both pinned and cantilevered. In other words, the pinned condition has three displacement constraints and the cantilevered condition has three displacement constraints and three rotation constraints. Both 4 and 8-nodes shell elements were used with varying element size and the results were very consistent with results varying within 2% for all cases. The mesh and boundary conditions are shown in Figure 2.11.

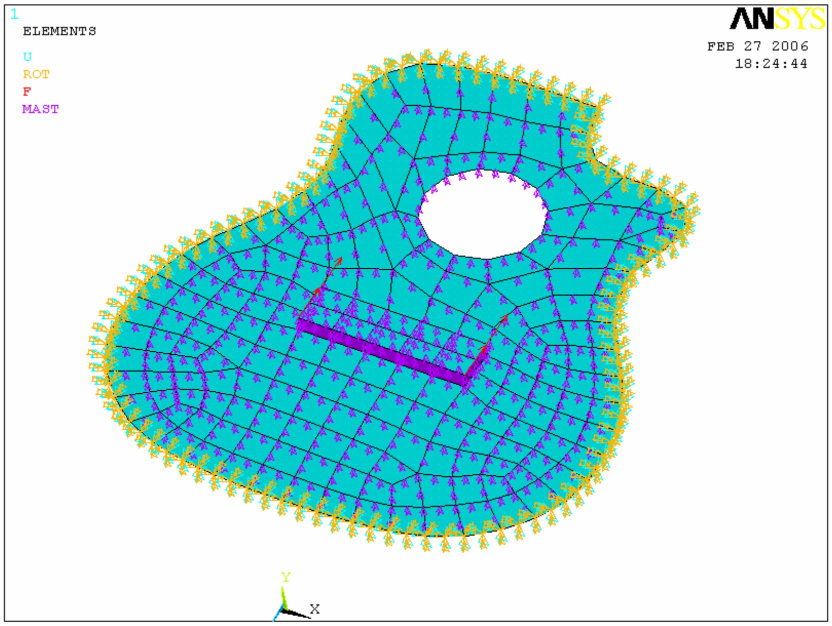

Figure 2.11. Mesh and boundary conditions of preliminary top plate FEA. Both pinned and cantilevered boundary conditions were tested independently.

Table 2.4 compares the frequencies between the two boundary conditions. The pinned modes are around 55% to 75% of the corresponding cantilevered modes. The mode shapes of both sets are visually very similar with the difference that the slope at the edges of the plate is zero for the cantilevered case which means that the contours begin closer to the edge for the pinned case. The first six mode shapes for the pinned case are shown in Figure 2.12. It is apparent that the cutaway in the plate cause the modes to be asymmetric with the asymmetry increasing with higher mode numbers. Essentially this data is for a guitar top plate that is vibrating in a vacuum since air was not included in the model. Adding the air effectively adds mass to the modes, causing the frequencies to decrease. Not only are the frequencies lowered but the air couples the top to the back of the guitar thus increasing the complexity of the system and altering the frequencies further.

Table 2.4. Modal frequencies of top with pinned and cantilevered boundary conditions.

	Mode 1	Mode 1	Mode 3	Mode 4	Mode 5
Pinned	113	292	310	455	635
Cantilevered	208	445	460	690	850

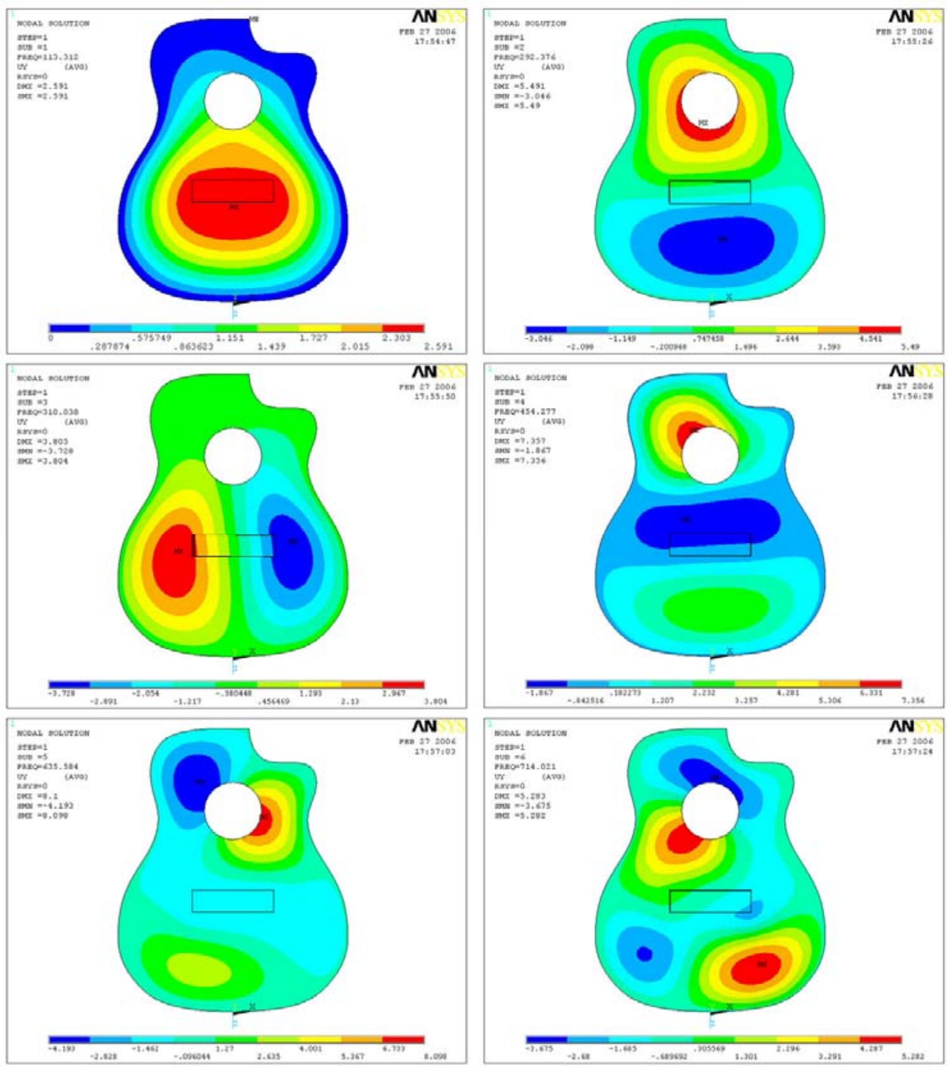

Figure 2.12. First six modes of the top plate under pinned boundary conditions. The properties are averaged over the thickness. Foam core is not dropped at the edges of the plate.

Modal analysis of the back plate was also performed but only for cantilevered boundary conditions. The frequencies of the first five modes are 312, 536, 662, 824 and 1040 Hz. The resultant mode shapes are shown in Figure 2.13.

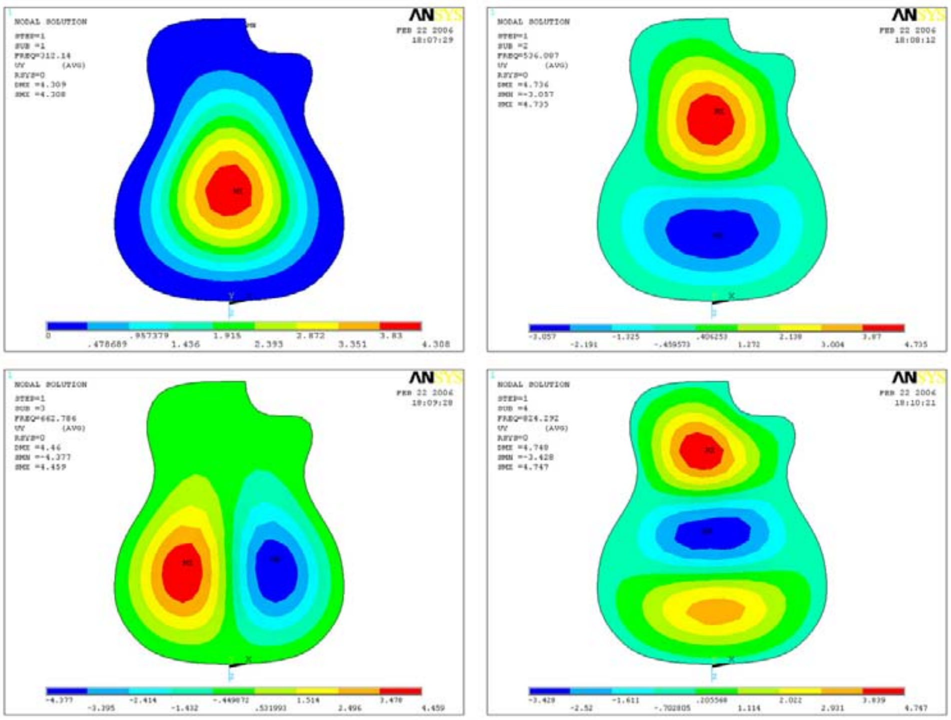

Figure 2.13. First four mode shapes of the back by FEA. Cantilevered boundary conditions were used on the edge.

The results obtained in the preliminary FEA helped to guide the design by giving general results. After the manufacturing process was completed however, it was necessary to revisit the numerical results and to refine them in order to obtain better accuracy and to correlate with the measurements taken on the constructed guitars. This work is presented in Chapter 5.

3 Manufacturing of the Guitars

3.1 Molds

Carbon fiber epoxy composite is a versatile material because it can be molded to any shape that may be as complex as can be manufactured. Thus in order to make the carbon fiber pieces for the sound box of the guitars, molds needed to be prepared to receive the material for layup. Although they appear flat, the top and back of many guitars actually incorporate a subtle radius. This radius aids the guitar in resisting the bending moment where the bridge is attached, and changes the shape of the air cavity, thus affecting the tone. In order to simplify the construction of the graphite guitars, the top and back are manufactured on a flat piece of glass. The glass was bonded to a sheet of particle board in order to protect it from cracking or breaking when being transported.

The side molds were machined out of high density rigid polyurethane foam on a TRAK K3E 2-axis CNC mill and coated with polyester body putty and glazing compound before being machined to final dimension. After this step the molds were tapered with a fly-cutter on a mill to give the lower bout of the guitar a greater depth. The molds were then sprayed with two coats of primer with sanding in between using 220-grit sandpaper and then coated with four coats of white acrylic lacquer paint, again sanding in between and a final sanding up to 1000 grit. Aluminum plates were also cut on the 2-axis plasma cutter to go on each side of the mold so that the carbon fabric could be turned up to create a surface for the top and back to be glued to. Some of the main steps of the mold making process are shown in Figure 3.1.

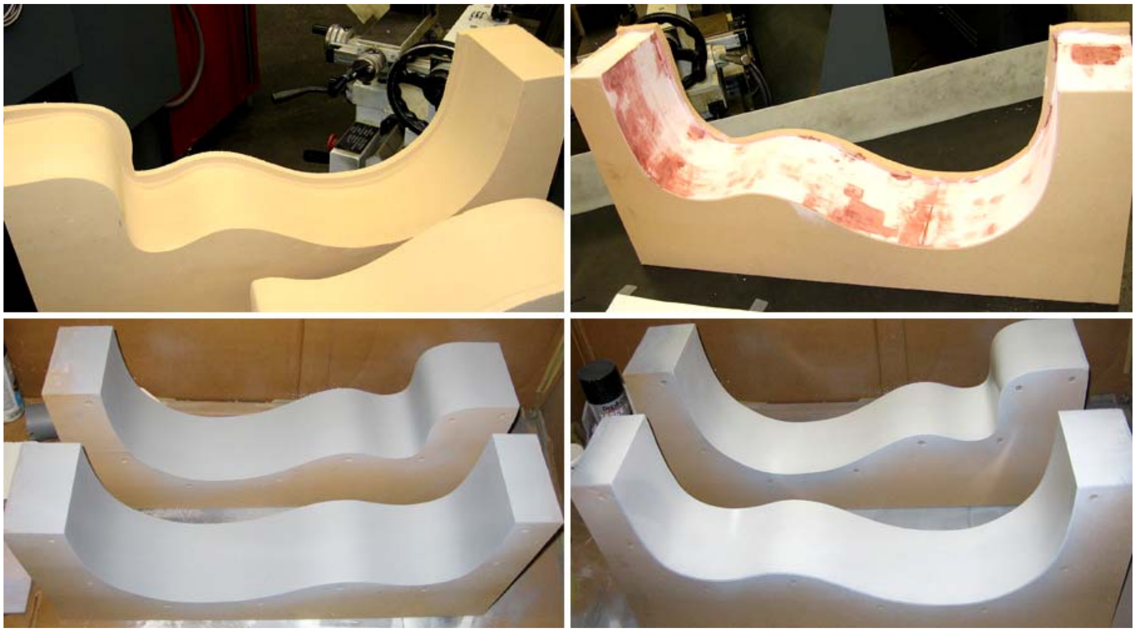

Figure 3.1. Mold construction process for side molds of the guitar. Left to right and top to bottom: milling, puttying, primer and paint. The molds were then buffed to a glossy finish.

3.2 Layups

The layups were done by a wet layup, vacuum-bagging process (see Figure 3.2 through Figure 3.4). First the material was prepped to the correct size; the carbon fabric was sized using an aluminum template as a stencil and marking the perimeter with chalk. The carbon fabric was cut with standard scissors, slightly larger than the dimensions of the final part by about one half of one inch. The eighth-inch polyurethane foam core was cut with a razor blade along another aluminum template and the edges were tapered down by sanding in order to prevent unsightly fiber lift. The taper of the foam was made from full thickness to approximately zero thickness over about one inch. The foam core for the side parts was scored with a razor blade perpendicular to the curvature of the part to help the foam conform to the curved mold. The core for the top part of the guitar was inlaid with a small piece of rosewood where the strings would pass through the top. The end of the strings are wound around a small piece of brass (called a "ball-end") that seats itself between the bridge pins (which are tapered) and the wall of the bridge pin holes. The rosewood inlay prevents the ball-ends from crushing the foam core as they pass through the top. The other layup materials (vacuum bagging, release cloth and breather layer) were also sized and cut out.

The molds were prepared with a polyvinyl alcohol (PVA) mold release agent. It is unfortunate that a release agent is necessary as it imparts a matte finish as opposed to the glossy finish of the glass. The PVA was applied with an air-brush and allowed to dry before commencing layup. The painted surfaces (i.e. the side molds) were treated with a silicone-free release wax prior to the PVA. The wax was applied in four coats with each coat allowed to dry and then buffed out before the next coat. At least an hour of drying time was given between the 2nd and 3rd coats.

Before any fiber is laid down a layer of epoxy is brushed onto the surface. The epoxy is made by West Systems and is usually used for marine applications. This particular resin/hardener combination is the 105 resin with the 206 hardener which was chosen for its pot life of 20 to 25 minutes. The epoxy was dispensed using calibrated pumps which made measuring easy and consistent. The pumps were always primed before use. After the first layer of epoxy was brushed onto the surface and any bristles are picked out, the first layer of carbon fabric is laid down. The first layer is 45 degrees off from the main axis of the guitar in line with the neck. The fabric is a standard weave with fibers in two orthogonal orientations and the angle of the layer is defined relative to one of these principle directions. This orientation is mostly arbitrary and was chosen for aesthetic reasons. After the first layer, either a brush or a flexible putty scraper is used to apply epoxy. A brush was used exclusively for the first layer so that damage was not inflicted on the release coating. The scraper helped bring epoxy through the fabric from the previous layer and thus ensured that too much epoxy was not used. Following the second layer of epoxy a second layer of fabric, aligned with the guitar axis (i.e. 0/90), was placed followed by more epoxy and then the foam core. The rest of the epoxy and carbon was then laid-up so as to render a symmetric layup.

Once the layup is complete, a piece of release fabric, which is woven from a nylon or nylon-coated fiber, is laid over the part which will allow the part to release from the breather layer and the vacuum bagging. The fabric gives the part a rough surface on the inside of the guitar which gives a stronger bond when the top and back are bonded to the sides of the guitar. On top of the release fabric is placed a breather layer which is a very porous batting material which absorbs extra epoxy and also allows the vacuum to reach the whole area of the part. Around the layup a sticky, putty-like tape is applied and gives a sealing surface for the vacuum bagging. For the side layups, the whole mold with the part is placed in a bag and the entire assembly has air pumped away from it. Before the vacuum bagging is set up, the end of the vacuum tubing is placed inside the perimeter of sticky tape and sealed in place with more tape. The vacuum bagging is then applied and sealed to the tape. The vacuum pump is turned on and a valve is slowly turned to start pulling the air out of the bag. The vacuum is applied incrementally so the vacuum bag can be fitted into the corners of the side parts and make sure that most of the wrinkles are smoothed out.

Once full vacuum is applied, leaks are checked for by listening to the sealing surfaces and checking to see that full vacuum is registered on the vacuum gage. If leaks are found, the bagging is pressed more firmly against the tape. Many of the small leaks are self sealing due to the vacuum. The part is then left under vacuum overnight for an initial cure which solidifies the epoxy almost to 100%. In the morning the vacuum is released and the bagging, breather cloth and release cloth are removed. To remove the top or the back, shims are forced under the edge of the part and systematically advanced towards the center of the part (see the bottom right of Figure 3.2). To remove the sides, first the aluminum plates are removed from the mold and then the part is slowly worked off the surface (see Figure 3.5). Even with the mold release, the parts can still stick a little to the mold. Following removal from the mold, the parts are post-cured at 150 C for at least three hours to finish the polymerization process and prevent creep problems later on.

Figure 3.2 and Figure 3.3 show the layup of a back part and a top part and Figure 3.4 shows the steps for the side parts.

Figure 3.2. Layup steps for the back of the guitar. From left to right and top to bottom: beveling the foam edges, cut carbon fiber fabric, layered fabric/foam with epoxy, layup covered by release cloth and breather cloth, vacuum applied to layup and removal of the part.

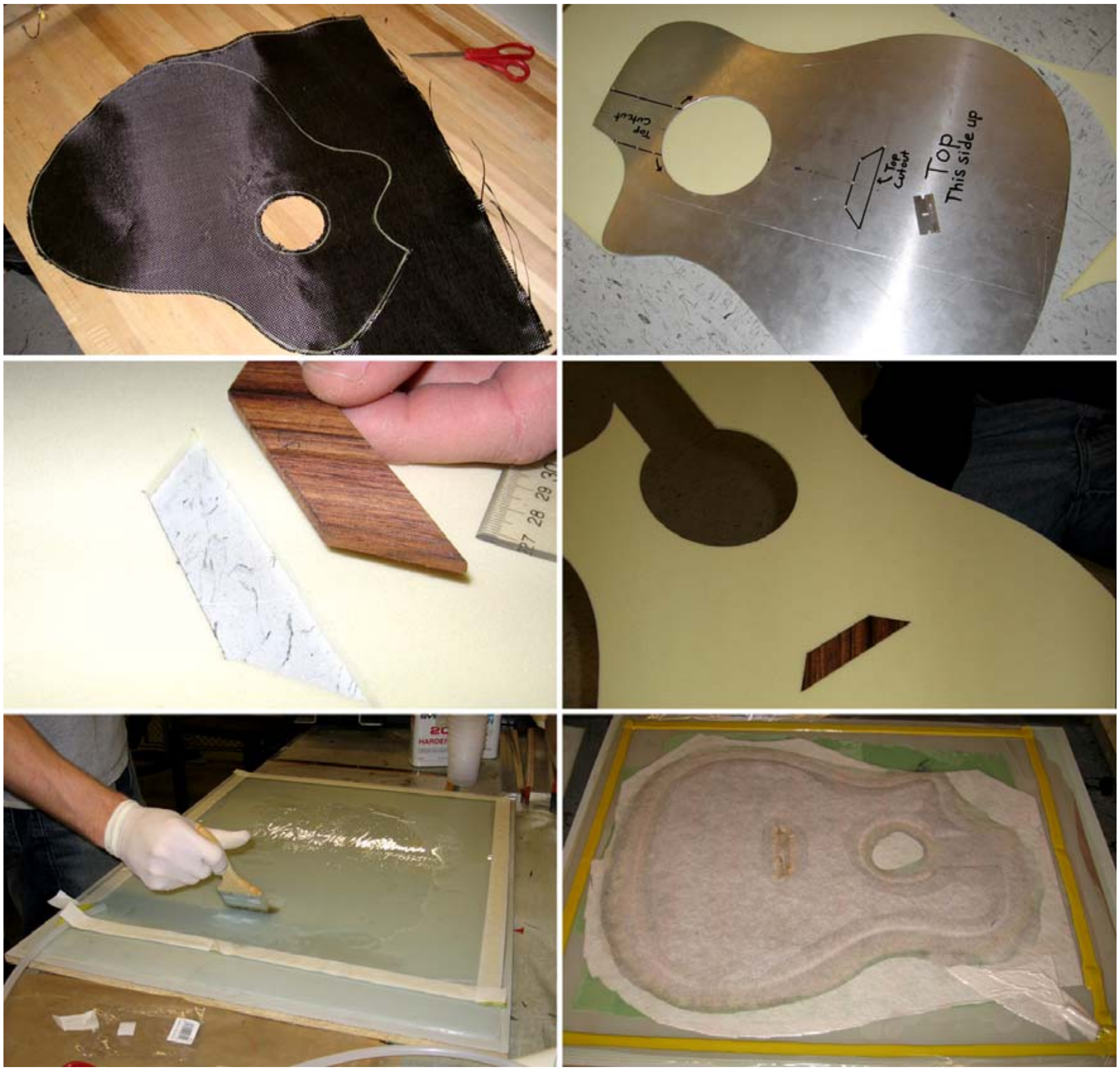

Figure 3.3. Layup steps for the top of the guitar. From left to right and top to bottom: cutting the fabric, template for the foam, inserting string-ball reinforcement piece, fully prepared foam core, brushing on the first coat of epoxy and vacuum applied to the layup.

Figure 3.4. Layup steps for the sides of the guitar. From left to right and top to bottom: brushing epoxy on the mold, spreading epoxy on a layer of carbon, inserting the foam core, release fabric, breather layer and vacuum bagging.

Figure 3.5. Removing the side from the mold. Once the layup materials are removed, the sides of the mold come off and the part is removed gently as to not damage the mold surface.

Figure 3.6. Parts for the body of the guitar after being removed from the molds. Parts have to be washed to remove release agent.

3.3 Neck Prototype and Vacuum Fixtures

3.3.1 First Neck Prototype

The first necks made were prototypes made from pine wood, which is much less expensive than mahogany. The neck of a guitar is traditionally shaped by hand using a chisel and a draw knife. Guitars that are mass manufactured are made using a variety of CNC tools; following this trend, the neck was made using CNC technology. The shape of the neck is primarily a lofted geometry which must be machined on every face of the stock material except one. This makes traditional fixturing difficult because usually a part is clamped in a vice which does not allow machining of most of three faces of the stock. The method that was tried on the first prototype was to attach the wood to be machined to another block of wood using wood screws such that this fixture block could be held in the vise. The procedure used on this first neck is as follows:

1. Plane the stock and fixture-pieces of wood so that the sides are parallel.
2. Band saw the profile of the neck from the stock to reduce later machining time.
3. Fasten the stock to the fixture block using wood screws along the region where the truss rod groove will later be machined.
4. Machine the neck to final shape using five machine setups.

Because this fixture was not rigid enough, additional claps were required in order to reduce vibration which would lead to large machining tolerances; step 4 above requires five setups for this reason. The five setups were:

1. Clamp the block and the bottom of the stock in vise and machine the heel of the neck—first do a rough machining pass to remove most of the material.
2. Finish machining pass on the heel of the neck.

3. Re-fixture so that only the fixture block is held in the vise; machine the lower part of the heel. An additional clamp is used to reduce vibration.
4. Re-fixture again so that the vise is centered on the neck and machine the long, thin portion of the part.
5. Add a clamp to reduce vibration of the headpiece; machine the headpiece.

Having so many setups introduces error into the part and allows for more mistakes. Every time the part is moved in relation to the machining table, the machine has to be told where the part is in x, y and z so that the part origin in the computer and in reality are coincident. In machining the first prototype, this was done incorrectly for one of the steps and an error was introduced into the part. The stock for the first prototype after band-sawing is shown in Figure 3.7 as well as the stock fastened to the fixture block. The finished prototype is shown in Figure 3.8.

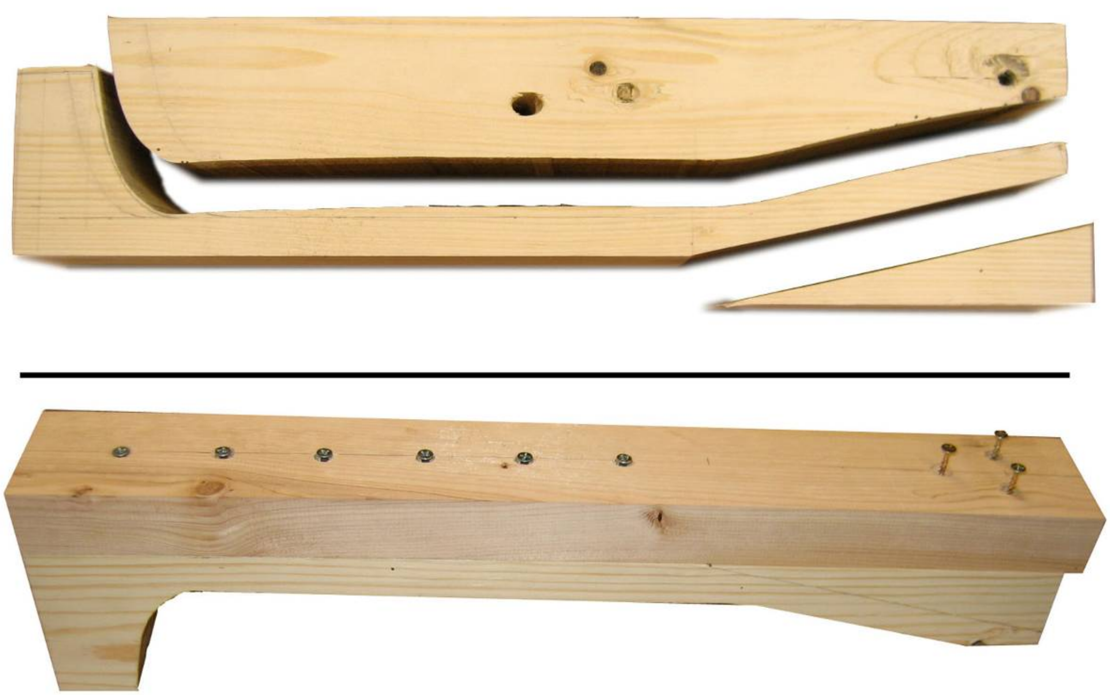

Figure 3.7. Stock pieces and fixture for the first neck prototype. This setup allowed for too much vibration in the part and required five setups.

Figure 3.8. First neck prototype finished. This first neck was machined out of pine and has a mortise on the heel for attachment to a tenon as opposed to the dovetail joint which is used on the final necks.

3.3.2 Neck Vacuum Fixture

Because of the difficulty in machining with a fixture block, a vacuum fixture was designed and machined out of Aluminum to reduce the number of setups required. Vacuum fixtures were used because this is the method that is used in industry for this machining process. The vacuum fixture has a recessed area from which air is evacuated by a vacuum pump via a port on the underside of the fixture. A rubber gasket in a groove maintains vacuum and pins position the stock. A ¼ inch base holds the fixture to the machining table by clamps (see Figure 3.9). The vacuum fixture reduces the number of machining setups to two and gives a more reliable way to tell the machine where the part is by establishing the coordinate system relative to the fixture. The reason two setups were used instead of one has to do with the ability to maintain a seal on the part. Because the wood was machined to flatness days before the part is machined, the wood changed dimensions in the variable humidity of the lab and shop environments. This made it difficult for the part to remain completely flat against the sealing surface so a clamp was used during the first half of the machining process to assist in keeping the part sealed against the fixture.

To test the effectiveness of the vacuum fixture, a second prototype neck was machined. This second prototype was also made out of pine and no tenon or dovetail joint was machined into the heel. This prototype was successful except that as the last part of the neck was being machined, the part was forced off the vacuum fixture because the seal was broken and no clamp was in place. This happened because as the neck was machined down to final dimension, the bending stiffness of the part decreased as the cross section became smaller; the decreased stiffness caused the part to deflect off the fixture locally and vacuum was lost. This led to a second clamp being used on the final necks.

Figure 3.9. The vacuum fixture for the neck of the guitar shown by itself and with a pre-machined neck stock. The neck stock is located on the fixture by the truss rod groove and two holes beneath the heel area of the neck.

3.4 Neck and Blocks

3.4.1 Neck Blank Preparation

The neck of the guitar was machined out of a blemish-free block of mahogany. Two necks were made from one block of mahogany as well as two neck blocks and two tail blocks. The process to produce the necks is as follows:

1. Cut off end of block and save for neck/tail blocks.
2. Mount block to milling table at slight angle (approx. 3 degrees), fly-cut both ends of the block.

3. Cut dovetail joint on both ends of the block.
4. Trace neck profiles on the side of the block and band saw two neck profiles and two rough planks that will be the headstock pieces.
5. Plane headstock pieces flat and parallel and then plane to final thickness.
6. Clamp headstock to neck stock and band saw the angle for the scarf joint (angled joint) and sand resulting surface to flatness on disk sander.
7. Glue scarf joint.
8. Mill truss rod groove and drill holes for vacuum fixture locating pins.
9. Trim neck on band saw to remove extra material before milling.
10. Mill neck surface on 3-axis mill.

Figure 3.10 through Figure 3.14 show the steps to prepare the neck blanks. The dovetail joint (Figure 3.10) is a traditional method of attaching the neck to the body. For guitars which are made by hand, crafting this joint can be very tedious and requires a lot of patience. With the help of a 10 degree dovetail cutter and a 2-axis CNC mill, the process is simplified greatly. In order to obtain the 3 degree angle in the neck, a fixture block was milled out of aluminum and provides the surface that the neck is clamped to in Figure 3.10. The scarf joint (Figure 3.13) is a stronger structural component than having a neck joint that is continuous wood because the wood grain is kept parallel to the geometry of the headpiece. Often finger joints are used in which the neck shaft and head stock are interlocked like fingers with a thin bondline between. In order to obtain a strong scarf joint, the surfaces need to be very flat and clamped well to get a thin bondline. This is accomplished by using the fixture shown in Figure 3.13, which prevents the two parts from shifting when the clamping force is applied across the joint. Additional clamps are used to clamp the parts to the planed board that they rest on to make sure the parts stay stationary while drying.

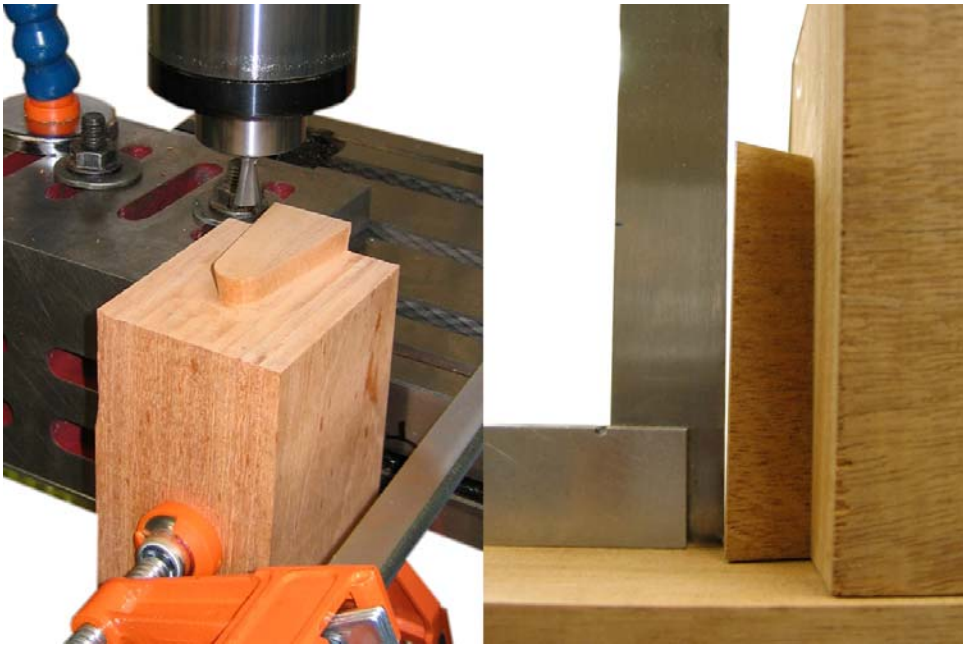

Figure 3.10. The dovetail joint of the neck. On the left, cutting the joint on a 2-axis CNC mill. On the right, a machinist square shows the slight angle that matched the taper of the body.

Figure 3.11. After band sawing the mahogany block, two neck shafts and two headstock pieces result.

Figure 3.12. The scarf-joint is prepared on the band saw and the surfaces are made flat using the disk sander.

Figure 3.13. The scarf joint prior to gluing. The scarf joint is bonded atop a planed board. Stop-blocks position the two pieces and then clamps are added to create a thin bondline.

Figure 3.14. Neck blanks ready to be milled on the 3-axis CNC mill, shown with vacuum fixture. The truss rod grooves are cut on a standard mill along with the locating holes. The blanks are trimmed down on the band saw.

3.4.2 Milling the Neck Surface

The neck profile was milled in two setups so that clamping could be used to ensure sealing against the vacuum fixture as well as to minimize air-cutting (air-cutting is when the machine is moving at cutting feedrates (slow) in areas where there is only air). The code for the CNC mill was generated in FeatureCAM™ from the CAD geometry for the neck. The inability of FeatureCAM™ to recognize generic stock shapes is what results in unnecessary air-cutting. The program really only recognizes blocks of material and thus doing a single setup would result in air-cutting most of a block as long, wide and high as the neck's length width and height. To minimize air-cutting the program was told to only cut the heel area of the neck first and then the second setup was for the low portion of the rest of the neck. The FeatureCAM^{TM} geometry is shown in Figure 3.15 with the stock shown as a light blue rectangular prism. The red portion in each case is the surfaces which are to be cut in that operation.

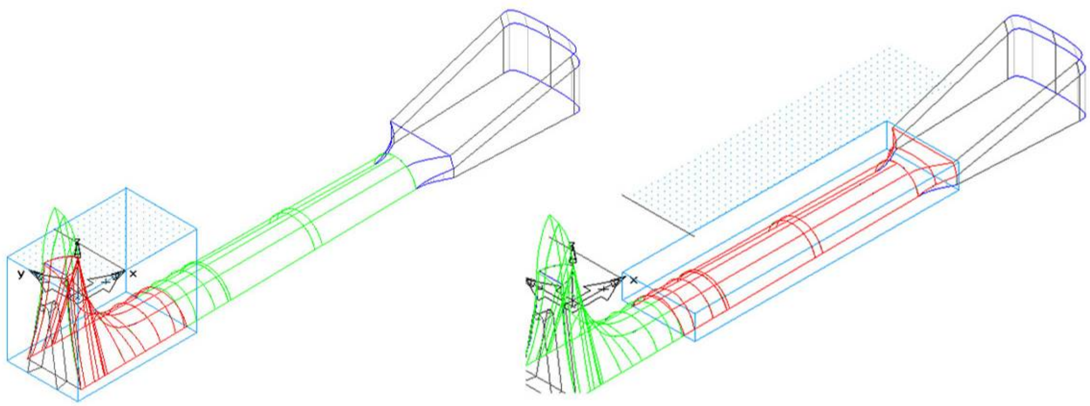

Figure 3.15. Geometry of the neck as seen in the CAM program. The light blue rectangular prism show the stock geometry in the program and the red surfaces are the surfaces to be machined in each operation.

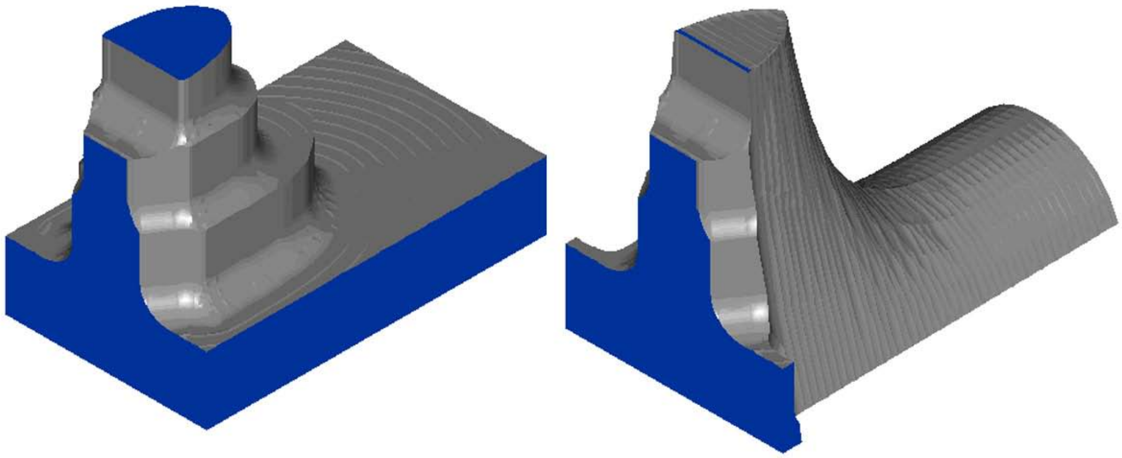

Figure 3.16. A preview of the milling result of the first milling setup. The first pass is a z-level rough pass to remove the bulk of the material and the second pass is a finishing pass.

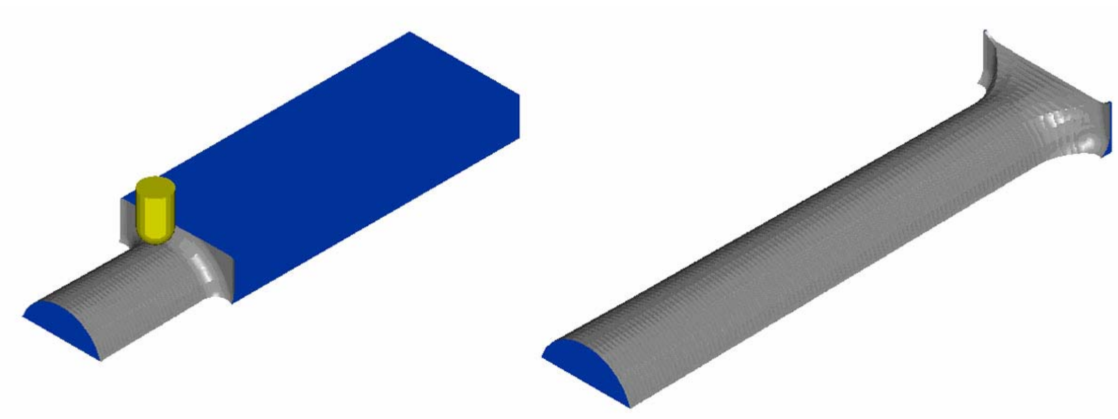

Figure 3.17. A preview of the milling result of the second milling setup. The second setup only has a finish pass since most of the extra material was removed by band sawing. The left image shows the simulated cutting tip.

Images of the neck milling progress are shown in Figure 3.18 through Figure 3.20. A new two-flute cutter was purchased for this operation so that the cutter was as sharp as possible and produced a good finish. The cutter used on the prototype necks was four-fluted, but the two-flute gives more room between the flutes for ship ejection when running at high federates. This was probably not necessary as the federates were kept low to minimize vibration and cutting forces. Examining Figure 3.18 closely one can see that the part over-hangs the vacuum fixture so that the ball-end mill can cut below the bottom surface of the part.

Figure 3.18. The first milling setup of the neck prior to milling. An extra clamp is used to ensure that the seal between the part and the vacuum fixture is not lost.

Figure 3.19. The second milling setup of the neck prior to milling. Two clamps are used, one on the heel and one on the headstock to ensure that as the bending stiffness of the part decreases due to milling, that the part does not lose vacuum.

Figure 3.20. The guitar neck after milling next to the second neck blank. The scalloping from the ball end mill needs to be sanded down and there is another millimeter of sanding tolerance which is excessive.

After the necks were milled, the headstock was shaped into the design of the headpiece using the band saw, disk sander, and spindle sander. The transition from the neck to the headpiece was shaped by hand using rasps and files. The holes for the tuning machines were drilled on a drill press. The location of the holes and the profile shape were transferred from a machine drawing printout. A good way to transfer a 1:1 pattern is to apply graphite from a pencil or graphite stick to the back of the sheet, then position the sheet on the wood and trace the pattern.

3.4.3 Milling the Blocks

The neck blocks, which attach the neck to the body of the guitar, and the tail blocks, which hold the two sides together at the bottom of the lower bout, were made from what was remaining after the necks were cut from the larger block of mahogany. The neck blocks were made from the same block of wood such that the two blocks nested with one another as shown in Figure 3.21. The dovetail was cut using the same cutter as for the necks. The neck and block were fit by progressively cutting the dovetail in the neck block deeper and deeper until the top of the block and the top of the neck were flush with one another. The taper was not added to the neck block until it was being fit with the body of the guitar. After this milling step, the individual blocks were cut out on the band saw and were sanded to shape with the help of a spindle sander. The curved inner profile of the blocks was somewhat arbitrary and more of an artistic design decision.

Figure 3.21. The neck blocks for the two guitars after the truss rod access and dovetail have been milled on the 2-axis CNC mill. The profile of the blocks is superimposed on top of the left image.

Figure 3.22. A finished neck block. The truss rod access and the dovetail were cut on a mill and the shape was cut on the band saw. Finishing was done with a spindle sander. The taper of the top and bottom was created using a disk sander.

The tail block was cut to rough shape on the band saw and was fit to final dimensions with the disk sander. Chamfered edges for the non-mating face of the block were added for stylistic effect. After shaping, a hole was drilled through the block to accommodate the pre-amp/end pin fastener which would pass through the guitar at that point. Also, using the 2-axis mill, a tapered step was milled into the block so that the sides could be given a matching taper and the block would be visible from the outside. This stylistic feature is called an endpiece. The tail block just before being bonded to the guitar is shown in Figure 3.23. Epoxy has been placed on both areas that will be bonded to the sides and is spread on one side, making it darker.

Figure 3.23. The tail block of the guitar with epoxy spread over one side of the area that will be bonded to the sides of the guitar.

3.5 Bonding of Back, Sides and Blocks

3.5.1 Bonding the Back, Sides and Tail Block

In order to bond the body pieces and the blocks of the guitar, a clamping jig was manufactured that can apply even clamping pressure along the bonding features of the parts. Traditionally luthiers use a variety of means to bond the guitar body pieces together including tape, spool clamps, or rubber bands. The clamping jig provides a rigid structure that can apply a lot of clamping pressure and is also useful for multiple bonding procedures. The clamping fixture is shown in Figure 3.24.

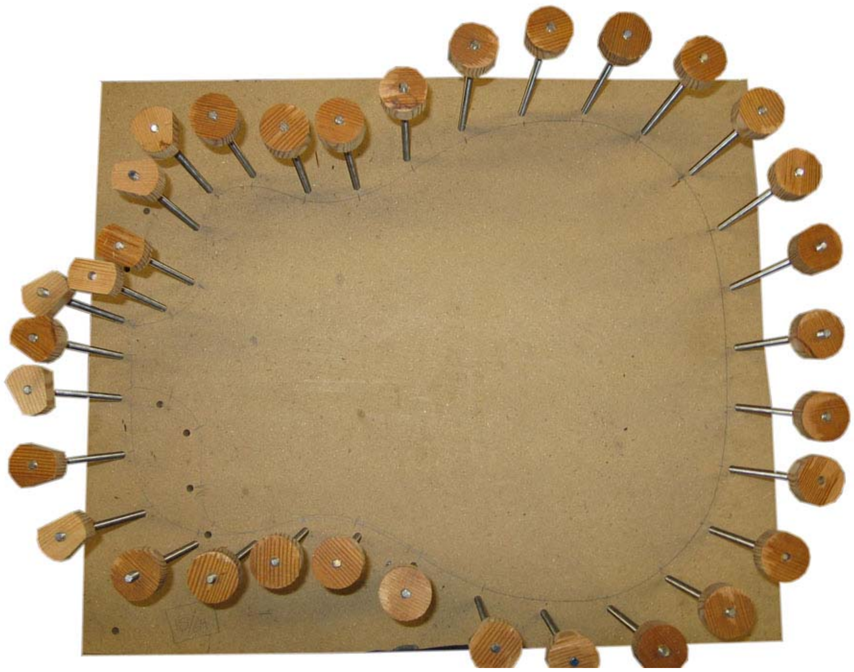

Figure 3.24. Clamping fixture for bonding guitar body. The fixture gives strong uniform pressure along the bonding surfaces.

The first step for bonding the body is to bond together the back, sides, and the tail block. Before any bonding occurs, the pieces need to be fit together, which involves trimming some of the composite flashing, especially the bonding surface of the sides. Once the pieces are trimmed, the bonding surfaces are sanded and cleaned with a rag. The top and back have good bonding surfaces already due to the release fabric transferring its texture to the part. The back is then placed in the fixture and high performance two-part 3M^{TM} epoxy was applied to the surface. The epoxy is under the Scotch-Weld^{TM} brand and is dispensed in accurate ratios with a 3M^{TM} adhesive gun with a mixing tip. The adhesive was also applied to the side parts and the tail block and then the pieces were positioned in the fixture. Once the parts are correctly situated, the clamps were gradually tightened down. A simple wooden jig was used to bond the sides to the tail block without the epoxy squeeze-out adhering the jig to the guitar. Several extra clamps were used here. Once full clamping pressure was obtained (finger tightening the wing-nuts), the assembly was left over night to cure. Figure 3.25 shows the back, sides and tail block in the clamping fixture. Figure 3.26 shows the bonded assembly after it is removed from the fixture.

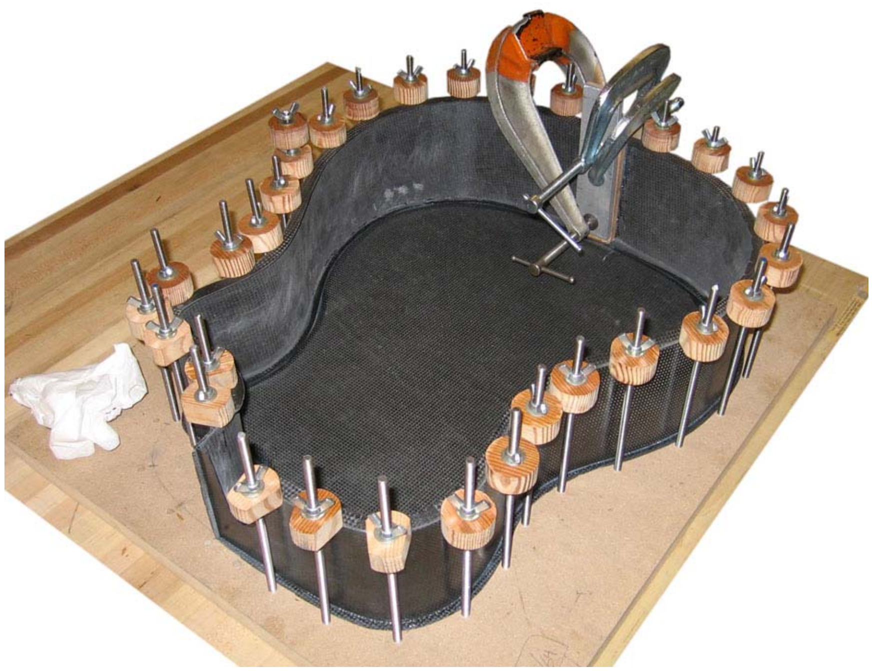

Figure 3.25. Bonding the back, sides and tail block—in the clamping fixture.

Figure 3.26. Bonding the back, sides and tail block—after epoxy has cured.

3.5.2 Bonding the Neck Block

The neck block was bonded in a separate step from the other parts in order to ensure accurate alignment of the block. A carbon fiber shim was used to add extra thickness between the neck block and the neck so that the dovetail joint would be tight enough (Figure 3.27). A long aluminum bar was used to press the neck block against the back of the guitar at the correct angle. The bar rested on the tail block at the lower bout of the guitar. A wooden dovetail jig was made to pull the neck block down towards the back of the guitar and also against the composite neck block/neck interface. A clamp was also used to secure the block against the inside of the cutaway. The clamping fixture which was used to bond the back to the sides was used to hold the existing assembly to the table and also to apply pressure on the aluminum bar. The same 3M™ epoxy was used to bond the neck block. The clamping fixture is shown in Figure 3.28 and a view from inside the guitar is shown in Figure 3.29. After this step the guitar is ready for bonding with the top of the guitar.

Figure 3.27. Composite shim for thickening neck/neck block interface.

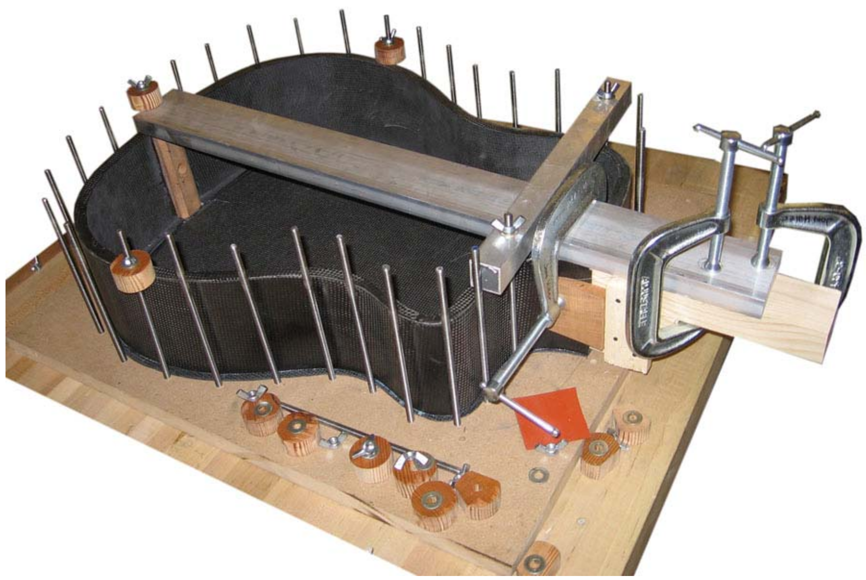

Figure 3.28. Neck block bonding setup. Several clamps and jigs were used in order to properly bond the block on three sides.

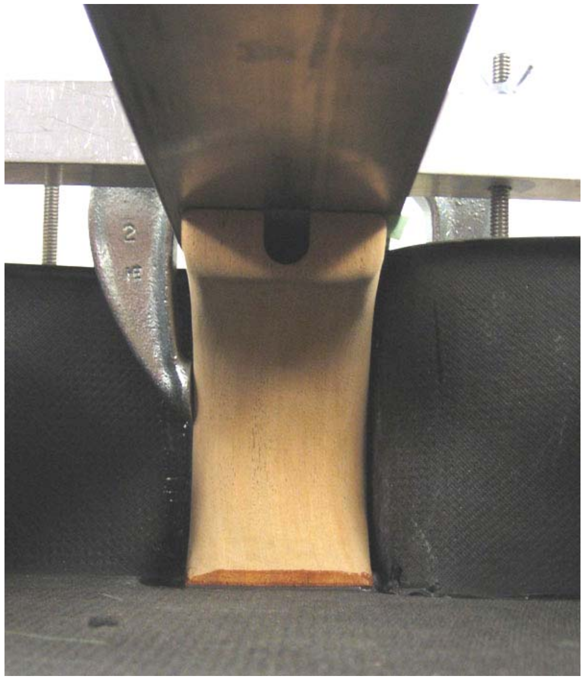

Figure 3.29. Neck block bonding setup from inside the guitar.

3.6 Fretboard Shaping and Bonding, Headpiece Veneer and Heel Cap

3.6.1 Fretboard Shaping and Bonding

The ebony fretboards were purchased with the slots for the frets already cut in them. Thus the remaining operations are to cut the fretboard profile and to add a slight radius to the top of the fretboard. The profile was cut on the band saw which results in a taper reducing from the sound hole to the nut, following that of the neck. The end of the fretboard near the sound hole was given a radius for aesthetic reasons. The edges were finished by sanding against a board with sandpaper bonded to it. The board had been planed flat. A 16-inch radius was added to the top of the fretboard using a radiused sanding block that was purchased from LMI. Once the fretboard was radiused, it was held on its side between two clamped boards and holes for abalone dots were drilled. These dots help the guitarist to know what the numbers of the frets are. Once the holes were drilled, the cylindrical pieces of shell were dropped into the holes following a small drip of glue. The dots are then pressed down until they are flush with the fretboard edge. Any variation in the height of the dots relative to the fretboard are sanded down later.

Figure 3.30. Fretboard with radiused sanding block to apply a 16-inch radius. The fretboard was shaped with a band saw and a sanding plank.

Figure 3.31. Fretboard and abalone dots for fret markers. A drop of wood glue is dripped into the hole and the dot is placed in and pressed flush with the fretboard edge.

The fretboard was glued to the neck following the application of the abalone dots. Before gluing, the double truss rod was placed in the truss rod groove and a small amount of sticky putty tape was placed in the groove as well to prevent any vibration of the rods creating what is called “truss rod buzz.” A piece of masking tape was placed over the truss rod groove and then wood glue was spread over the bonding surface on both the neck and the fretboard with the masking tape preventing glue from entering the truss rod groove. It is important not to use too much glue in this step as it can squeeze out into the truss rod groove. The masking tape was removed and the pieces were clamped together. The fretboard was aligned at the end of the neck at the fourteenth fret slot. The tips of a few finishing nails were used to ensure that the fretboard did not slip while applying clamping pressure. The nails were cut with wire cutters and were fit into small drilled holes in the neck side of the bonding interface. When the fretboard was pressed against the tips of the nails which stuck out from the neck, it was secured relative to the bonding plane. A wooden fixture the shape of the guitar neck was machined on the 3-axis mill to assist in clamping the neck. Nine clamps were used to hold the pieces together while the glue set. The neck with the truss rod placed in the truss rod groove is shown in Figure 3.32.

Figure 3.32. The truss rod in the truss rod groove prior to gluing the fretboard.

Figure 3.33. The neck of the guitar after the fretboard is bonded. The glue squeeze-out can be seen between the neck and the fretboard.

3.6.2 Headpiece Veneer

The headpiece veneer is a decorative piece of carbon fiber that is laminated on the outer face of the headstock. The composite material for the veneer was laid up on a sheet of glass and the laminate was compressed using weights instead of vacuum while curing for simplicity. The veneer consists of two plies of carbon fiber. A piece of veneer roughly matching the profile of the headpiece was cut from the layup with shears. Holes for the tuning machines were not cut in the veneer at this point. Blocks and clamps were used to create a thin bondline between the headpiece and the veneer; epoxy was used as the adhesive.

3.6.3 Heel Cap

The design of the neck is such that the heel does not reach all the way to the back of the guitar. The main reason for this is that the Bridgeport CNC mill used to cut the necks has a z-height restriction. Because of this and for aesthetic reasons, a heel cap was bonded to the heel of the neck. The heel cap is made from a piece of ebony and a piece of composite veneer. Once the heel cap was successfully bonded to the heel, the scallops from the machining operations were sanded down and the neck was sanded to final dimensions.

3.7 Bridge Plate and Bonding the Top

A rosewood bridge plate is traditionally used to stiffen the region of the top directly under the bridge to ensure that no overt local deformation occurs due to the string forces. Also, the ends of the strings, the string balls, rest against the bridge plate so the strings don't pull out. The bridge plate design component was incorporated into the composite guitar for the same reasons. The plate was positioned relative to the sound hole and was bonded in place with epoxy with the bonding force of a heavy weight. The trapezoidal shape of the bridge plate is the same shape that is used on traditionally-made steel-string guitars so that it fits between the X-braces. Since there is no bracing in the composite guitar, a rectangular shape would have been sufficient as well. Also, the entire bridge plate could have been inlayed into the foam core as the string insert was, but a more traditional design was incorporated instead. The bridge plate after bonding is shown in Figure 3.34.

Figure 3.34. The bridge plate after bonding to the underside of the top plate of the guitar. The bridge plate is cut from a plate of 1/8th inch thick rosewood.

The top was glued similarly to the back of the guitar using the clamping jig. Prior to bonding, the sound hole was trimmed and sanded to final dimension using a spindle sander. The aluminum template that was used to size the carbon fiber fabric before layup was used to distribute the clamping force and, more so, to help bond the top to the neck block. The same epoxy was used for the top as was for the other components. Again, the guitar stayed under clamping pressure for 24 hours to allow the epoxy to cure. The top plate setup is shown in Figure 3.35.

Figure 3.35. Bonding the top of the guitar using the clamping fixture. The aluminum plate gives more even clamping force on the neck block.

Once the back, sides and top of the guitar are bonded together with epoxy, the composite edges of the body are trimmed so that the top and back plates are flush with the sides of the guitar. This was initially done with an end-nipper tool, but this proved to be very laborious and so most of the material was removed using a spindle sander which quickly abraded away the excess material. A ventilation/dust collection system and dust masks were used to prevent inhalation of the carbon fiber particles. The guitar after trimming with the neck is shown in Figure 3.36.

Figure 3.36. The guitar after trimming the top and back pieces. The neck is not bonded to the body yet, but is set in the neck block.

3.8 Laser CNC Abalone Accents

Traditionally graphic designs are conceived and used to decorate the guitar by inlaying. Inlaying is the process by which a piece of material (often wood or shell) is glued into a hole that has been cut to fit the piece. Inlaying is not very simple to do into a carbon fiber surface because it is not as easily machined as wood is. Thus to simulate the inlays that are created for wood guitars, designs were cut out of a thin piece of abalone veneer and were epoxied to the guitar's surface. Traditionally more expensive and desired guitars have inlays that are intricate and delicate; since the designs for the composite guitar were created on a computer and were cut with a CNC laser cutter, they could be made with great complexity quite simply.

The abalone accents were designed in SolidWorks and were saved as DXF files. These files were loaded into AutoCAD and arranged to minimize the material waste from the 5 by 9 inch, 0.15 mm thick sheet. The abalone was cut by a Universal Laser Systems Inc. XL-3200. Designs for the rosette (annulus around the sound hole), headpiece and fretboard were all created by this process. Part of a sheet of abalone after cutting is shown in Figure 3.37 where the precision of the laser CNC machine can be observed. Figure 3.38 shows a rosette design created by Jon Hiller for one guitar prior to being bonded to the guitar top surface. The rosettes were cut as four separate pieces to reduce material waste.

Figure 3.37. Abalone accents directly after the laser cutting process. The fine precision of the laser can be seen.

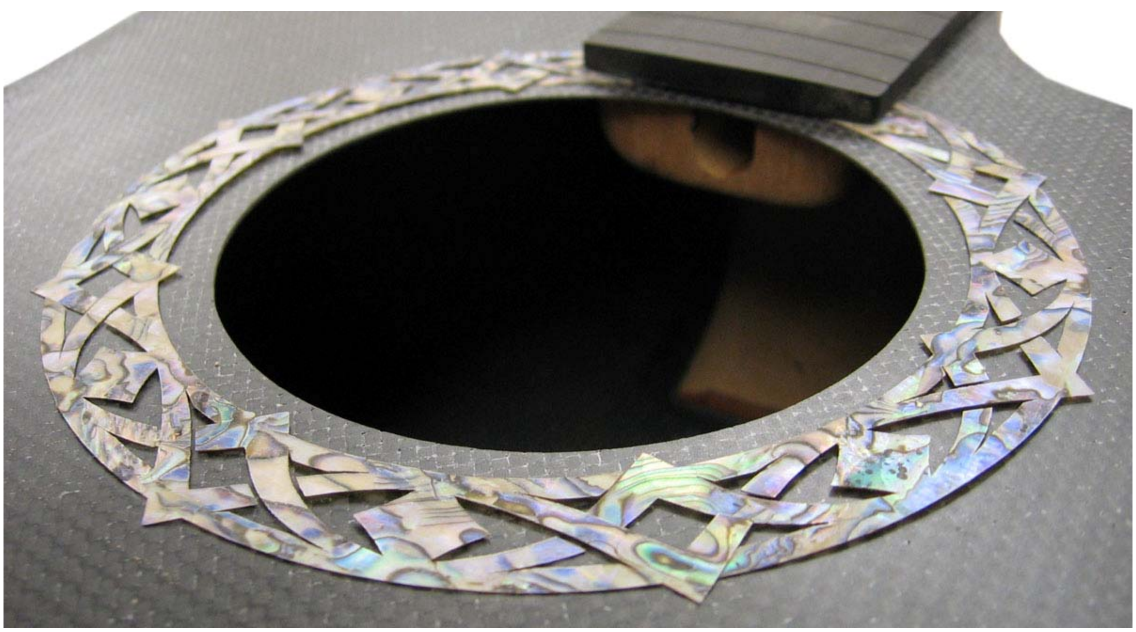

Figure 3.38. Abalone rosette design created by Jon Hiller. This design was cut in four pieces and then placed together almost seamlessly to reduce material waste. The picture shows the abalone prior to bonding.

3.9 Epoxy Abalone and Fill Voids

In order to make the abalone accents appear to be flush to the guitar top surface and headpiece, epoxy was built up and sanded down repeatedly until the transition between the surface of the guitar and the top of the abalone was smooth. Also, epoxy was used to fill small voids that were left in the composite due to air bubbles. These bubbles most likely were caused by stirring the resin/hardener and/or the spaces in between the weave of the fabric. Figure 3.39 shows the body of the guitar while still wet from an application of epoxy that has not yet cured. Around six coats of epoxy were applied and sanded down to make the inlays on the body and headpiece flush and to fill voids.

Figure 3.39. Bonding the rosette to the body and making it flush. Voids in the composite were also filled during this step.

3.10 Bridge Manufacture

Initially it was thought that the bridges would be manufactured using the 3-axis CNC mill and a vacuum fixture to hold the work piece in place. A test vacuum fixture was developed (Figure 3.40) and it was found that there was not enough area to create sufficient force by vacuum to resist the machining forces. Thus the bridges for the guitars were mostly made by hand with the bridge pin holes and the saddle slot being milled on a 2-axis CNC mill. The profile of the bridge was traced onto the blank from a CAD drawing and was cut on a band saw. The bridge material is ebony which is a very dense, oily tropical hardwood. The density of ebony is around 1100 kg/m^3 which is more than twice as dense as mahogany which is 450 kg/m^3. Ebony dust causes allergic reactions after prolonged exposure with a cumulative effect so dust masks and gloves were utilized when handling it. After the profiling operation (Figure 3.41), the bridge was shaped with a rasp and spindle sander. A series of progressively higher grit sandpapers and polishing pads led to a shiny surface (Figure 3.42).

Figure 3.40. Bridge vacuum fixture. The fixture was not used when testing showed that enough resistive force against machining could not be created because of the small area of the bridge.

Figure 3.41. The ebony bridge after milling, drilling and profiling operations. Milling of the saddle slot and drilling the bridge pin holes was done on a 2-axis CNC mill and the profile was cut on a band saw.

Figure 3.42. The bridge with the final surface shape created by rasping and sanding operations.

3.11 Neck Finishing

Mahogany is a porous wood which requires filling in order to give a smooth surface without dimples after lacquering. ColorTone water-based grain filler was used and applied by brushing. Once set, the filler was scraped flat with a flexible putty scraper. After filling, the neck was sealed using Behlen Nitrocellulos vinyl sealer. The sealer is used to build a level surface upon which the lacquer will be sprayed.

Figure 3.43. The neck after the mahogany has been filled. After filling the neck is sealed.

3.12 Attaching the Neck

The neck of the guitar was attached to the body prior to lacquering in order to achieve a continuous lacquered surface across the neck/body joint. The wood-to-wood interfaces were bonded with Elmer's^{TM} wood glue and the wood-composite interfaces were bonded with 3M^{TM} epoxy. In order to give a tighter fit to the neck joint, a brass shim less than a millimeter in thickness was made and placed in between triangular-shaped dovetail bonding areas on the neck and neck block. All bonded surfaces were coated with adhesive and the neck was bonded and clamped with a bar clam and a "C" clamp. The bonding area on the top of the guitar can be seen in Figure 3.44. The area that was to be bonded was masked so that the area around it was higher due to multiple epoxy applications. The wood-to-wood bonding surfaces of the neck and neck block are shown in Figure 3.45. The clamping apparatus is shown in Figure 3.46.

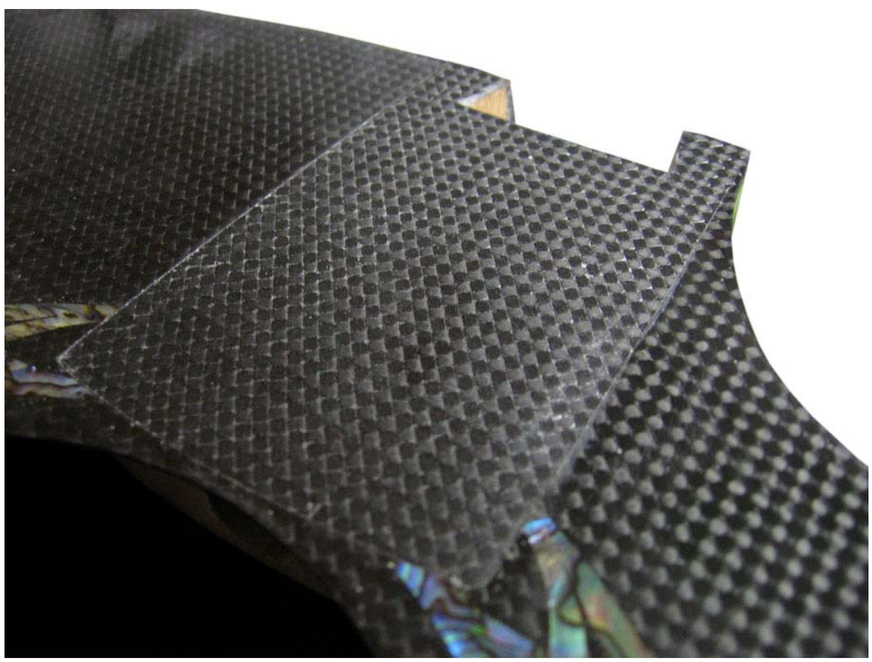

Figure 3.44. The bonding area for the fretboard to the top of the guitar. The contrast between the epoxy that has been built up around the rosette and the original top surface can be observed.

Figure 3.45. The neck and neck block dovetail joint with wood glue applied just prior to bonding. Epoxy was applied to any wood-composite interfaces and wood glue to wood-wood interfaces.

Figure 3.46. Clamping the neck to the body while glue and epoxy harden.

3.13 Lacquering, Sanding and Polishing

Once the neck of the guitar was bonded to the body, the guitar was ready for lacquering. A nitrocellulose instrument lacquer was used which results in an easily sanded and buffed, high gloss surface that is very hard and resistant to cracking. The lacquer was applied with an HVLP (high volume, low pressure) gun in order to get appropriate atomization. Six coats of lacquer were applied 1-2 hours apart. If any drips were formed, the lacquer was allowed to harden (24 hours) and then the drip was sanded down. The final surface was obtained by sanding with progressively finer and finer grits and then using 3M™ polishing pads which had a grit size down to one micrometer. A more standard method would be to sand the surface with 800 grit sand paper and then buff the surface with a bench-top buffing wheel which was not available. A spray paint respirator mask was used to prevent inhalation of the solvent and the lacquer.

Figure 3.47. Guitar after lacquering prior to sanding and polishing. The high-gloss surface will be transformed into a mirror-like surface.

3.14 Fretboard Inlays and Staining

The fretboard is traditionally decorated with a wide range of designs from simple dots, to extravagant designs of dragons, American flags, mermaids, etc. by inlaying precious woods, stones, or shells. The same material used to overlay the body and headpiece was used to decorate the fretboard surface. One guitar had actual inlays of abalone into the fretboard while the other guitar had abalone overlays. The inlays look cleaner up close and are less likely to be damaged, but from a short distance away from the guitar, the difference is not noticeable, particularly when the guitar has strings on it. A cyanoacrylate adhesive was used to bond the abalone to the fretboard. A “capo,” which is a tool used by a guitarist to change the scale length of the strings, was used to clamp the overlays to the fretboard while the adhesive set. An overlay and an inlay can be seen in Figure 3.48.

It is difficult to find perfectly black, uniform ebony, therefore the fretboard is often stained to give it a darker, more even appearance. The fretboard also darkens by sanding with a very fine grit.

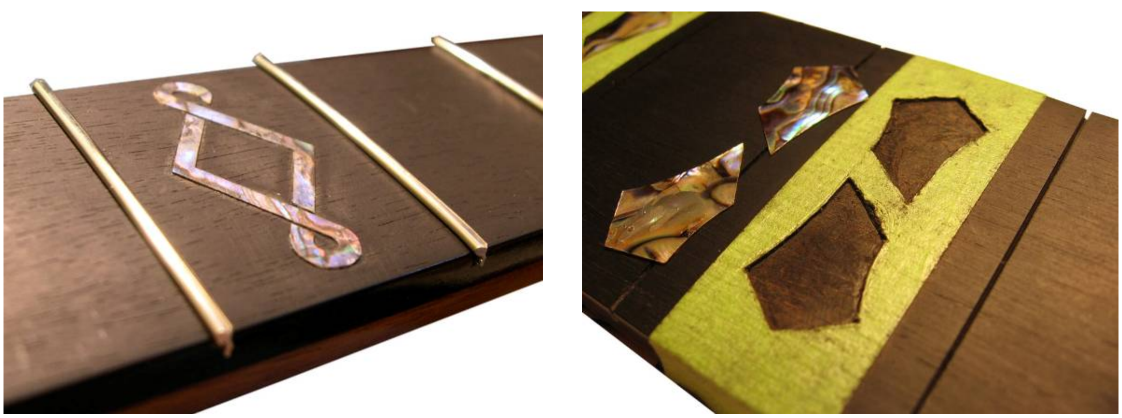

Figure 3.48. Abalone overlay during the fretting process and an inlay prior to being glued into its meticulously carved location on the ebony fretboard.

3.15 Fretting

Fretting the guitar is a careful, tedious process which requires a lot of patience. The most important part of fretting is to ensure that the frets are level so that the strings do not buzz against a fret that is higher than the others. The process of fretting the fretboard involves the following:

1. Cut fret wire to length.
2. Deepen fret slots with a saw if necessary.
3. Hammer the fret into the slot, starting in the middle and working out (Figure 3.49).
4. Trim the frets with an end-nipper.
5. Bevel the ends of the frets. This is assisted by a file that has been fit into an angled slot cut into a piece of wood. (See Figure 3.50.)
6. Level the frets with a flat file.
7. Crown the frets with a special crowning file (Figure 3.51).
8. Sand and polish frets. Use a fret mask to avoid damaging the fretboard.

A long straight-edge with a 0.001 inch precision is used to check the level of the frets along the entire scale length. To spot-check for high frets, a fret-rocker was manufactured on the 2-axis CNC mill. The fret-rocker is a rhombus-shaped plate with sides of different lengths such that the tool can span three frets anywhere on the fretboard. If the middle of the three frets being checked is high, then the fret-rocker will rock back and forth, but if all three are level, then it will not.

Figure 3.49. Fret wire lengths being hammered into the fret slots. A hammer with a double-head, one plastic, and one brass, is used so as not to mar the frets.

Figure 3.50. Tool used for beveling the ends of the frets after trimming. A file set in the block files at a 45 degree angle. A piece of cloth allows the block to run smoothly over the frets.

Figure 3.51. Crowning file used to apply a radius to the top of the frets.

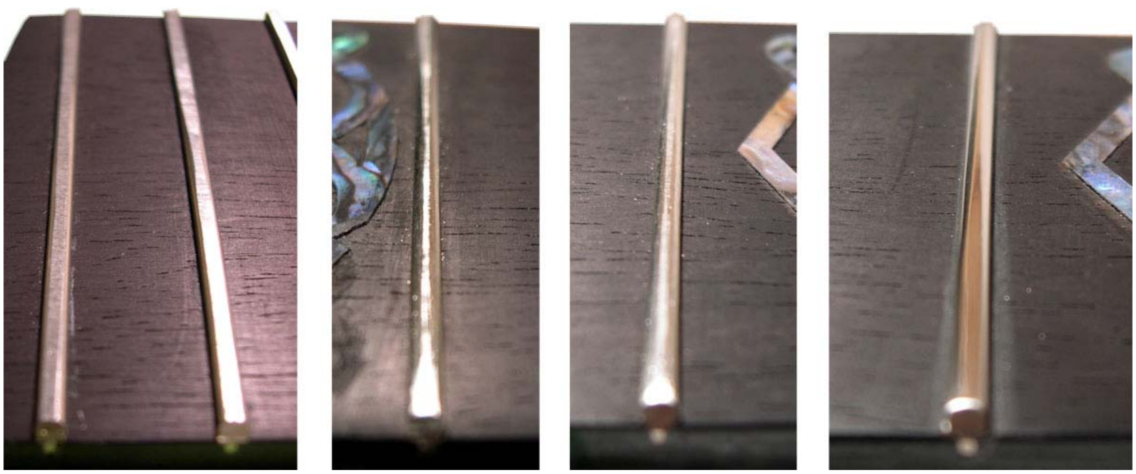

Figure 3.52. Progress of fret finishing. From left to right: leveling, crowning, sanding and polishing. A thin piece if metal with a slot, called a fret mask is used so the fretboard is not damaged.

3.16 Epoxy Bridge

The placement of the bridge is critical to the intonation of the guitar. In order to place the bridge correctly, a jig called a "Saddlematic" was purchased. This device consists of a block that rests on the 12th fret (which is at half the length of the strings) and a rod that connects to another block with adjustable pins that fit into the saddle slot. First the jig is placed on the 12th fret facing the nut and the end block is adjusted such that it stops at the nut, then the pins are adjusted to match the compensation angle of the saddle slot. Then the jig is turned 180 degrees and the pins are placed in the saddle slot to locate the bridge. The bridge pin holes are used to locate the bridge from left to right. Prior to placing the bridge, masking tape is applied in the bridge area. Once the bridge is located, the outline of the bridge is traced onto the masking tape. Then the masking tape inside this profile is removed with an Exacto™ knife and the lacquer is scraped away to expose the epoxy beneath. The bridge underside is roughed with sand paper and is expoxied to the top and clamped with a deep "C" clamp through the sound hole. An aluminum bar and some rubber foam are used to distribute the clamping pressure.

Figure 3.53. The bridge being placed using the "Saddlematic" placement jig.

3.17 Last Touches

3.17.1 Tuning Machines

In order to make the guitar playable, a number of small tasks are necessary. First, the bridge pin holes in the bridge are drilled through the top of the guitar so that the bridge pins can seat properly. The tuning machines are also installed around this time. The tuners are held to the headpiece by a nut and also a small wood screw which is fastened into the wood. Gotoh™ tuning machines were used (Figure 3.54).

Figure 3.54. The tuning machines installed on the headpiece. Gotoh™ tuning machines were used on this guitar.

3.17.2 Nut and Saddle

The nut is shaped before the saddle by filing and sanding; both are made out of small bone billets. The string grooves in the nut are made with files that are roughly the width of the strings that pass through them and are radiused on the filing surface. The grooves are progressively filed down until the "action" (the height of the strings above the frets) is minimized without the frets buzzing. Next the saddle is shaped. This is when the action for the whole fretboard is set. First the guitar is strung up and the height of the strings is measured at the 12^{th} fret. The ideal action (as suggested by Cumpiano and Natelson []) is subtracted from the measured action. In order to reduce the action at the 12^{th} fret, the height of the saddle must be reduced by twice the difference between the desired and measured action. After the height of the saddle is obtained, the shape of the saddle cross section is shaped. The main feature of the saddle shape is the offset B-string compensation. Due to the nature of the wire gages used for guitar strings, the B-string (second from the bottom edge of the fretboard, nearest to the cutaway) is improperly intonated if its length is set evenly between the strings on either side of it. Thus a compensation is formed in the saddle where this string crosses it so that the notes played on it stay in tune all along the fretboard. The nut and saddle after shaping are shown in Figure 3.55 and Figure 3.56.

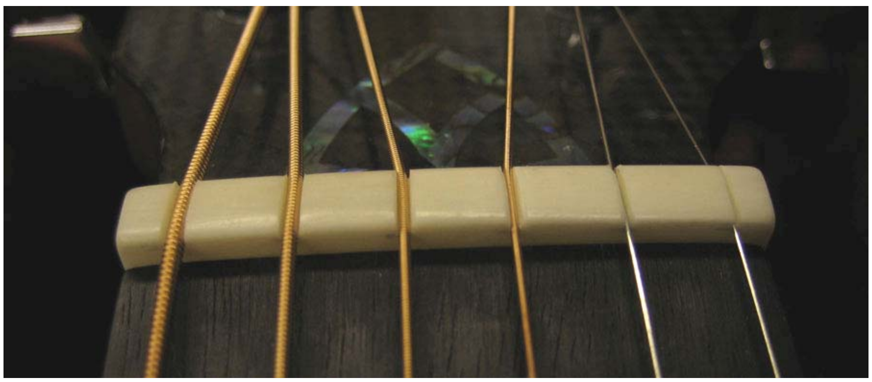

Figure 3.55. The nut of the guitar with string grooves.

Figure 3.56. The saddle of the guitar after shaping. The compensation for the B-string is visible (the second string from the right).

3.17.3 Pick Guard

A pick guard is traditionally a piece of plastic that is adhered to the top of the guitar to the right of the strings between the sound hole and the bridge. As its name suggest, the pick guard prevents the top from damage from the guitar pick or fingernails as the top wood is a soft wood. The pick guard is not as necessary for the composite guitar since the epoxy and lacquer are very hard, but one was made anyway from a 0.005 inch sheet of mylar with an adhesive side to provide extra protection.

3.17.4 Pickup, Preamp and Strap Pin

An L.R. Baggs™ pickup and preamp were installed in each guitar. The pickup is adhered with double-sided tape to the bridge plate directly underneath the saddle. The manufacturer provides a plastic locating jig which accurately places the pickup using the bridge pin holes. The pickup is piezoelectric and transforms the vibration of the top into an electrical signal. The preamp is fixed to the tail block and allows an audio cable to be plugged in through the tail block. The hardware on the outside of the guitar which holds the preamp to the tail block is also used as a strap pin which the guitar strap attaches to. The other end of the guitar strap attached to an ebony pin of similar design to the bridge pins (but larger) which is fit into a hole which is drilled in the heel of the neck.

3.17.5 Truss Rod Adjustment

The tension of the strings bends the neck slightly which increases the action of the guitar. In order to adjust for this, the double truss rod is tightened to bring the neck back into proper position. Once this is done, the guitar is ready to be strung up a final time, tuned and played.

3.18 Finished Guitar

The finished guitar is shown in Figure 3.57 and Figure 3.58.

Figure 3.57. The finished guitar body.

Figure 3.58. The finished guitar full length view.

4 Comparison of Graphite and Wooden Guitars

One of the best measures of the similarity between two instruments is the eigenfrequencies of vibration as measured on the soundboard. These modal frequencies are influenced by most all of the details of the design and manufacturing process. Another good measure to compare the guitars would be the acoustical frequency spectrum measured by a microphone, or array of microphones. The difficulty with this second method is that, much more than the structural vibration, the sound field should be measured under very strict, anechoic conditions, which were not able to be maintained in the testing environment available.

Of interest is what the frequencies are associated with each mode shapes. Usually to measure this the mode shapes are visualized by the Chladni speckle patterns or by some sort of holographic method or scanning laser vibrometer. Since these methods were not available and are expensive or time consuming to develop, the mode shapes were not directly mapped. However, from FEA studies and looking at literature it is clear that the lower mode shapes (<1000 Hz) are already well defined and are very similar between a wood and composite guitar. Thus only the frequency of the modes must be determined and to some extent this can be done by comparison of frequency spectra.

4.1 Procedures

Previously, tests on wooden guitars were conducted by tapping the guitar bridge or other location with a hammer-like object in order to excite a broad frequency spectrum (see Chapter 2). This method worked reasonably well but was not very repeatable, so for these tests, the guitars were excited by a set of two speakers which were facing the soundboard. The wood guitar tested here is a Yamaha FG403S.

4.1.1 Equipment

The guitar was excited by a single Event™ PS6 biamplified direct field monitor with a 6.5 inch low frequency driver and a 1 inch high frequency driver. The frequency response of the monitor is 45 Hz to 20 kHz, ±3dB, Ref 500 Hz. The monitor has a built-in amplifier which provides 70 watts to the low frequency driver and 30 watts to the high. The noise is greater than 100 dB below full output. The monitor produces full output at a 0.9 V input; a 0.1 V input was used for these experiments and the adjustable sensitivity was set to a maximum. The laser vibrometer was used to verify the output of both the high and low frequency drivers at several frequencies which revealed complete accuracy. The input to the monitor was generated by an HP 8904A multifunction synthesizer with a 600 kHz frequency range.

The vibration of the guitar top was measured with a laser sensor, Polytec model OFV 302 sensor head with the OFV 2600 vibrometer controller. The output of the vibrometer was analyzed by an HP 3561A dynamic signal analyzer.

For a portion of the experiment, the signal generator was controlled by a program written by block-diagram method in National Instruments' LabView which ran on a laptop computer.

4.1.2 Boundary conditions

The guitars were hung from the ceiling with a one-inch nylon strap which was looped around the nut area of the guitar neck. The guitar hung freely from the strap, vertically. The strings of the guitars were tensioned to standard tension and were damped by placing a piece of rubber foam between the strings and the fretboard near the 12th fret. The guitars were otherwise un-bounded in any other way; they were free to rotate, but the torsional rigidity of the nylon strap kept the guitars in the same relative position during testing.

As far as acoustic boundary conditions, the guitars were tested in a room with rigid walls, windows, vinyl floors and acoustic ceiling tiles. The room also contained a lot of other equipment, fixtures, furniture and printed matter. The testing was conducted above a wooden table surface near a wall. A top view of the experimental setup can be seen in Figure 4.1. The monitor and the sensing head were both placed on 2-inch thick foam blocks to reduce error in the measurement.

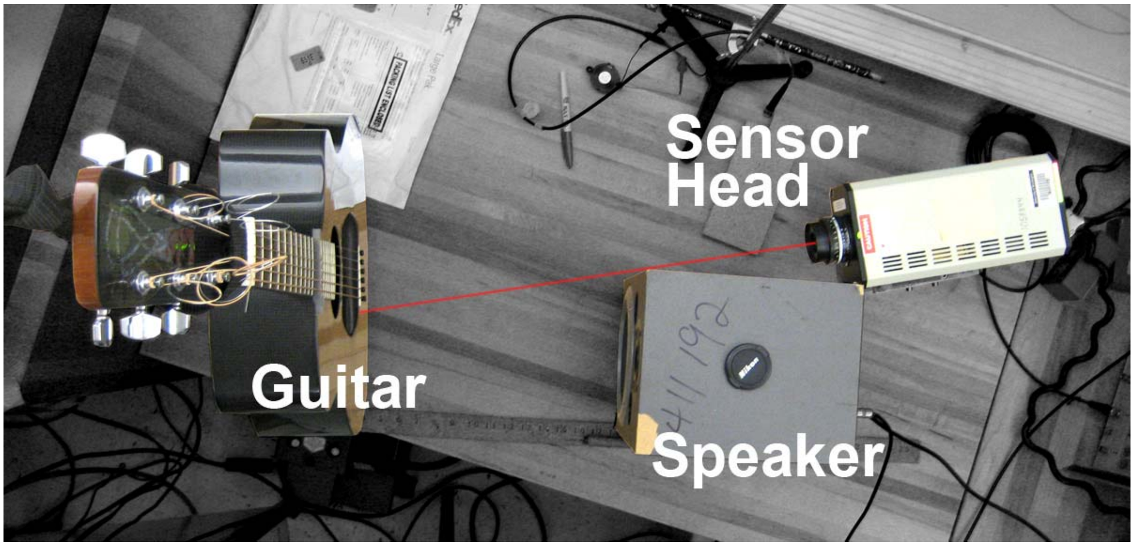

Figure 4.1. Top-view of vibration testing setup showing location of the speakers, guitar and the laser sensing head. The laser beam is artificially superimposed on image for effect.

4.1.3 Testing Procedure

Each guitar was setup for testing with string damping material and a piece of reflective tape to scatter the laser back to the sensing head. The reflective tape was placed approximately 8 cm to the left of center under the bridge. This position is critical to pick up the (2,1) mode, however it allows the (3,1) and possibly the (1,2) modes to be missed depending on the specific shapes of those modes. Testing consisted of two parts, the first is a sine wave frequency modulation from 0 to 1000 Hz with a period of 10 seconds. The frequency modulation gives initial positions of the modal frequencies which are then refined.

The second step is controlled by LabView; the guitars are excited at discreet frequencies across a small spectrum that spans each peak that was found in the first step. Starting at the beginning of the frequency span, the speakers drive the top at a single frequency for a long enough period of time that the response reaches steady state. The program then averages the amplitude of the response by quick, repeated measurements and records the pertinent data to a file. This process repeats across the range specified with a discrete frequency interval which was 0.25, 0.5 or 1.0 Hz depending on the width of the peak. The amplitude was measured after a specified delay to allow the response to reach quasi steady state. The amplitude only gives indication of where the peak is, but is not useful to a great degree in comparing the strength of the modes. The mode strength is complicated and a strong mode can be due to contribution from other modes. In other words, the modes are too coupled to extract this data from the frequency response. In addition, the top plate was not always normal to the laser beam due to its rotational freedom which changes the amplitude from the sensor's perspective. A front view of the graphite guitar during testing is shown in Figure 4.2.

Figure 4.2. Front view of vibration testing without the speaker present. The laser beam is artificially superimposed on image for effect. This image shows the testing location centered below the bridge, but most testing was done offset from the center to avoid the nodal line of the T(2,1) mode.

4.2 Results and Discussion

The frequency modulation part of the testing was conducted numerous times in order to accurately pick out which peaks were the strongest and occurred most frequently. Some frequency spectra were taken over intervals smaller than 1 kHz, but the equipment was limited in that the interval had to start from 0 Hz, so detail could only be observed at lower frequencies. Characteristic response curves for the Yamaha and composite guitar are shown in Figure 4.3 and Figure 4.4, respectively. Addition recorded frequency response curves are given in Appendix C. These spectra reveal several distinct peaks below 500 Hz and then many smaller peaks up to 1 kHz. The two largest peaks around 100 and 200 Hz are clearly the two T(1,1) modes moving in antiphase and in-phase, respectively.

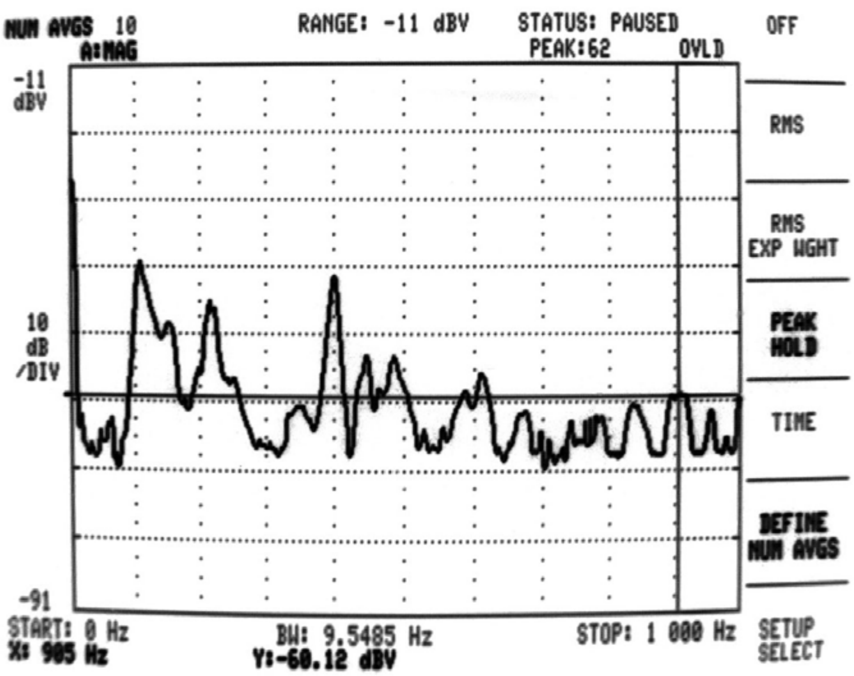

Figure 4.3. Frequency response of a Yamaha FG403S to a 0-1kHz frequency modulation.

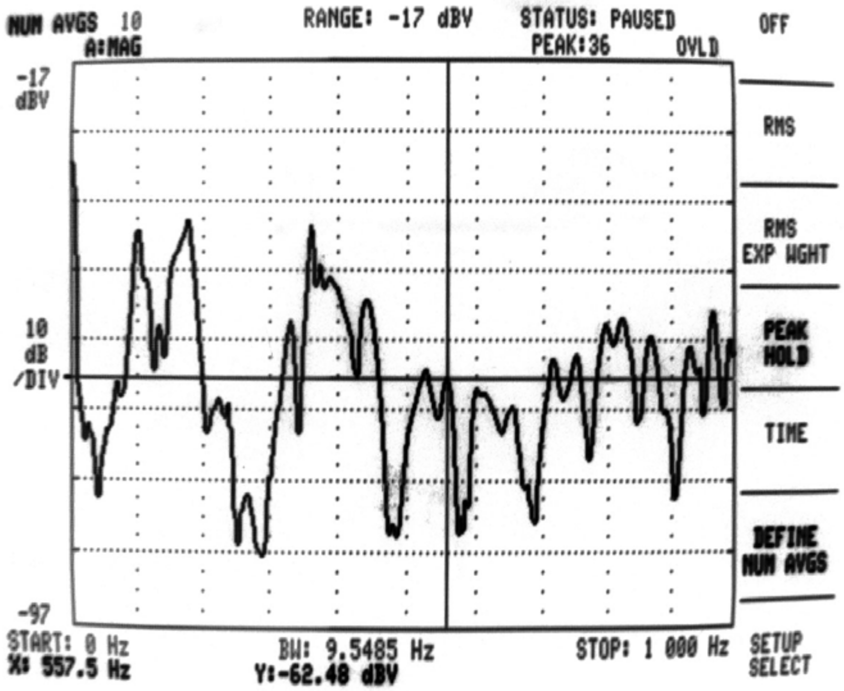

Figure 4.4. Frequency response of the composite guitar to a 0-1kHz frequency modulation.

The discreet peak evaluation is shown in Figure 4.5. One issue that was encountered was that the peaks were sometimes distorted because the response had not reached steady state. To compensate, a longer delay was specified such that the peak was steady as it was averaged, but there were some limitations and difficulties with the custom LabView program which was designed for a different resonance system. Some of the peaks in Figure 4.5 are made up of several measurements on top of one another. The peaks were examined up close to determine their precise location. Some regions of the spectrum had several peaks and so a wider sampling space was used and multiple peaks were found. Such was the case for the composite guitar between 800 and 850 Hz. The frequency locations of the peaks are given in Table 4.1. The entries marked with a tilde indicate that the value is approximate which indicates that the peak was not sharp enough to determine it specifically. The question marks indicate peaks that were not very clear and thus the location is guessed from the frequency spectra found with the sweep. In order to obtain some of the higher frequency peaks, the input was not strong enough; rather than increase the amplitude, the speaker was moved closer to the guitar.

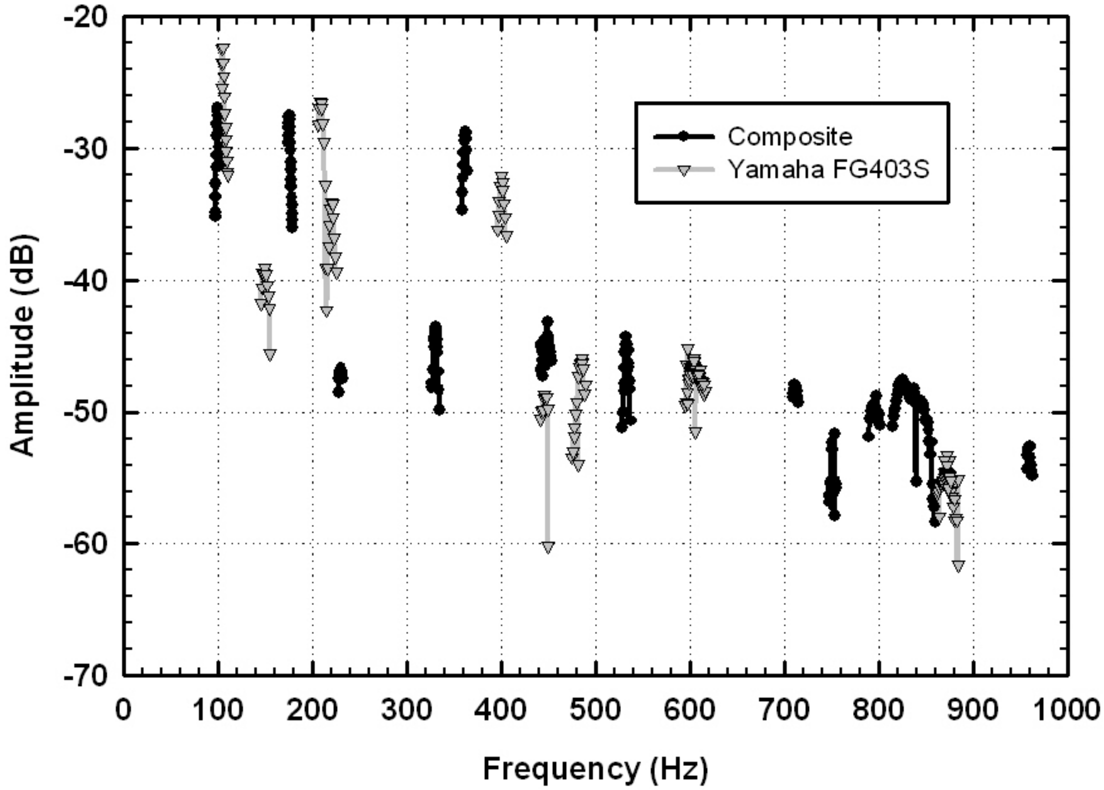

Figure 4.5. Response peaks of a wood and composite guitar. Some of the peaks include multiple measurements.

Table 4.1. Peak locations of wood and composite resonances. The "~" indicates that the peak was not sharp or clear enough to determine exactly. The "?" indicates that the peak was hardly distinguishable though it was seen in the initial sweep.

Composite	99.25	175.25		230	330.5	362.25	~450	~533		711.5	750?	~795	825	845	960
Yamaha	105	~149	208	220		400	~446	485	604					~871	

From this data it is difficult to determine which modes are associated with which peaks. Thus the data existing in the literature can be used to infer this information. Data from Wright [23] is shown in Figure 4.6 and Figure 4.7 with the mode shapes listed near the corresponding peaks. The figures are for two different driving positions, at the low E string and the G string of a classical guitar. The mode shapes were determined by sprinkling dried tea over the surface and observing the displacement at the antinodes. Additional results from literature are given in Table 4.2, mostly for classical guitars and only for the first four mode shapes. Some researchers record up to three T(1,1) modes which correspond to the top and air coupled without the back, the top and back moving in anitphase and the top and back moving in phase. Also, two instances of the T(1,2) mode shape were commonly found.

Comparing the frequency modulation response to Wright's data and that of other researchers, the first few mode shapes can be placed with frequency peaks with good confidence. The literature makes it clear that at least two T(1,1) modes always exist; the first with the top and back moving in antiphase (the breathing mode) and the second with the plates moving in phase. The first T(1,1) mode is missing from Wrights spectra because he has plugged the soundhole to prevent "breathing" of the body.

The comparison of the existing data with that presented here makes it clear that the first two major peaks are the $T(1,1)_1$ and $T(1,1)_2$ modes. For the composite guitar these occur at 99 and 175 Hz; for the wooden guitar they are at 105 and 208 Hz. The next mode is the T(2,1) mode which should be close to the $T(1,1)_2$ mode. It is most likely that this mode is at 220 Hz for the composite guitar and around 250 Hz for the wood guitar. The 250 Hz peak in the Yamaha response was not investigated in detail using LabView because it seemed to be a part of the T(1,1) peak, but after analyzing the literature data it is clear that this is probably the T(2,1) mode.

The next mode T(1,2) sometimes appears twice due to coupling various air and back modes. This makes it difficult to tell which is the T(1,2) mode and which is the T(3,1) mode. As the data collected seems to match the shape of Wright's curves in this area, it is assumed that the mode appears twice, which places the T(1,2) modes at 330.5 and 362 Hz for the composite guitar and 360 and 400 Hz for the Yamaha. Similar to the peak at 250 Hz in the Yamaha response, the peak at 360 Hz was not investigated closely using LabView. The T(3,1) mode always seems to follow the T(1,2) modes which would place it at approximately 450 Hz for the composite guitar and approximately 446 Hz for the Yamaha. It is odd that this mode would be lower than the corresponding mode in the composite guitar since this has not been the trend for the previous mode. Though this does not invalidate the mode placement, it should be noted that a near-by peak at 485 Hz could be the true T(3,1) mode of the Yamaha.

Estimating higher modes becomes risky as the peaks become less pronounced. Also, by this methods of comparison, the determination of each successive mode is influenced by the previous mode determinations, thus if a mode is incorrectly placed, this error will propagate to the subsequent mode placements. Thus no higher modes were placed on the frequency spectra, though there are distinct peaks. The mode placements are given in Table 4.3.

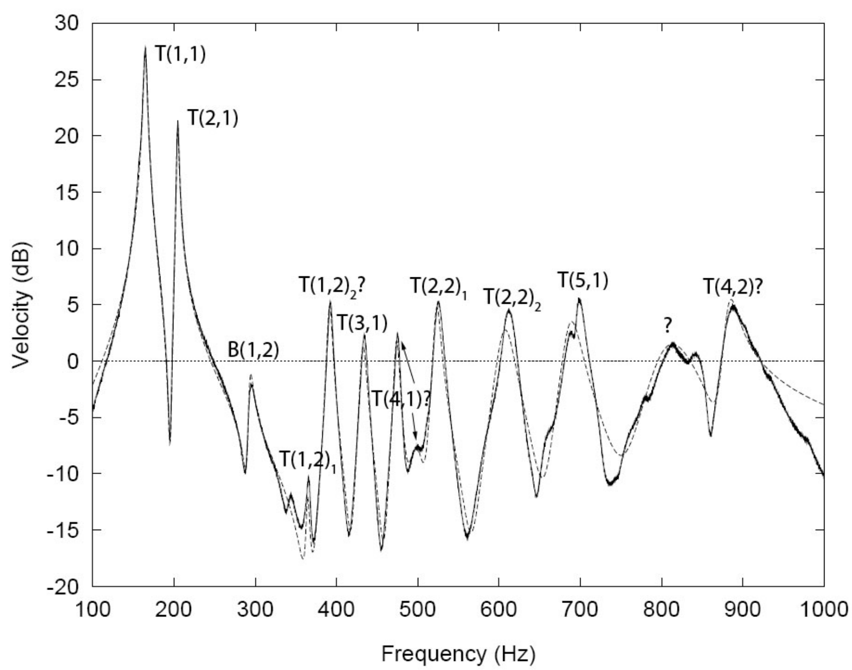

Figure 4.6. Frequency response of a classical guitar with the sound hole plugged from Wright [23]. The modes were identified by sprinkling dried tea on the top plate similar to Chladni patterns. The top was driven at the bridge at the low E string.

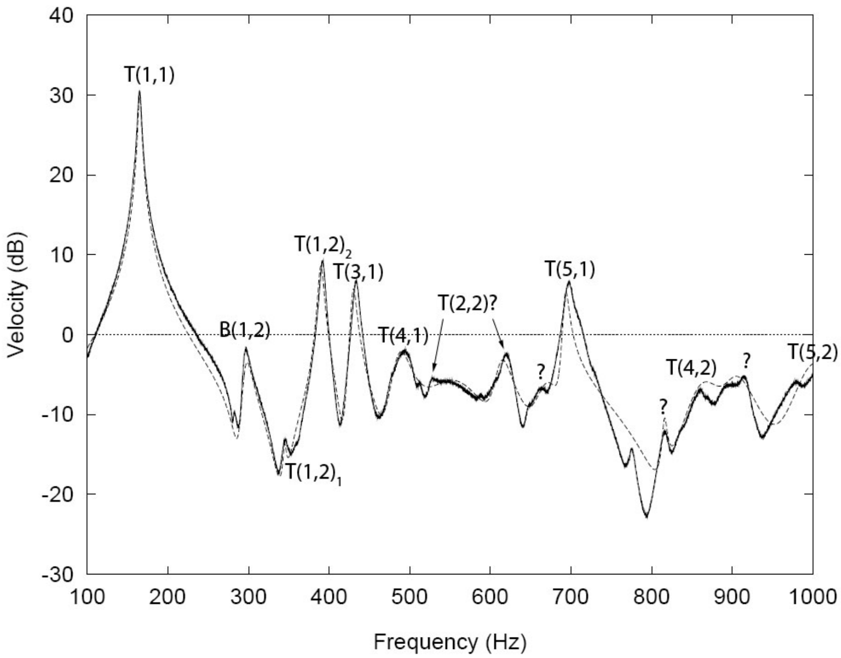

Figure 4.7. Frequency response of a classical guitar with the sound hole plugged from Wright [23]. The modes were identified by sprinkling dried tea on the top plate similar to Chladni patterns. The top was driven at the bridge at the G string.

Table 4.2. Modal frequencies from literature. The type of guitar is noted and makes clear that by far the most research has been done on classical guitars.

T(1,1)	T(2,1)	T(1,2)	T(3,1)	Guitar Type	Maker/notes	Reference
100	-	-	-	Steel	Taylor Dread.	[18]
102 / 193	-	-	-	Steel	Martin D-28	[18]
116 / 224	-	-	-	Steel	Yamaha	[18]
92 / 162 / 242	210	259 / 290	-	Classical	-	[11]
101 / 180	239	282 / 323	-	Classical	-	[11]
94.3 / 183.1	219	363.1 / 418.1	-	Classical	-	[27]
101 / 155 / 210	-	-	-	Classical/Radial	Eban	[15]
92 / 191 / 216	231	325	420	Classical	Caldersmith	[25]
105 / 221 / 223	295	428	600	Classical	Ramirez '67	[25]
105 / 212 / 223	275	420	586	Classical	Ramirez '74	[25]
108 / 219 / 248	296	424	585	Classical	Ramirez '82	[25]
104 / 219 / 242	311	423	662	Classical	Kohno #20	[25]
95 / 197 / 216	258	320 / 416	496	Classical	Smallman '82	[25]
92 / 209	239	338	438	Classical	Smallman '83	[25]
101 / 221	227	385	536	Classical	Smallman '86	[25]

Table 4.3. Frequencies of mode shapes for composite and Yamaha guitar. Modal frequencies are inferred from measured peaks and existing data for other guitars.

	$T(1,1)_1$	$T(1,1)_2$	T(2,1)	$T(1,2)_1$	$T(1,2)_2$	T(3,1)
Composite	99.3	175.3	220	330.5	362.3	~450
Yamaha	105	208	250*	360*	400	~446
Difference (%)	5.4	15.7	12.0	8.2	9.4	0.9

5 Detailed FEA Model

5.1 Material Testing

5.1.1 Procedures

The initial material testing that was done on the carbon fiber layup was not done in accordance with ASTM standard D3039 (Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials), which is the appropriate test for the materials used for the guitar. Also, the previous tensile coupons were made from full layups of graphite fabric (in different orientations) and foam. This data was used to give bulk material properties for the shell elements that were used in the initial FEM.

In refining the FEM it was determined that a better method was needed than was used before. The previous model did not take into account the changes in the guitar structure at different locations in the guitar structure. Treating the guitar shell as everywhere having a foam core adds extra stiffness to the edges where the actual guitar has the foam layer dropped, for example. Thus the guitar was modeled with different layered structures in the different areas of the guitar. In order to model the layers of the layup accurately, the material properties of each woven layer were needed. Previously the layup was approximated by alternating uniaxial carbon layers which gives a higher elastic modulus than a woven layer.

ASTM standards D3039/D3039M along with D3518/D3518M, were used to determine the orthotropic elastic moduli, shear moduli, and Poisson’s ratios for a standard woven layer of carbon fiber impregnated with epoxy. The testing was conducted on May 15, 2007 in the Mechanical Engineering Building at UW by Stephen Probert and Bill Kuykendall. Eight layers of fabric were used in each coupon and specimens were cut such that one sample was tested in one of the principle fiber orientations and one such that the load was 45 degrees offset from the principle fiber axes.

Sample rectangles from which the coupons were machined were laid-up on April 18, 2007 around 7:00pm and were left overnight under vacuum in order to cure at room temperature. The vacuum bagging was removed around 10:00am and the samples were cured for approximately 3 hours at 150 C starting at 2:30pm. Minor warping of the panels occurred with the largest occurrence in the -45/45 panel with the largest out-of-plane deflection approximately 5mm which is allowable by the standard. Each rectangle is approximately 6 inches by 12 inches with 8 layers of woven fabric. The approximate %wt of carbon to total weight was calculated to be 71%. This makes the epoxy %wt at 29%. The weight percents were not calculated using standards, but were found by comparing area weights of the panels to that of fabric that had not been impregnated with epoxy. These numbers agree with several similar calculations that were made before construction of the guitars. The results show that the weight percent of constituents is consistent to a few percent between layups made a different times, highlighting the relative consistency of the process.

The test coupons were cut from the rectangles using a diamond cutting wheel on a K.O.LEE milling machine, model Leematic 2000. The cutting wheel is approximately 1-2 mm thick and 13 cm in diameter. The feed rate was 17 inches per minute and the speed was 5 rps. The depth of the cut was approximately 0.38 mm. The radius of the edge of the wheel left a small step on one side of each test coupon. This radius caused an error in measuring the actual width of the sample. This will be discussed later.

The surface quality of the machining operation was shown by optical microscope for both samples in Figure 5.1. Some voids are apparent in the -45/45 specimen, but the overall surface finish is good and felt smooth to touch due to the diamond grit cutting wheel.

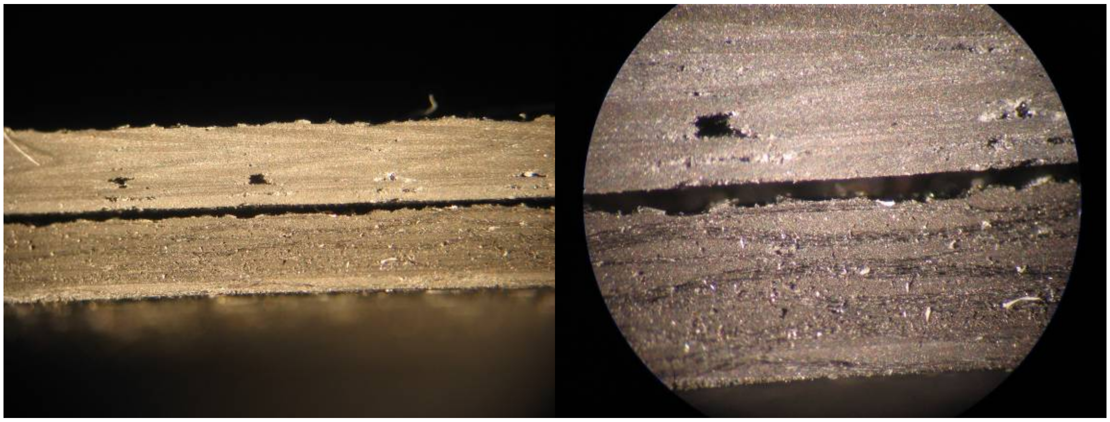

Figure 5.1. Edge quality of sample coupons prepared for tensile testing. The top sample is the -45/45 weave and the bottom sample is the 0/90 weave.

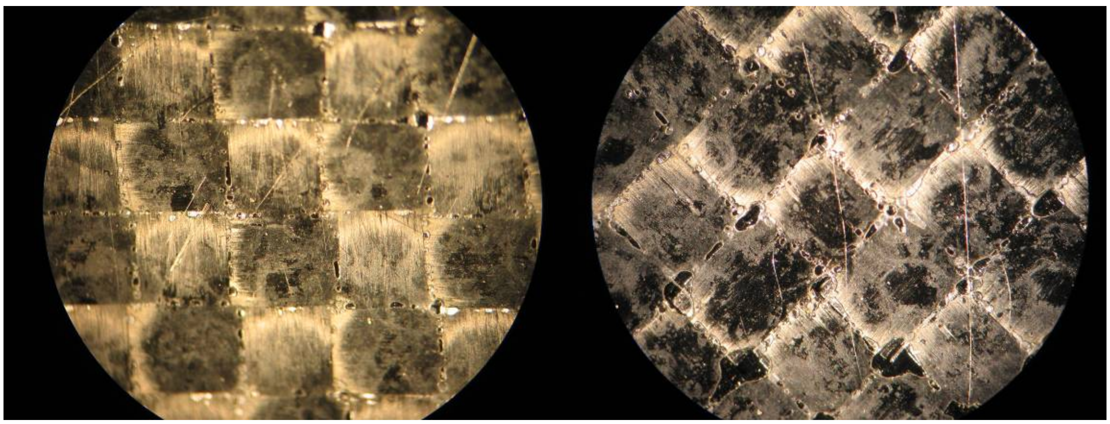

Figure 5.2. Surface quality of the tensile coupons prepared for tensile testing. The left sample is the 0/90 weave and the right sample is the -45/45 weave. Both samples exhibit porosity in some places, particularly at the locations between the tow.

Due to the expense of the strain gauges that would be used to measure both axial and transverse train on the front and the back of the test coupons, only one sample of each orientation was tested. ASTM standards require at least five samples per test for statistical significance, thus the results that were obtained are not statistically significant. It is also important to know that the error induced by using data that is not statistically significant may not be the largest error to bear on the results to be obtained from the FEM.

The final geometry of the test specimens are given in Table 5.1. The width and thickness dimensions were averaged for at least four measurements distributed along the gage length. The dimensions of the coupons fall within ASTM guidelines except that the thickness is recommended to be 0.1 inches. This was the intended dimension, but the final thickness of the layup was not well predicted.

Table 5.1. Dimensions of test coupons for tensile testing.

Sample Type	Length (in)	Width (in)	Thickness (in)	Cross Section Area (in^2)
0/90	>12	1.025	0.0648	0.0664
-45/45	>12	1.027	0.0653	0.0671

Resistance strain gauges were used to measure the axial and transverse strain on each side of the test coupons. Due to the small thickness of the coupons, any eccentricity in the loading of the machine could cause large bending stresses in the gage length; this is why strain gages were mounted on both sides of the coupons. The surface of the specimens were cleaned and sanded with 400 grit sandpaper. Alignment lines were polished onto the sample with a pencil to aid in accurate gage placement. The gages came as T-rosettes so the axial and transverse gages were already oriented correctly to each other. Cyanoacrylate adhesive was used to fix the gages to the specimens. The strain gages used for these tests are model CEA-06-250UT-10C from Vishay Micro Measurements. They are 1000-ohm gages in order to minimize the heating effect which occurs in composite testing since heat is not drawn away from the gage area (as it is with metals). A gage width of 0.25 inches was selected such that the gage would cover at least a 3-tow width of the weave to accurately estimate the bulk properties of the sample. A cross-head speed of 2 mm/min is standard but by accident the first sample tested (0-90) was tested at a slower rate of 1 mm/min. This slower rate still caused failure within 10 minutes as recommended. In order to ensure correct setup, the first sample was initially pulled up to a strain of 650 μm/m and then released from tension. When this sample was then tested to failure, the stress-strain plots overlaid each other, indicating that no plastic deformation had occurred within the sample. An example of a bonded strain gage is shown in Figure 5.3. This picture was taken after failure which is why part of the strain gauge has delaminated from the surface; the violent failure caused delamination.

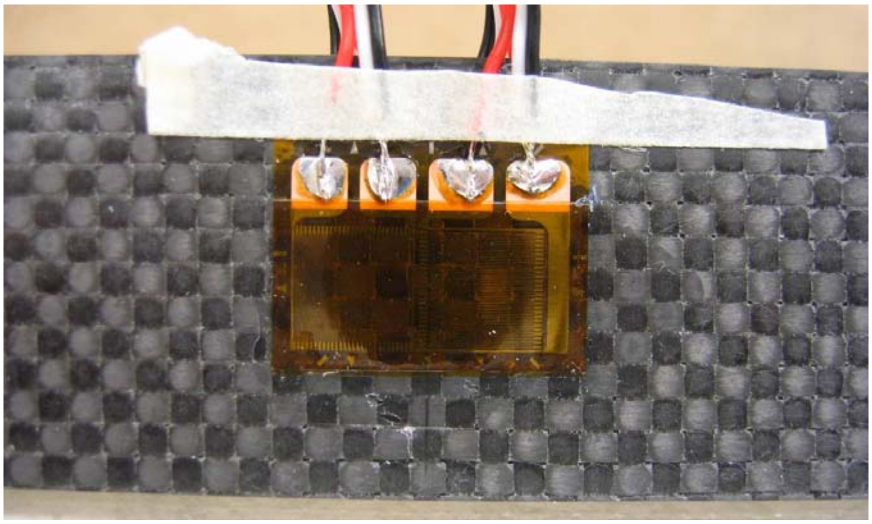

Figure 5.3. Example of a T-rosette strain gage bonded to a 0/90 tensile coupon that has failed. The violent failure caused the gage to partially delaminate from the coupon.

5.1.2 Results and Discussion

The results of the tensile test are shown in Table 5.2 for both types of weave. The data collected was elastic modulus (for 0/90), shear modulus (for -45/45), Poisson's ratio and the percent bending between the front and back of the sample. The standards recommend checking the percent of bending at the 2000 μm/m point and to use back to back strain gages on subsequent samples if the percent bending is greater than 3%. From the data it is seen that if further samples were tested, the 0/90 coupons would not require back to back strain gages and the -45/45 coupons would. The elastic and shear modulus are calculated using the modulus chord method. For the 0/90 sample, the elastic modulus was calculated at 1000 and 3000 μm/m; the shear modulus from the -45/45 sample was calculated at 1500 and 2200 μm/m. Poisson's ratio was calculated using the same strain ranges that were used for calculation of shear and elastic moduli. These measurements are consistent with the standards.

Table 5.2. Material data obtained from tensile tests.

Sample Type	Elastic Modulus (GPa)	Shear Modulus (GPa)	Poisson's Ratio	Percent Bending
0/90	62.38	-	0.056	0.82
-45/45	-	14.69	0.813	4.62

The 0/90 sample failed orthogonal to the loading direction (i.e. the axial direction) and the -45/45 sample failed along a line 45 degrees from the loading plane. Thus both samples failed normal to one of the principle fiber directions. It is difficult to tell where the first sample (0/90) failed because the failure was so violent that three breakages occurred; one near the upper grip, one adjacent to the lower grip and the third a little above the strain gages. The violence of the fracture and the energy released caused the stain gages to delaminate from the coupon. The -45/45 sample showed significant bending which was registered by the strain gages, but was also apparent by observing the sample; the sample showed bending along the width of the sample and also showed torsion along the length. The classification of the 0/90 failure is a lateral failure in the gage area at various locations, abbreviated LGM. The classification for the -45/45 specimen is an angled failure in the gage area at the center of the sample (SGM).

The purpose of the mechanical tests is to determine properties of the material in the elastic region (as the loads on a musical instrument are subtle); therefore it is not as critical to have statistically significant data. Material properties which depend on failure or are obtained from a single point of data rather than from a trend, such as ultimate tensile strength, elongation at break and fracture toughness, need statistically significant data as the nature of the measurement is inherently scattered.

The plots of the data obtained from the tensile tests are shown in Figure 5.5 through Figure 5.8. The first two figures show the stress-strain data for each coupon and the second two show the percent bending against the strain data. It is seen that the variation in bending is significantly different across the strain range with a large amount of bending occurring in the -45/45 sample. The nature of the bending in the -45/45 sample seems to indicate that the grips may have been misaligned when they were tightened on the coupon, which is indicated by the large bending at the onset of the test which decreases as the coupon is stretched. Interestingly, from the appearance of the sample, it would be hypothesized that the bending was increasing during the test since the sample became increasingly warped as the test progressed. Perhaps this warping was compensating for the misalignment and cancelled the difference in bending stress across the sample.

The stress-strain plots show very linear behavior for the 0/90 specimen which promotes confidence in the calculation of the elastic modulus. Initially it was surprising to see the linear data after seeing the testing machine display a stress strain plot based upon the extension of the cross-heads rather than the strain gage data. This cross-head-based plot indicated regions of plastic deformation in the specimen, but the strain gages verified the more accurate local stress state in the specimen gage length. This emphasizes the general hazard of using cross-head extension to calculate strain in a material.

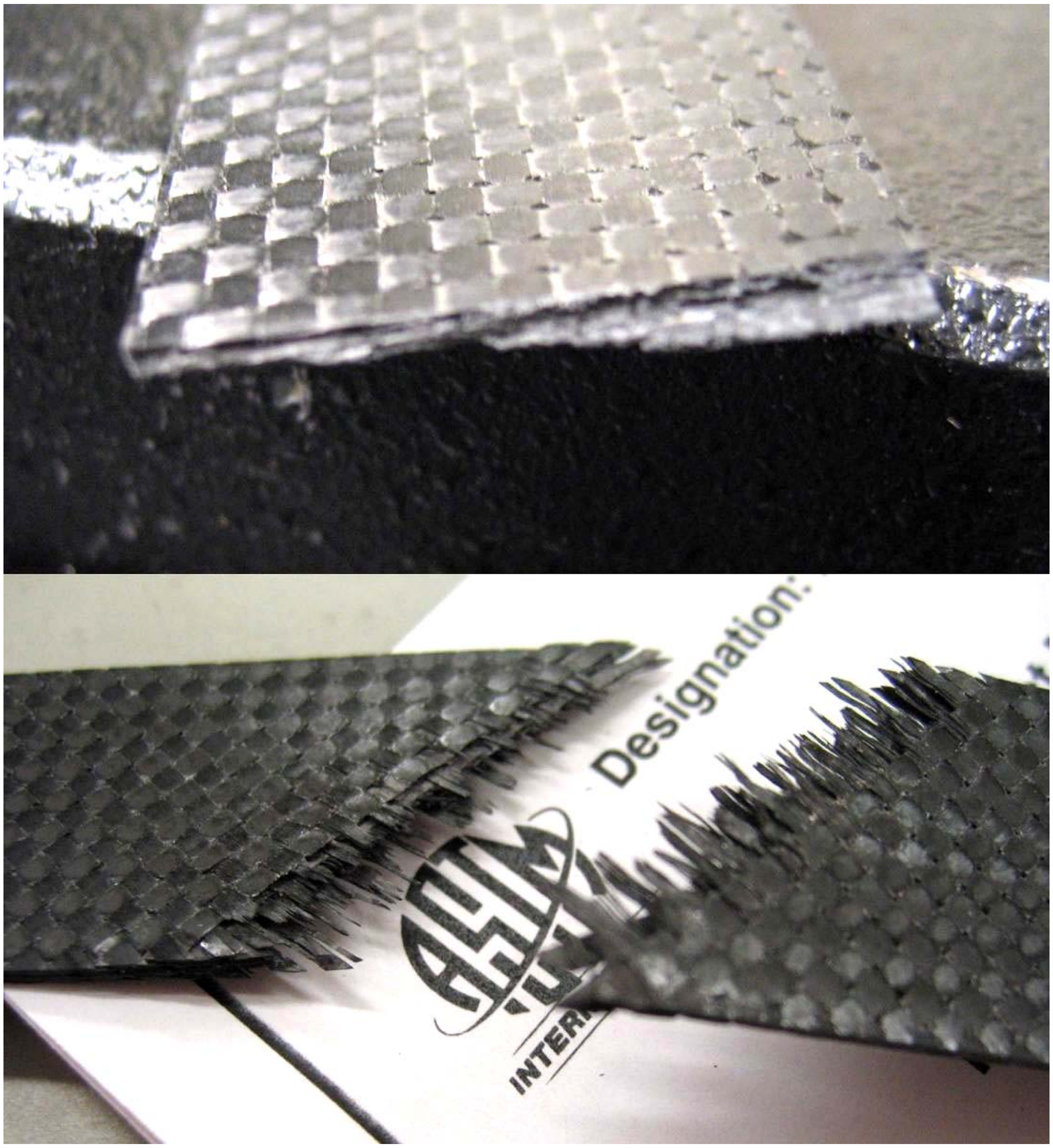

Figure 5.4. Failure modes of 0/90 and -45/45 specimens respectively. The 0/90 specimen failed orthogonal to load and the -45/45 failed 45 degrees from the load.

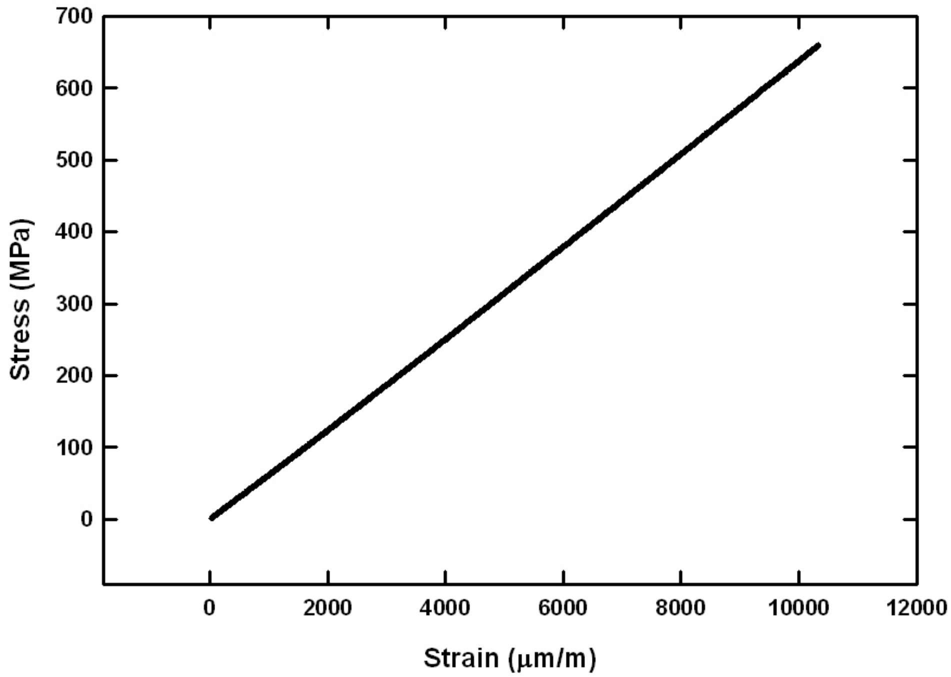

Figure 5.5. Stress-strain plot of 0/90 tensile coupon. Note the linear nature of the entire testing regime.

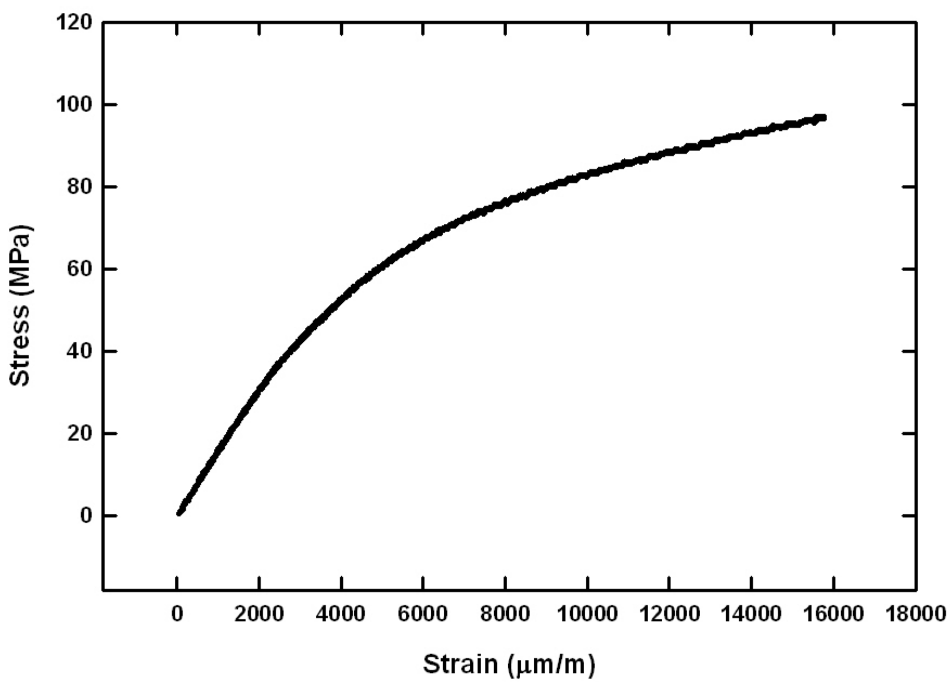

Figure 5.6. Stress-strain plot of -45/45 tensile coupon. This material did not show an entirely linear regime, but showed plastic deformation as the fibers "scissored."

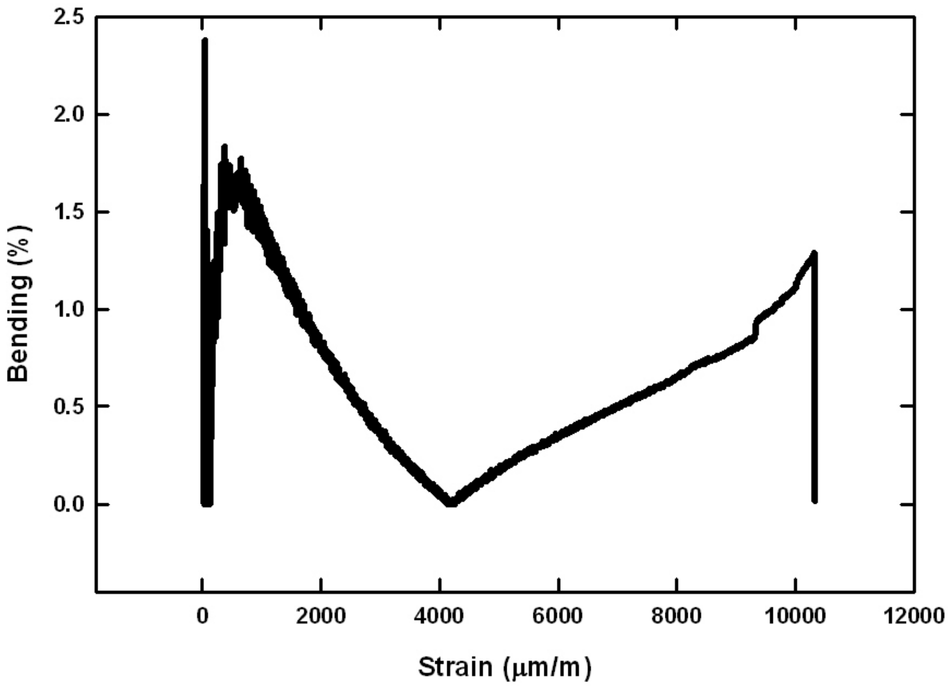

Figure 5.7. Bending versus strain of 0/90 test coupon. The maximum bending of 2.5% occurred at the onset of the load.

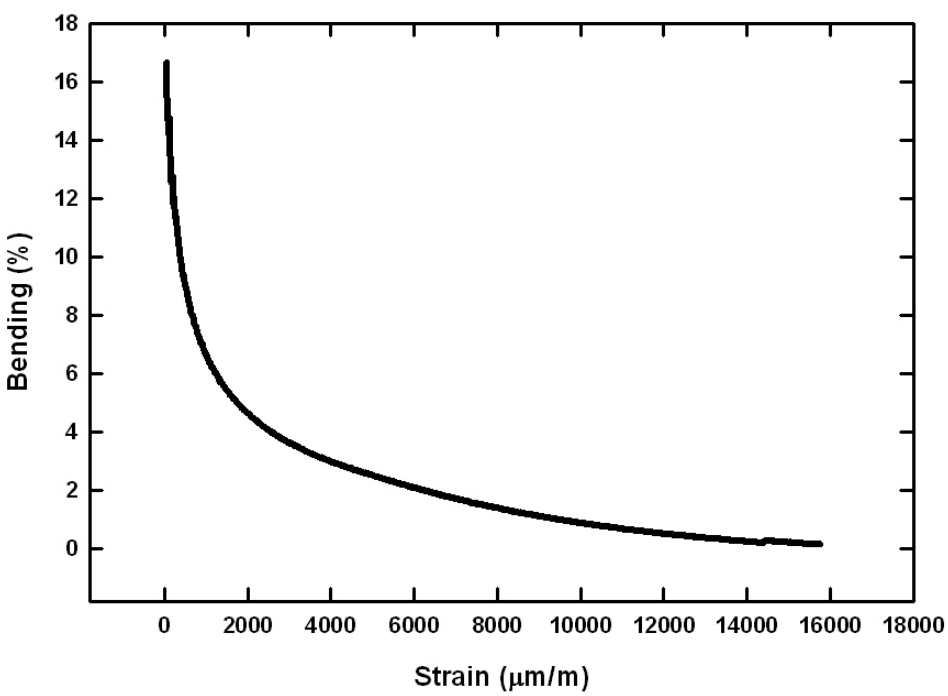

Figure 5.8. Bending versus strain of -45/45 test coupon. The maximum bending of 17% occurred as the sample was initially loaded indicating misalignment of the grips.

5.2 Finite Element Model Creation

The finite element model (FEM) previously used was based on a single solid geometry of the guitar body shape and the areas which bound this solid were used to define 2-D shell elements. The averaged layer properties used for the old material models in ANSYS were taken from material tests of the entire foam sandwich layup. Initially this same method was attempted for the refined model but in order to apply layers, the SHELL99 elements were used which were given orthotropic material properties from the mechanical testing just described and additional areas were defined on the solid by using split-lines in SolidWorks. This enabled defining the edge regions where there is no foam core and the bonded regions between the top, back and sides.

The limitations of this approach was that the blocks could not be modeled into the geometry very well and no acoustic modeling could be performed as the shell elements in ANSYS can only have an interface with another domain on one side; the guitar has two air-structure interfaces. It was later discovered that ANSYS does not have the ability to do any acoustic-structural interfaces and can only do fluid-structure interfaces with computational fluid dynamic elements which involve flows and are therefore not helpful to this analysis. Once it became clear that fluid loading effects and coupling between air and structural loads could not be modeled in ANSYS, the focus of the analysis shifted to a detailed structural model of the guitar. Essentially this model is of the guitar in a vacuum. Comparison was done with results from literature where finite elements were used to find the modal response of a guitar with and without air [11].

In attempting to improve on the limited shell model, a model using SOLID46, solid layered elements was developed. In order to complete this model, all the geometry of the guitar needed to be recreated with the regions of different layer properties now represented by solid geometry instead of just areas on a single solid guitar shape. This geometry did not already exist since the CAD geometry that was originally created did not account for the layup details. Once the geometry was created, it was converted into an initial graphics exchange specification (IGES) file to be imported into ANSYS. This proved to be the difficult part of creating the geometry as ANSYS had difficulty recognizing the solids. In order to get the geometry into the program, the assembly of parts were saved as a single part in SolidWorks which caused the individual parts to become generic solids. When this part was then transferred to ANSYS as an IGES file, ANSYS had less trouble understanding the volumes and areas. ANSYS always seemed to have trouble recognizing a volume with a guitar-shaped void in the center representing the air around the guitar. This type of volume was never successfully imported into ANSYS but became unnecessary in the pure structural analysis. The CAD geometry used is shown in Figure 5.9.

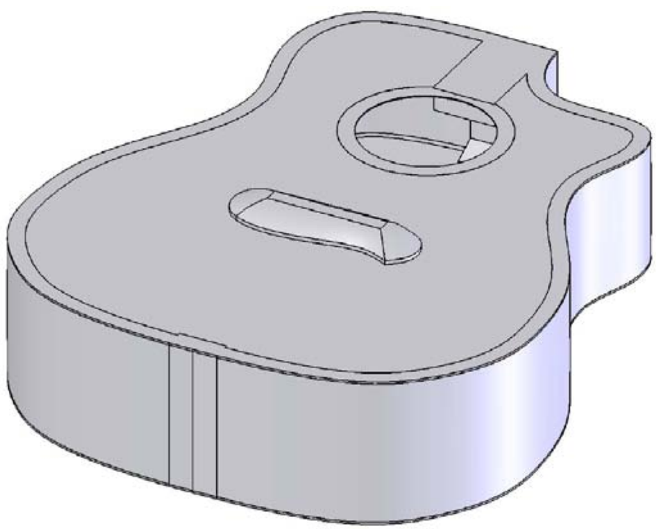

Figure 5.9. CAD geometry for the finite element model. This guitar structure consists of thin, shell-like volumes representing the different regions of the guitar layup as well as the blocks, bridge and bridge plate.

Once the geometry was represented in the finite element program it needed to be meshed. This proved difficult for some of the thinner features such as the volume around the sound hole which was only four fabric plies thick (approximately 1 mm). In order to create a coherent mesh for this volume, a smaller element size was utilized. SOLID45 elements with wood properties from Elejabarrieta [11] and a wood handbook [41] were used for the blocks, bridge and bridge plate. The full mesh contains 28,237 tetrahedral elements with 8,927 elements in the top plate of the guitar. The mesh is shown in Figure 5.10 and the number of elements in each component is given in Table 5.3. Three element edge lengths were specified for the model; the lines associated with the area around the sound hole had an element edge length of 5 mm; the lines around the lower side and blocks were 10 mm; the lines around the upper side were 20 mm. The nodes were merged together to attach all of the volumes as a single structure. Previous tests showed that the model was not very sensitive to element size.

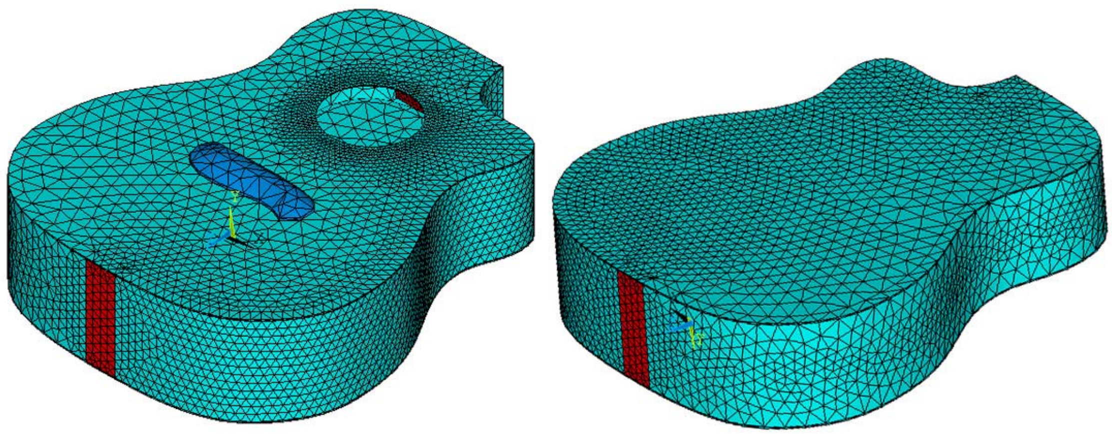

Figure 5.10. Finite element mesh of the guitar box with blocks, bridge and bridge plate.

Table 5.3. Number of elements in each volume composing the finite element model.

Volume	**Number of Elements**
Back, Center	5989
Back, Outer	1139
Top, Center	6242
Top, Outer	1353
Top, Rosette	1332
Side, Upper	3238
Side, Lower	5402
Bridge	226
Bridge Plate	157
Neck Block	2224
Neck Block Area	412
Tail Block	523
Total	**28,237**

The model incorporated three different layered structures. The thickness of the foam layer was 3.33 mm and the thickness of each ply of carbon was 0.257 mm. The top center, back center and the sides were given a [45/0/foam/S] structure; the region around the soundhole where no core exists was given a [45/0/S] structure; the bonded region at the edge of the plates was given a [45/0/S/S] structure which is the second structure, doubled. The stacking sequence of the layered composite elements are shown in Figure 5.11 through Figure 5.13 by means of ANSYS' layered element plot.

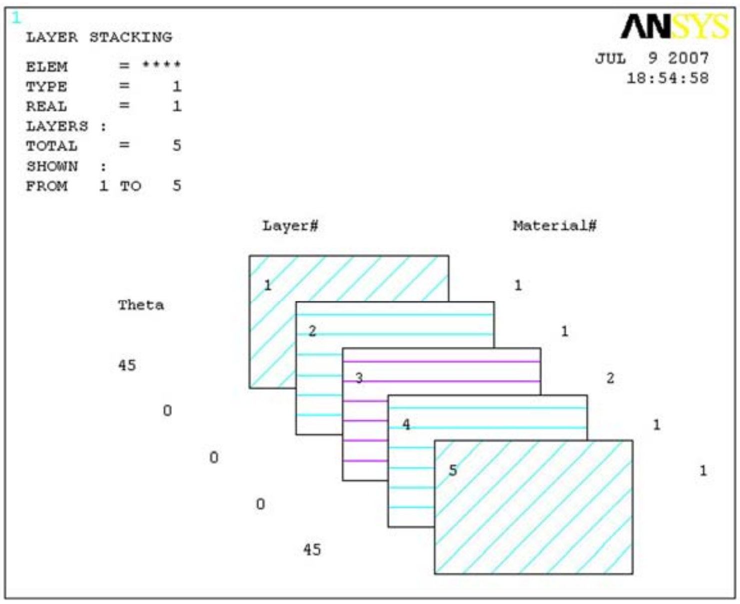

Figure 5.11. Stacking sequence and orientation of primary composite layered element with foam core.

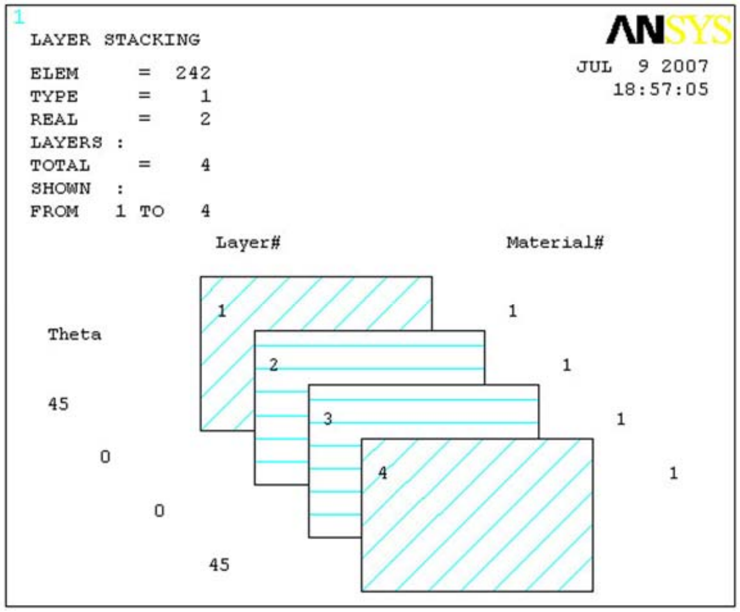

Figure 5.12. Stacking sequence and orientation of composite layered element for the rosette area.

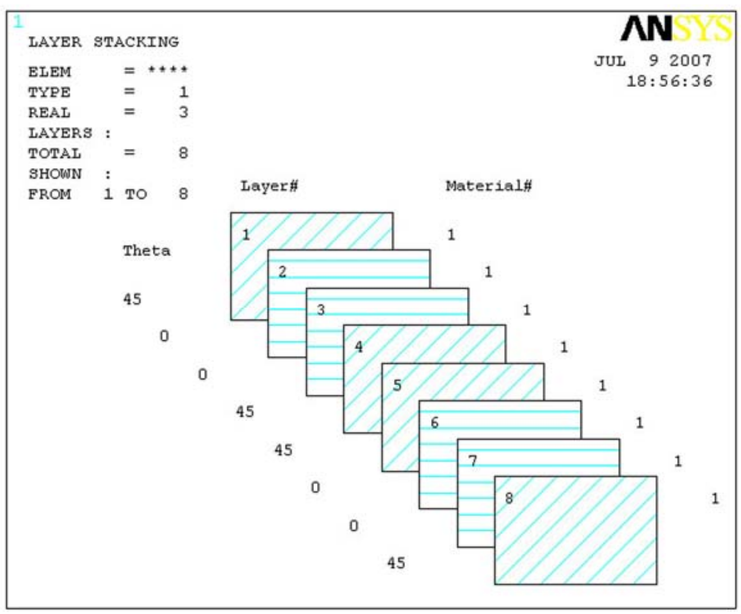

Figure 5.13. Stacking sequence and orientation of composite layered element for the bonded edges of the top and back to the side flanges.

The material properties used in the model are given in Table 5.4. Some of the material properties which were not available for the wood types were inferred from the other wood values that were given. The material data for the composite is taken from the material tests described previously.

Table 5.4. Material properties used in the finite element model. Density in kg-m^{-3} and stresses in GPa.

Material	Density	E_X	E_Y	E_Z	P_{XY}	P_{YZ}	P_{XZ}	G_{XY}	G_{YZ}	G_{XZ}
Composite	1436	62.40	62.40	10.00	0.40	0.40	0.40	14.70	14.70	14.70
Foam	50	0.03	-	-	0.32	-	-	-	-	-
Mahogoany	450	10.67	0.53	1.18	0.30	0.26	0.03	0.94	0.63	0.22
Ebony	1100	19.00	2.11	0.95	0.30	0.26	0.03	1.67	0.40	1.12
Rosewood	775	16.00	2.20	0.72	0.36	0.26	0.03	1.10	0.30	0.84

5.3 Finite Element Analysis Results and Discussion

5.3.1 Results

A modal analysis was conducted in ANSYS to extract the natural frequencies of vibration of the guitar in a vacuum. This was done for the entire sound box with the bridge, bridge plate and blocks in a vacuum and also for just the individual plates (top and back) in vacuum. The plate vibrations were analyzed in addition to the body because a lot of existing research has been done on top and back plates alone. For the plate simulations, the edges were given pinned boundary conditions as is common in the literature. The first ten modes of the assembled sound box are given in Figure 5.14 and Figure 5.15 showing the top and the back of the guitar for each frequency. The modes of the hinged top plate are given in Figure 5.16 and the modes of the hinged back plate are given in Figure 5.17. The frequency of vibration is given in each instance.1436

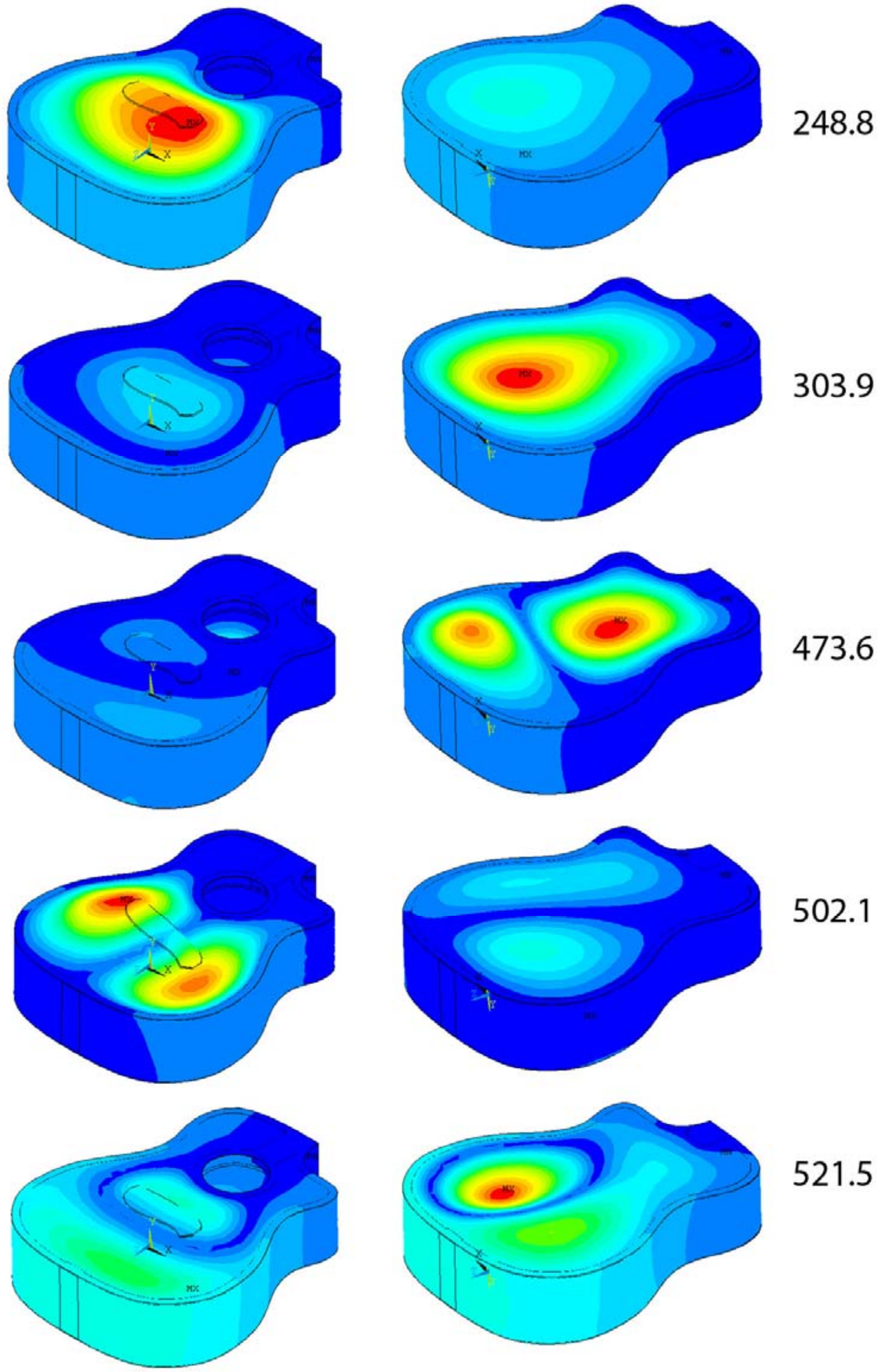

Figure 5.14. First five modes and frequencies of the guitar body with blocks, bridge plate and bridge. The back response is shown to the right of the top response.

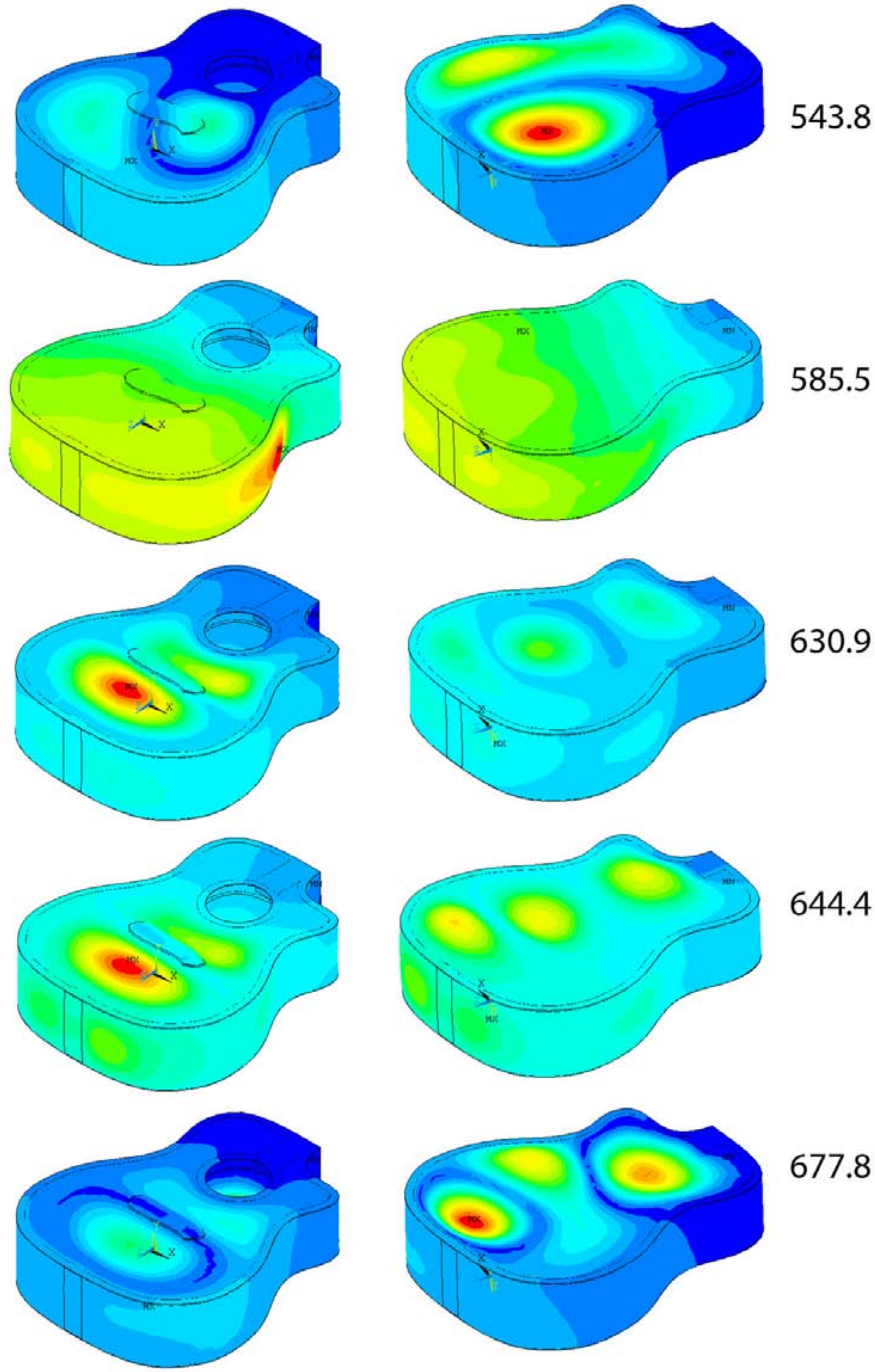

Figure 5.15. Modes and frequencies six through ten of the guitar body with blocks, bridge plate and bridge. The back response is shown to the right of the top response.

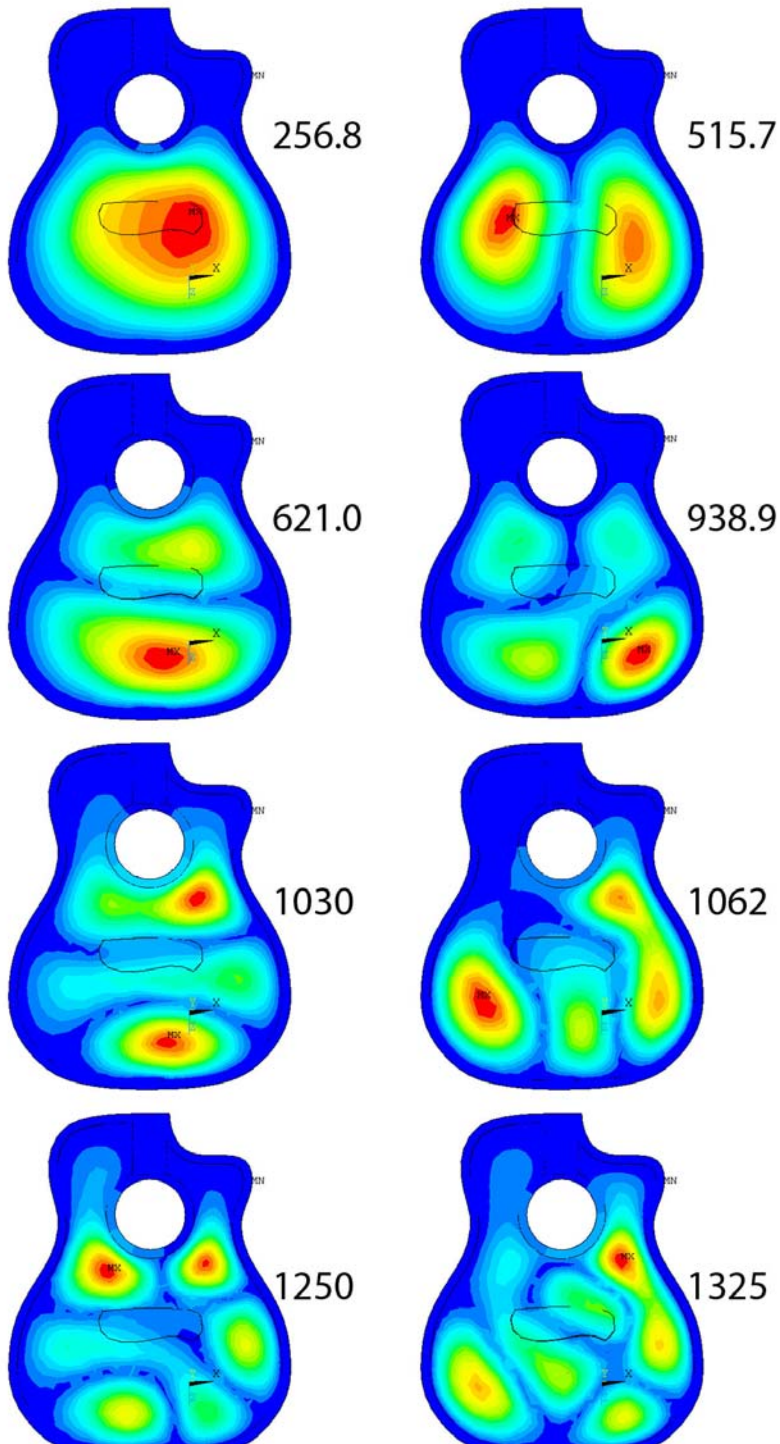

Figure 5.16. Top plate modes and frequencies. The plates were constrained with pinned boundary conditions at the edge of the plate excluding the sound hole. The bridge and bridge plate are included.

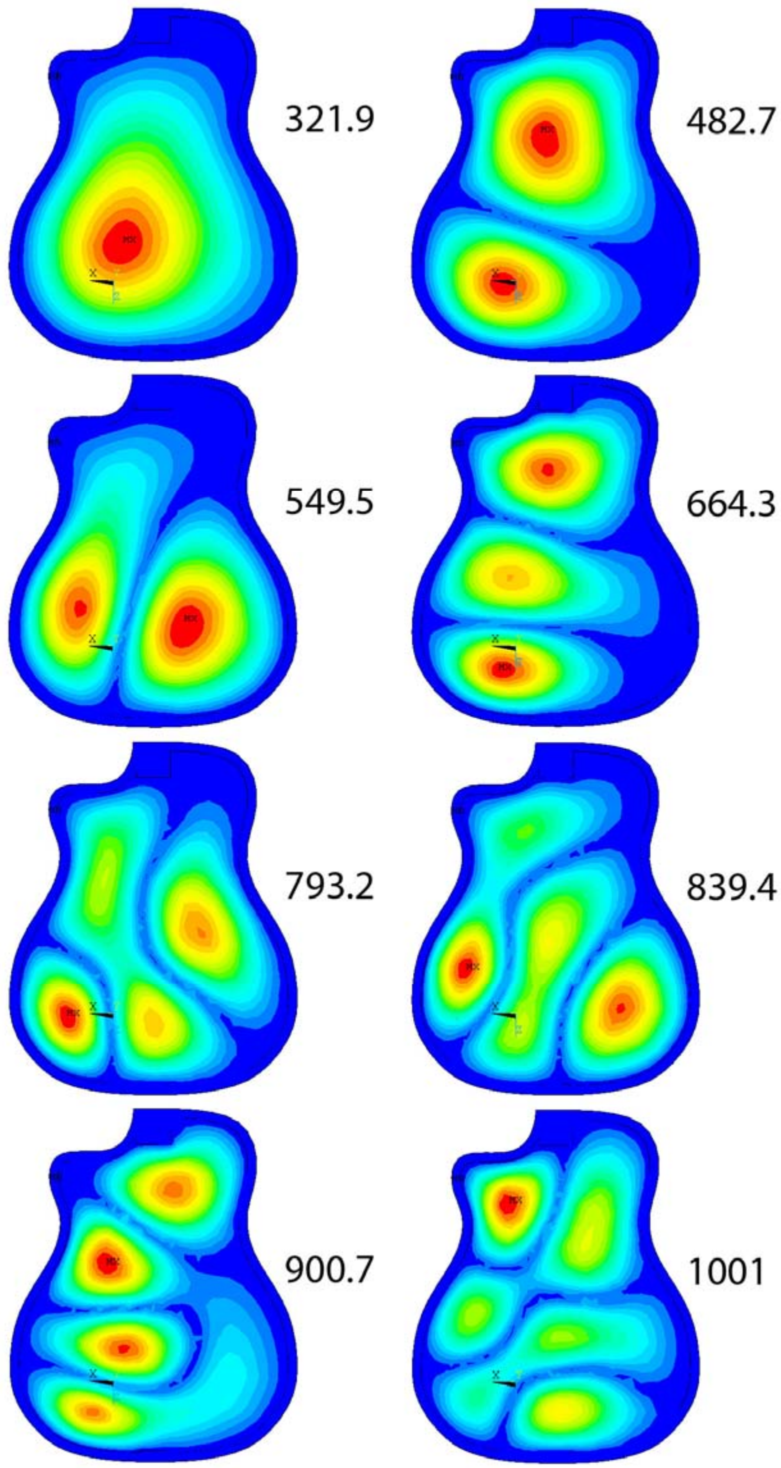

Figure 5.17. Back plate modes and frequencies. The plates were constrained with pinned boundary conditions at the edge of the plate.

5.3.2 Discussion

The modes of the guitar body are matched closely with the modes of the individual plates with hinged boundary conditions. For lower modes (below 600 Hz), the plate frequencies are all higher than the corresponding body frequencies by an average of 13.7 Hz. Above 600 Hz the modal frequencies seem to be lower for the plates. This is probably due to the structural coupling that occurs for these modes which alters the modal frequencies. In this way the plates give a good indication of the pure normal modes of vibration. In order to get more pure modes, researchers have fixed the sides of the guitars in the model which eliminates the interaction of the side modes and prevents coupling of the top and back through the sides [11]. The cutaway in the guitar and the asymmetry of the bridge have a clear effect on the symmetry of the mode shapes. For instance, the B(1,1) antinode is off-center due to the cutaway, but the T(1,1) antinode is off-center in the opposite direction, showing that the smaller size of the right side of the bridge makes the mode more responsive there.

Table 5.5 summarizes the modal frequencies of the body and the plates and compares the corresponding modes. Plate modes are only included up to the highest body mode. The side mode that showed up most dominantly was a vibration near the waist of the guitar on the lower side at 585.5 Hz. This mode is designated S(waist).

Table 5.5. Comparison of body modes and plate modes.

	T(1,1)	B(1,1)	B(1,2)	T(2,1)	$B(2,1)_1$	$B(2,1)_2$	S(waist)	T(1,2)	T(1,2), B(1,3)	B(1,3)
Body	248.8	303.9	473.6	502.1	521.5	543.8	585.5	630.9	644.4	678
Top Plate	256.8	-	-	515.7	-	-	-	621	-	-
Back Plate	-	321.9	482.7	-	549.5	549.5	-	-	-	664
Difference	8	18	9.1	13.6	28	5.7	-	-9.9	-	-13.5

Comparing the finite element results to the measured results of the guitar shows large discrepancies though the modes are in the same order (see Table 5.6). Discrepancies are expected due to the difference that the FEM did not include air effects, but existing data indicates that the discrepancies should not be as large as they are [11].

Elejabarrieta et al.. found modal frequencies of a classical guitar with and without air by numerical methods and compared the results to measurement of the modeled guitar using modal analysis. The frequencies they calculated and measured are reproduced in Table 5.7. Instead of giving subscripts for repeated modes, the frequencies are separated by a forward slash in the same column. The largest error between their FEA result of the guitar without air and the modal analysis is 37 Hz between the T(1,1) modes. Since some modes become two modes when air is added, the difference was taken between the airless mode and the closest with-air mode.

Comparing the FEA result of the guitar with and without air from literature, the modes that are split by coupling with the air are generally near the upper split-mode frequency with the exception of the T(1,1) mode which lay in between the split-mode frequencies. Most modes split; the T(1,2), T(2,1) and the B(1,3) modes, which did not split were reduced by 5, 5 and 10 Hz, respectively. The B(2,2) mode of the airless guitar seemed to morph into the B(2,1) mode since the frequencies are similar and the upper part of the B(2,2) mode was weak to begin with, making it look very similar to the B(2,1) mode. The T(3,1) frequency of the airless guitar might have been out of the range of analysis once the air was added, or the mode number was too high and the researchers only looked at the first eight modes.

Table 5.6. Comparison of FEA and experimental results. Measured frequencies we taken beneath the bridge on the top of the guitar, offset to the left.

	$T(1,1)_1$	$T(1,1)_2$	B(1,1)	B(1,2)	T(2,1)	$B(2,1)_1$	$B(2,1)_2$	S(waist)	T(1,2)	T(1,2), B(1,3)	B(1,3)
Body	-	248.8	303.9	473.6	502.1	521.5	543.8	585.5	630.9	644.4	677.8
Top Plate	-	256.8	-	-	515.7	-	-	-	621	-	-
Measured	99.3	175.3	-	-	220	-	-	-	360	400	-
Difference	-	73.5	-	-	282.1	-	-	-	270.9	244.4	-

Table 5.7. Data from Elejabarrieta et al.. [11] with FEA data of top and back plates, sound box without air and sound box with air. Measured values from a modal analysis of the guitar that was modeled are also included.

	T(1,1)	B(1,1)	B(1,2)	T(2,1)	B(2,1)	B(2,2)	T(1,2)	T(1,3)	B(1,3)	T(3,1)
Plates	139	177	250	205	-	-	281	325	332	386
Box, no air	138	175	289	215	-	337	293	-	383	415
Box, air	92/162	92/162	259/290	210	332	-	259/290	-	373	-
Measured	101/180	101/180	282/323	239	372	-	282/323	-	393	-

5.4 FEM Sensitivity Analysis

In order to determine the possible causes of error between the model and the measured guitars, a sensitivity analysis was conducted. From the standard model that has already been presented, individual variables were altered and the resulting changes in frequencies were recorded. This is similar to work that has already been conducted by Ezcurra to evaluate the effect of material properties on guitar top plates [31]. The properties that were altered were the material properties of the composite material and also the thickness of the foam core. The first ten modes were extracted from the model although sometimes the order and strength of the modes change. For some of the parameters that altered the modes to a great extent the way the modes changed was difficult to describe and impractical to give full detail of.

5.4.1 Poisson's Ratio Sensitivity

The effect of Poisson's ratio was evaluated by varying both the in plane ratio and also the two out-of –plane ratios together. The two out-of-plane ratios were varied in unison since the symmetry of the layup caused them to have the same effect. Previous alterations of Poisson's ratio in the rough FEM with shell elements showed that it did not largely affect the modal frequencies. Figure 5.18 shows the trend of the modal frequencies with changing in-plane Poisson's ratio. At higher Poisson's ratio, the frequencies increase more dramatically with a stronger effect at the higher frequencies. The mode shapes are listed in the legend. Initially the 8th mode that appears is mostly just T(1,2) and the 9th is a mix of T(1,2) and B(1,3); at 0.8 the T(1,2) component has mostly disappeared from the 9th mode and is only in the 8th. In the range of Poisson's values that are reasonable for this composite structure, the modes change negligibly.

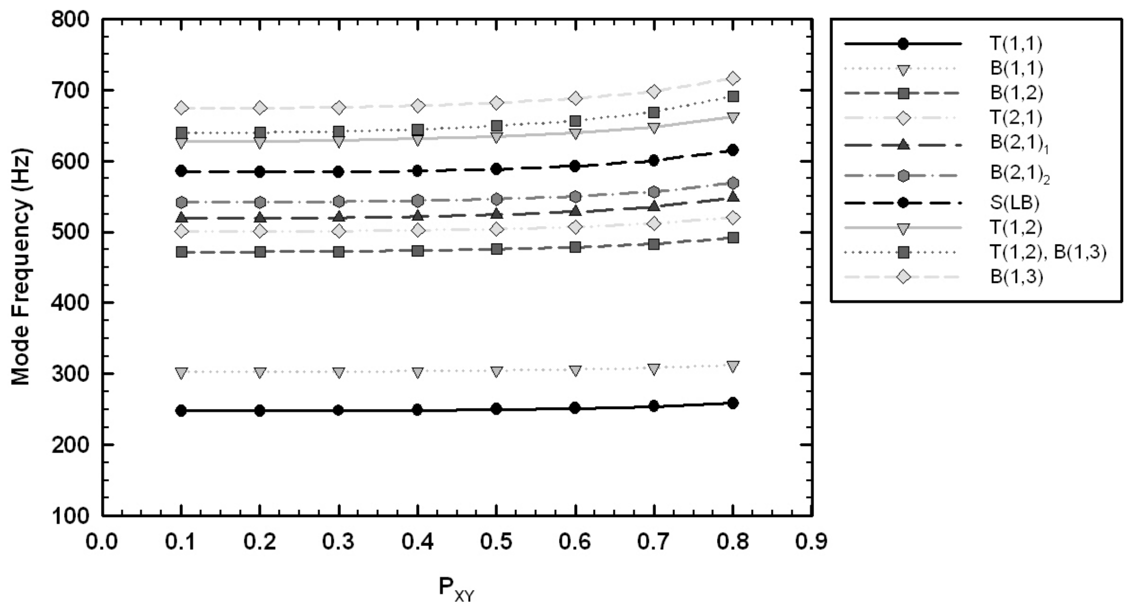

Figure 5.18. Modal frequency variation with changing Poisson's ratio of strain in the plane of the layup.

The effect of the out-of-plane Poisson's ratios is much more subtle as is expected for a thin structure. At the lower values, the 8th mode has some B(1,3) coupling and the 9th mode is biased more towards B(1,3) with some subtle interaction with a dipole side mode at the lower bout with a nodal line at the tail block which is designated S(LB), with LB indicating the lower bout location. The 10th mode becomes more and more asymmetric with increasing Poisson's ratio as there is more interaction with a higher order, 4-antinoded mode. Overall the effect of these Poisson's ratios are insignificant, especially in the applicable range.

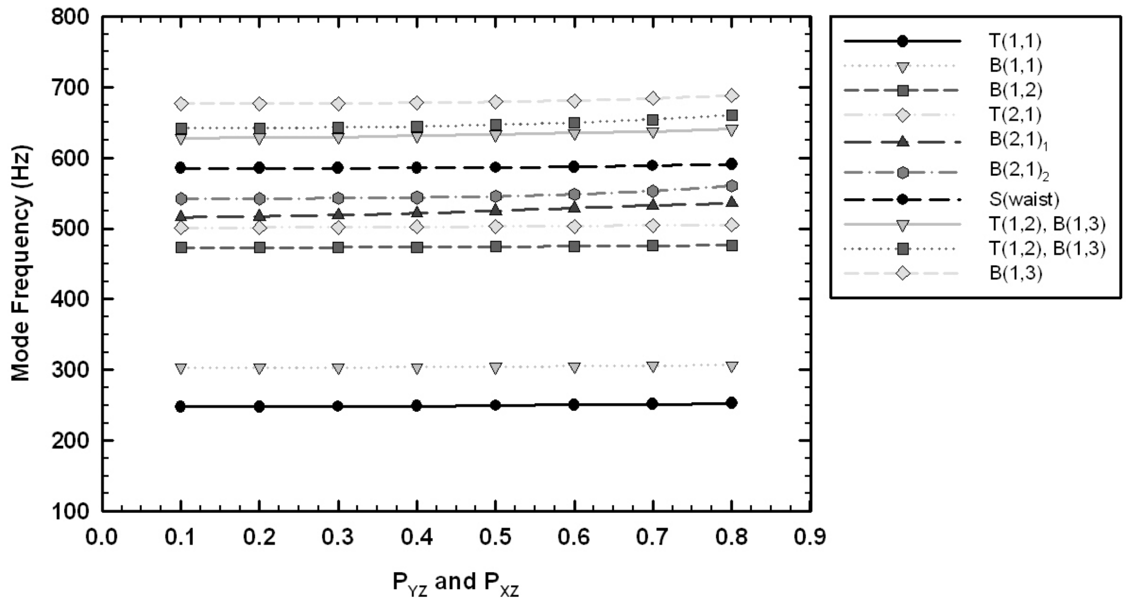

Figure 5.19. Modal frequency variation with changing Poisson's ratio of strain out of the plane with respect to the principle in-plane directions. Due to the symmetry of the layup, these parameters have the same effect and thus were changed in concert.

5.4.2 Elastic Moduli Sensitivity

Again, due to the symmetry of the layup, the effects of the two in-plane elastic moduli are the same and were thus varied together. For the case of these in-plane elastic moduli, the effects of the S(LB) mode change as they are varied. The moduli were varied between 30 and 100 GPa; for the lower values (less than 50 GPa), the 8th mode is dominated by this side mode. In the high range (greater than 62.4 GPa), it has surpassed the T(1,2)/B(1,3) coupled mode and is the 9th mode with both T(1,2) and B(1,3) contribution. In the intermediate range the S(LB) mode has died down and the 8th mode is mostly a T(1,2) mode. Increasing modulus increased the modal frequencies as expected with a greater effect at higher modes. The effect is mostly linear across the range of moduli tested. The results for these two elastic moduli are given in Figure 5.21.

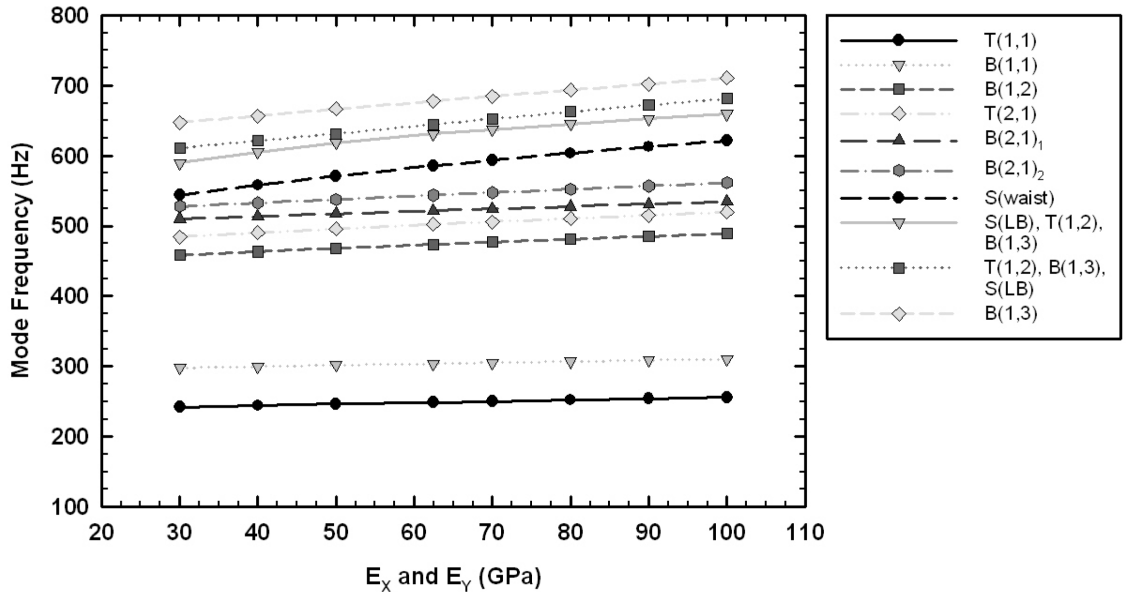

Figure 5.20. Modal frequency variation with changing elastic moduli in the in-plane directions.

The variation of the out-of-plane elastic modulus was more drastic, but this could be due to the range that was selected which was 1 to 35 GPa. The results are given in Figure 5.21. Again, the effects of the S(LB) mode seemed to be sensitive to the modulus. The modes behaved much like they did for the other changing elastic moduli. At the lower values showed a more dominant S(LB) mode as the 8th mode with T(1,2) coupled to B(1,3) as the 9th mode. The higher modulus values shoe the T(1,2), B(1,3) and S(LB) coupled at the 9th mode and a strong T(1,2) at the 8th mode. Increasing the out-of-plane elastic modulus increased the modal frequencies as expected, but the trends were very different from mode to mode. Some modes exhibited a rapid increase between 1 and 5 GPa and others showed a faster rate of increase at the higher values.

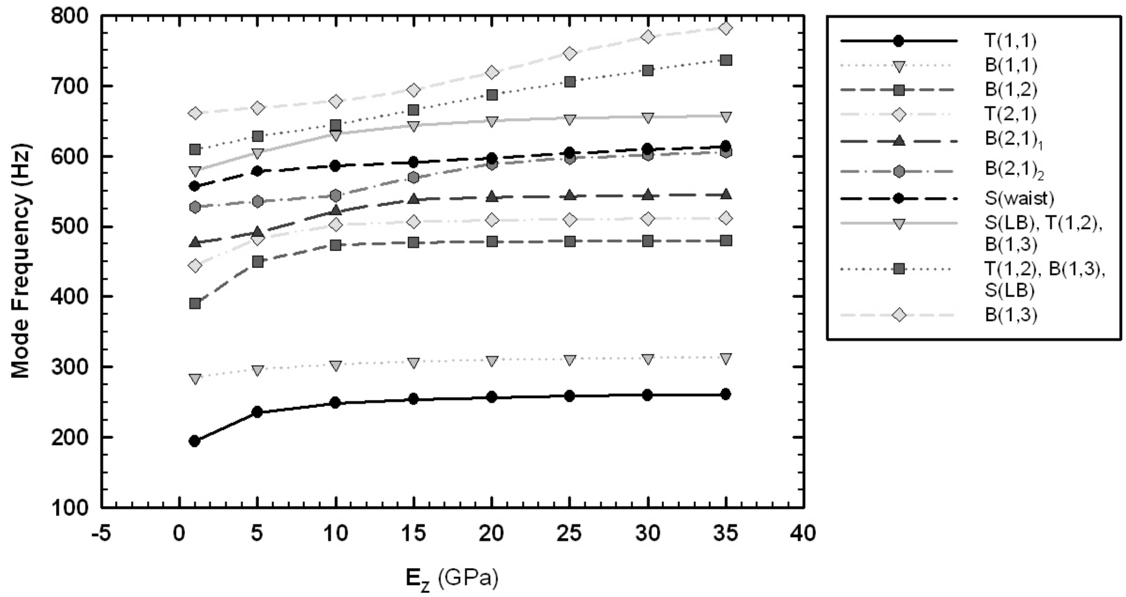

Figure 5.21. Modal frequency variation with changing elastic modulus in the out-of-plane direction.

5.4.3 Shear Modulus Sensitivity

The increased stiffness caused by the increased shear moduli in general caused increased modal frequencies. The shear moduli were all varied from 5 to 35 GPa. For the in-plane shear modulus, this was a very linear and uniform trend with the higher modes having more sensitivity. The only variation of the mode shapes was the 8th mode having more significant B(1,3) contribution at low values. The results of the in-plane shear stress sensitivity analysis is shown in Figure 5.22.

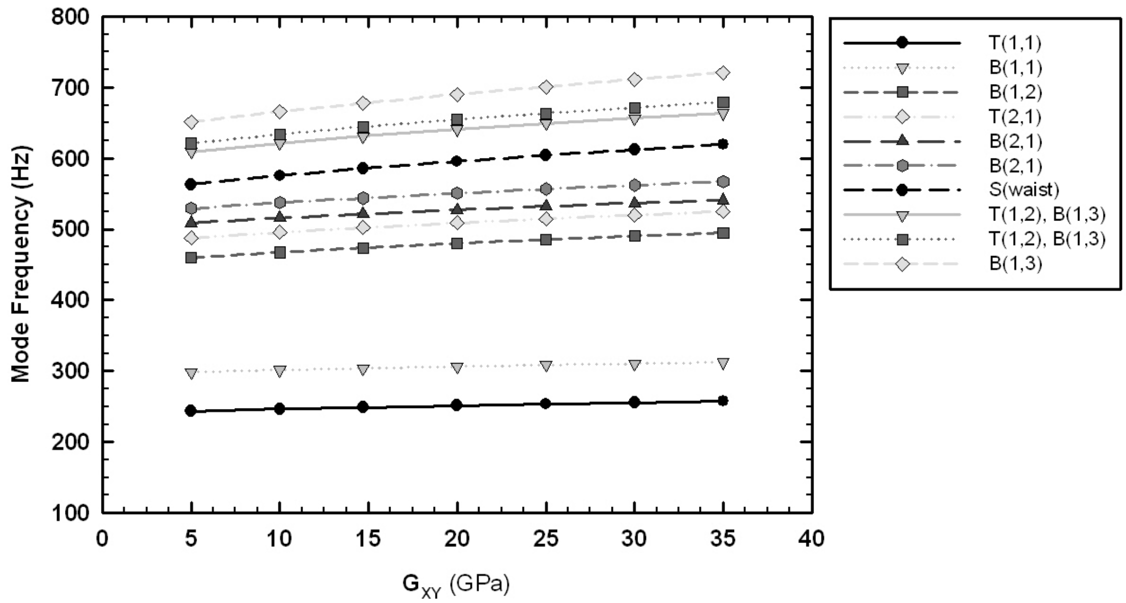

Figure 5.22. Modal frequency variation with changing shear modulus in the x-y plane.

The out-of-plane shear moduli were different in that there was almost no sensitivity in the lower modes (modes one through three and most of four through six), and the top mode, B(1,3), was barely sensitive. The modes in between (the side modes, T(2,1) mode and the T(2,1)/B(1,3) coupled mode) were quite sensitive to the shear moduli in complicated ways. Both of the out-of-plane shear moduli were tested separately although their responses came out the same, as expected due to symmetry (see Figure 5.23 and Figure 5.24). The first figure shows the modes grouped by order and lists them in the legend by mode number in the cases that the mode shape is not consistent. In Figure 5.24 the modes have been separated by mode shape to give clarification of the trends.

The lowest value of shear moduli (5 GPa) causes a doubling of the T(2,1) mode such that it is both the 4^{th} and the 5^{th} mode. This causes the other modes to shift up. The side mode at the waist which would be the eighth mode, does not exist and is replaced by the S(LB) mode. The T(1,2) mode is after this and the T(1,2)/B(1,3) coupled mode disappears which leaves the B(1,3) mode as the 10^{th} mode appearing. At 10 GPa, there is no longer a second T(2,1) mode and the modes look more like the modes at the standard conditions though mode 8 does have some of the S(LB) mode coupled to T(1,2). At 20 GPa, the 8th mode is a strong T(1,2) mode with a little bit of contribution from the B(1,3) mode. The 9th mode, instead of being a T(1,2)/B(1,3) coupled mode, is a coupling between B(1,3) and S(LB) modes. The modes at 25 GPa are much like they were at 20 GPa. At 30 GPa the 7th mode is mostly T(1,2) with some B(1,2) and the 8th mode is a mix of T(1,2), B(1,3) and S(waist). Mode 9 is just B(1,3) and the 10th mode is a coupling of B(1,3) with S(LB). At 35 GPa the 8th mode is just the S(waist) mode, the 9th mode is B(1,3) and the 10th is a coupling of T(1,2), B(1,3) and S(LB). Clearly the side modes are largely affected by the material properties and as they change, they couple differently to the T(1,2) and B(1,3) modes for the most part.

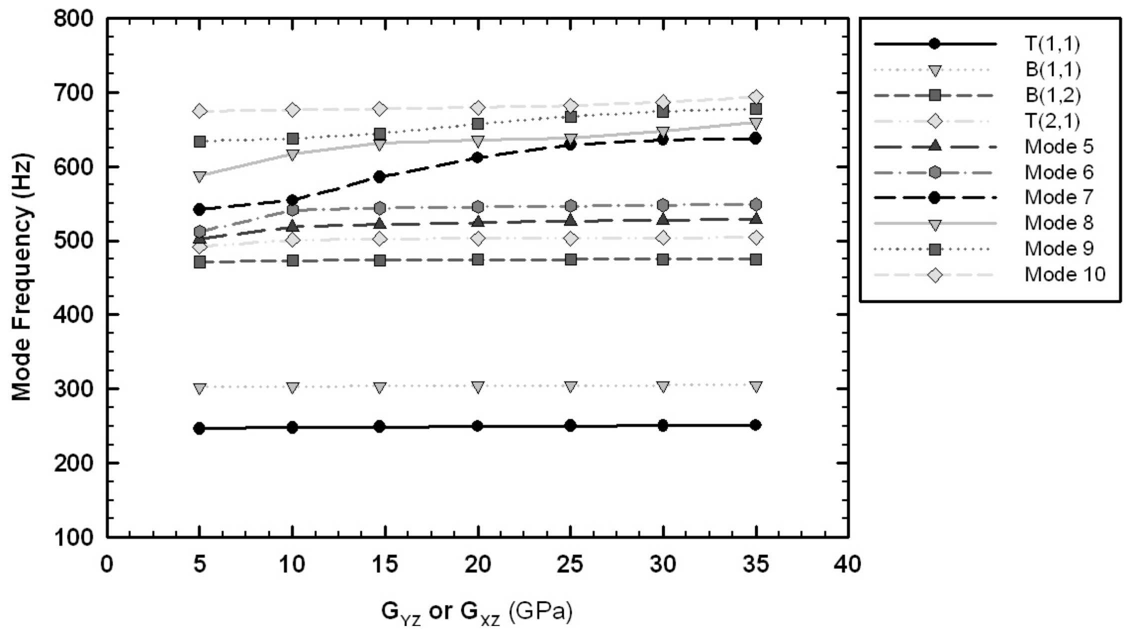

Figure 5.23. Modal frequency variation with changing shear modulus in the x-z plane with the upper modes defined by mode number instead of mode shape.

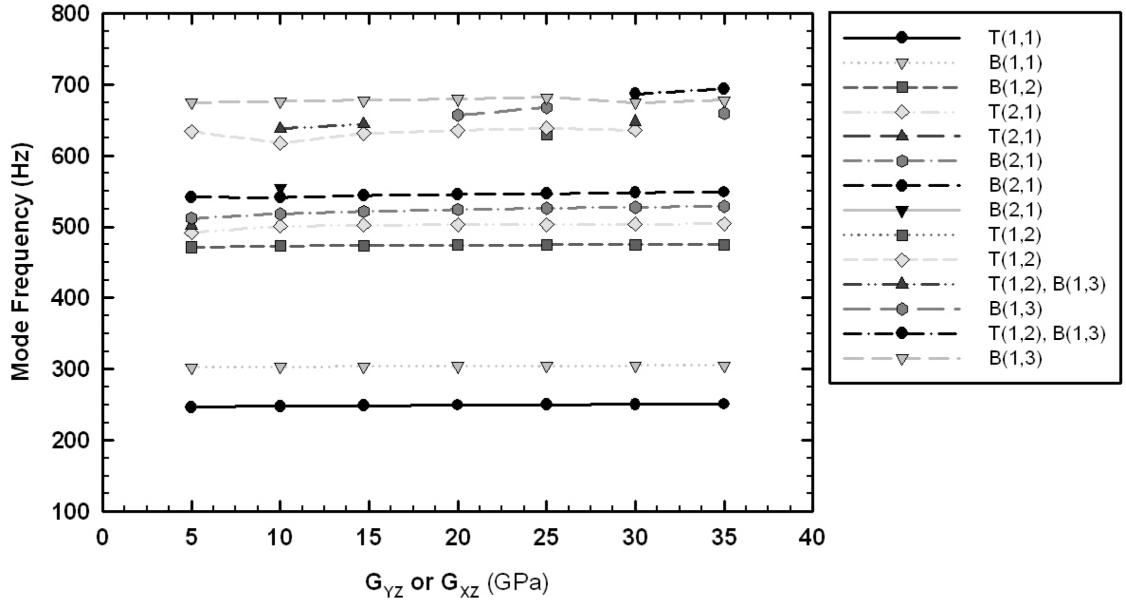

Figure 5.24. Modal frequency variation with changing shear modulus in the x-y plane with all the modes defined by mode shape.

5.4.4 Foam Thickness Sensitivity

The foam thickness was varied around the measured thickness only slightly; from 3.0 to 3.6 mm. The results are shown in Figure 5.25. The results shown subtle, linear, decreasing trends with varying levels of sensitivity. The negative trends indicate that the increased mass of the foam, which is not much, is a larger factor than the increased bending stiffness caused by further separating the two composite layers. Some of the modes were barely effected by the foam thickness; the S(waist) mode was not affected at all and the B(1,1) mode was very subtle. The larger thicknesses caused more coupling between the T(1,2), B(1,3) and S(waist) modes at the higher frequencies. In those cases the both the 8^{th} and 9^{th} modes have more B(1,3) contribution.

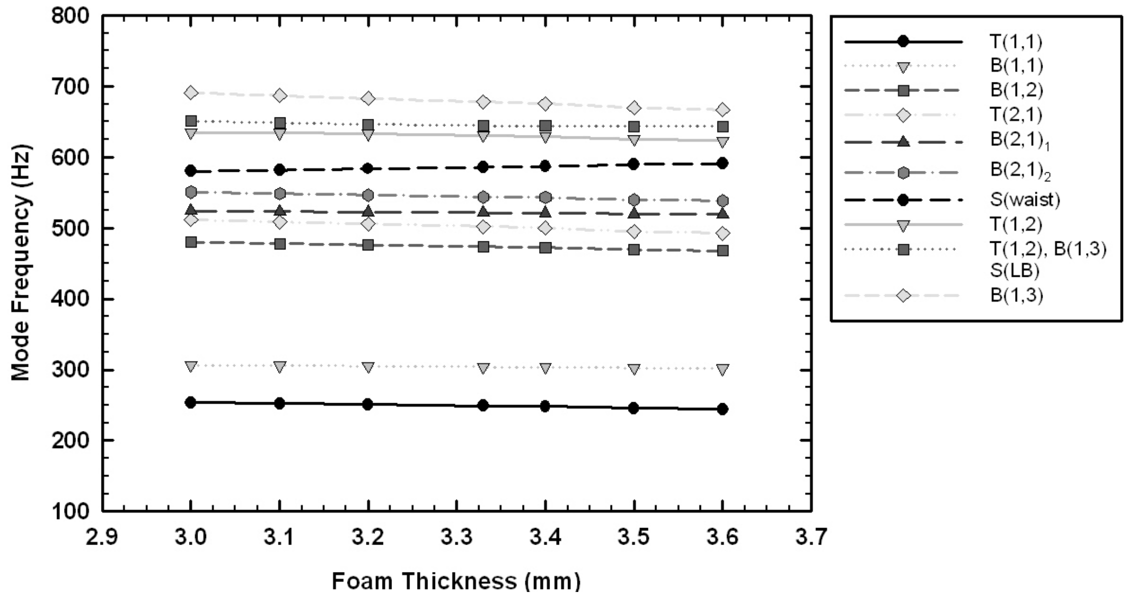

Figure 5.25. Modal frequency variation with changing foam core thickness. The decreasing trend indicates that the mass of the foam has a greater effect than the increased stiffness.

5.4.5 FEA Sensitivity Conclusions

Most of the parameters examined do note seem influential enough to account for the error between the model and the measured data. Most factors, even if they are influential, are only influential at higher modes, but not the first order top and back modes. The only factor that substantially influences the frequencies of the lowest modes is the out-of-plane elastic modulus, E_Z, but this is only at its lowest values. E_Z was set to 10 GPa in the standard model, but even reducing it to 1 GPa (placing the T(1,1) mode at 194 Hz, about 20 Hz higher than measured), would place the next mode, T(2,1) at 444 Hz, which is twice the measured value at 220 Hz.

Other major factors that were not examined that could have an effect are the mass of the bridge and the properties of the bridge and bridge plate material. These factors should not influence the frequencies more than the parameters already examined. Thus the overall conclusion is that the model needs more refining, possibly in its geometry and boundary conditions.

5.5 Conclusions

The sensitivity analysis did not clarify the discrepancy between the measured response and the FEA result. Perhaps the edge of the plates require more accurate modeling. For instance, the foam core is tapered to near-zero thickness while the model has a step from the core region to the non-core region. Also, the effect of the extra coats of epoxy and lacquer were not accounted for in the model which would add mass and lower the modes. In addition, the density of the foam core and composite material were measured prior to the layup which does not account for epoxy soaking into the foam surface.

Using the back plate of the guitar, the suspicion of added mass from epoxy soaking the foam was tested. The areas of the back were calculated from the CAD model and using the thicknesses and densities from the FEA model, the mass of the back plate was calculated. An actual back plate was massed prior to bonding, filling or lacquering. The calculated mass was 251 g and the measured mass was 259 g which is a 3% error indicating minimal soaking of the foam.

To test the idea of the extra epoxy and lacquer on the surface affecting the plate mass, the thickness of the top plate was measured with thickness calipers capable of reaching 5 cm in from the edge of the soundhole. This area is one of the thicker areas on the guitar. Comparing to a guitar plate with no extra epoxy or lacquer, the thickness of this outer coating was estimated generously. Using the density of WestSystem's epoxy (1176 kg-m^{-3}) and the estimated volume of the coating, the mass of the extra epoxy and lacquer was calculated. This mass was then lumped into the FEA model by increasing the density of the foam core. The result was that the first five modes were lowered between 5.8 and 18.8 Hz. This is a significant change but does not fully explain the inaccuracies.

In addition, the density of the foam which had been estimated at 50 kg-m^{-3} previously, was re-measured at 96 kg-m^{-3} using a submersion method. Including this increase in density and the effect of extra coating on the surface of the guitar, the modal frequencies were increased as shown below in Table 5.8. Though this does not account for the large differences seen, scrutinizing the model has made it more accurate.

Table 5.8. Evaluation of mass compensation for foam density and epoxy/lacquer coating.

	T(1,1)	B(1,1)	B(1,2)	T(2,1)	B(2,1)
Old	248.8	303.9	473.6	502.1	521.5
Compensated	238.8	284.3	442.0	475.4	491.0
Difference	10.0	19.6	31.6	26.7	30.5

Perhaps several errors have added to each other to result in the large difference between the experimental and numerical results. This highlights the need for careful measurement and documentation of materials. Not enough attention was given to the importance of mass location in the guitar and too much attention was given to stiffness. Another mass factor that could be affecting the results greatly is the mass of the bridge and the bridge plate which were not massed prior to bonding. In addition, the mass of the bridge pins, saddle and pickup (attached to the bridge plate) were not accounted for.

6 Psychoacoustical Study of Graphite and Wooden Guitars

6.1 Procedures

The purpose of this study was to determine the perceived differences in tone quality and tone characteristics of carbon fiber acoustic steel string guitars and their wooden counterparts without the study participants or the musician knowing what materials the guitars are made of. This study was conducting with approval by the University of Washington Human Subjects Division.

A group of 33 students in a UW physics of music class (taught by Professor Vladimir Chaloupka) were presented with music played on three separate guitars. The guitars were:

- Inexpensive laminate wood guitar with a solid top (Yamaha FG403-S)
- Composite acoustic guitar described in Chapter 3
- All solid wood guitar (Tacoma DM9)

The Tacoma guitar was introduced in a previous chapter (see Figure 2.2) and the Yamaha guitar is quite similar to the one shown previously (Figure 2.1) and was studied in Chapters 4 and 5. Each guitar was strung with new strings of the same brand two days before the study was conducted. Martin Marquis phosphor bronze light strings were used. The string type (material, gage, manufacturer, etc.) and the age of the strings on the guitar influence the sound the guitar produces to a great degree. The instruments were tuned before the study by the same person and were tuned to standard pitch using a Korg™ electronic tuner. Each guitar, after being strung, was given approximately equal play time and stretching to the strings to ensure that they were equally broken in.

The music played included both plucked notes and strummed chords to give two commonly used excitations to the guitars. In order to maintain the “blindness” of the audience, the musician playing the guitars was at the back of the auditorium while the subjects were at the front facing away from the music. The musician was blindfolded such that his impression of the appearance of the guitars will not affect how he played the various instruments. If a musician has a certain opinion of a type of guitar made by a specific manufacturer or an opinion about the materials used in guitars, this opinion could color the way the guitars are played and thus effect the audience's perception. It is impossible to limit the effect of how the guitar feels to the player or how he compensates his playing as he hears the guitar.

A rating scale was used by the audience for each guitar that uses subjective quality characteristics similar to those used by Caldersmith to evaluate violins [35]. His criteria were:

- Power or loudness
- Projection or carrying power
- Tone quality or timbre, bright (dull or muted)
- Full or rich (shallow)
- Open (closed or boxy)
- Clear (muffled)
- Evenness

These criteria were used because they describe the tone of the guitar instead of asking whether the guitar sounds good or bad, which is an opinion that is more variable. The participants were asked to grade each guitar in each of the above categories on a -2 to +2 scale with zero being the rating of what they thought an average guitar to be. Each category included guidance for a negative and positive direction of scoring. For instance in the "Tone Quality" category, the guitar receives a more positive score if it is brighter sounding and a more negative score if it is more dull or muted. The survey also included questions about the hearer to get an idea for their musical background. This information was correlated with the data in order to remove groups that may be more inconsistent or inexpert in there rating. Specifically, as the subjects come from both musical and non-musical backgrounds, the persons who have experience in music, and especially guitar will have their opinions weighed more heavily. In the musical training that is undergone by some students at the University of Washington, the ear is taught to be more perceptive than is naturally the case.

The procedure of the study is as follows:

1. Give introduction to the study.
2. Arrange audience and guitarist and pass out survey forms.
3. Blindfold guitarist.
4. Play two segments on each guitar (15 seconds each), audience just listens.
    a. Hand guitar to blindfolded guitarist.
    b. Announce guitar designation (A, B or C)
    c. Guitarist plays two segments (strumming and plucking)
    d. Repeat a-c for each guitar.
5. Play two segments on each guitar (15 seconds each), audience grades guitars
    a. Hand guitar to blindfolded guitarist.
    b. Announce guitar designation (A, B or C)
    c. Guitarist plays two segments (strumming and plucking)
    d. Audience given a moment to finish grading/commenting
    e. Repeat a-e for each guitar.
6. Collect survey forms.

It should be noted that one student arrived late to the class and was not aware of the intended blindness of the study. He was inadvertently given a survey form by the professor which was not separated from the rest at the end of the study. Thus his grading of the guitar will slightly color the results. This is not deemed a significant error.

6.2 Results and Discussion

The study seemed to be executed without much difficulty with no one reported having trouble and the participants seemed to be able to make quick judgments without requiring a lot of time to do so. The participants were encouraged not to make judgments in categories where they did not understand the description. The guitarist's playing was a bit softer than would have been appropriate for the size of the room and to give the audience a more full view of the guitars' characters. The age of the audience varied from 18 to 70 with the mean age at 24. Most participants graded each guitar in every category with a few exceptions. Hardly any special comments were made.

The results for each guitar were averaged in each category to find a mean and standard deviation. This was done for the group as a whole as well as for several subsets which were: music majors, people with a significant musical background and people with little musical background. These categories were organized based on the information provided by the participants. The prerequisite for the category of people with a musical background was people with several years of musical experience (formal or informal) on one or several instruments (or voice) in recent years and did not include people who only had experience in middle or high school.

A complete grade for each guitar was determined by averaging the grades in each category such as to have a total mean and total standard deviation. These values are tabulated in Table 6.1 for each subset of participants. Several observations can be made from these results. First, the standard deviation across all categories and subsets is rather high and therefore not highly statistically significant. Second, the different subsets of the participants seem to be in pretty good agreement in the direction and magnitude that each guitar was rated, whether positive or negative, with the exception of the grades of guitar B (the composite guitar) with the three participants who were music majors. Whether this is significant due to the small number of music majors is hard to ascertain. To better understand the variation of opinion amongst the various subsets, the standard deviations of the responses across categories and instruments were averaged. The mean and variance of the standard deviation were calculated and appear in

Table 6.2. This shows that the lowest to highest variance occurs in the music majors, people with music experience, and those with little music experience, respectively. This is the expected result due to the enhanced perception of those who are trained (formally or informally) in musical ways.

Table 6.1. Grading results by subset of the sample. Mean and standard deviation are given for each guitar as well as the size of the subset. Grades on a [-2, 2] scale.

	Guitar A		**Guitar B**		**Guitar C**		**Subset**
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Size
Entire Sample	-0.13	*1.05*	0.08	*1.05*	0.52	*0.95*	33
Music Major	-0.40	*0.76*	-0.38	*0.98*	0.62	*0.67*	3
Music Background	-0.26	*0.94*	0.17	*0.99*	0.56	*0.89*	20
Little/No Music Background	0.11	*1.23*	-0.11	*1.07*	0.39	*1.05*	13

Table 6.2. Mean and variance of the standard deviation of each group subset across all three guitars.

	Mean	Std. Dev.
Entire Sample	1.02	*0.15*
Music Major	0.80	*0.47*
Music Background	0.94	*0.15*
Little/No Music Background	1.12	*0.26*

Even though the music major subset had the lowest average variance, the size of the subset is not useful, thus the most important responses that were focused on were those of the participants who had a significant musical background (which includes the music majors). The compiled results from this group are displayed in Table 6.3. The average ratings for each guitar, shown at the bottom of the table, reveal a preference for the solid wood guitar (guitar C), a subtle preference for the composite guitar (guitar B) and a subtle dislike for the solid topped, but otherwise laminate guitar (guitar A). In order to determine if the audience was more varied in their responses in one category as opposed to another, the average variance of each category was calculated and compared. The range of this calculation was between 0.89 and 1.07, which shows that the variation is rather consistent. The category that had an average variance of 1.07 was “Tone Quality” and the next highest value was 0.95 which shows that tone is one of the most subjective or most poorly defined criterion used.

Table 6.3. Grades for guitars by study participants with musical backgrounds.

	Yamaha FG403S		**Composite Guitar**		**Tacoma DM9**	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Power/Loudness	-0.50	*0.76*	-0.15	*1.27*	0.25	*0.79*
Projection/Carrying Power	-0.65	*0.75*	0.25	*1.12*	0.65	*0.88*
Tone Quality	-0.20	*1.24*	-0.10	*1.12*	0.53	*0.84*
Full or Rich	-0.20	*1.01*	0.90	*0.85*	0.55	*1.00*
Open	-0.29	*0.92*	0.06	*0.90*	0.47	*0.94*
Clear	-0.05	*0.94*	0.15	*0.88*	0.80	*0.83*
Evenness	0.05	*0.94*	0.10	*0.79*	0.70	*0.92*
Averages	**-0.26**	***0.94***	**0.17**	***0.99***	**0.56**	***0.89***

The data in Table 6.3 is organized into a bar graph in Figure 6.1. The graph shows better the relative magnitude of the ratings between the guitars. It can be seen from the figure that the sound of the all solid wood guitar performs the best in the categories given and the guitar with laminate materials performs with an impression that it is lacking in the categories. The composite guitar is somewhere in the middle with mostly a positive impression but not as much so as the Tacoma guitar.

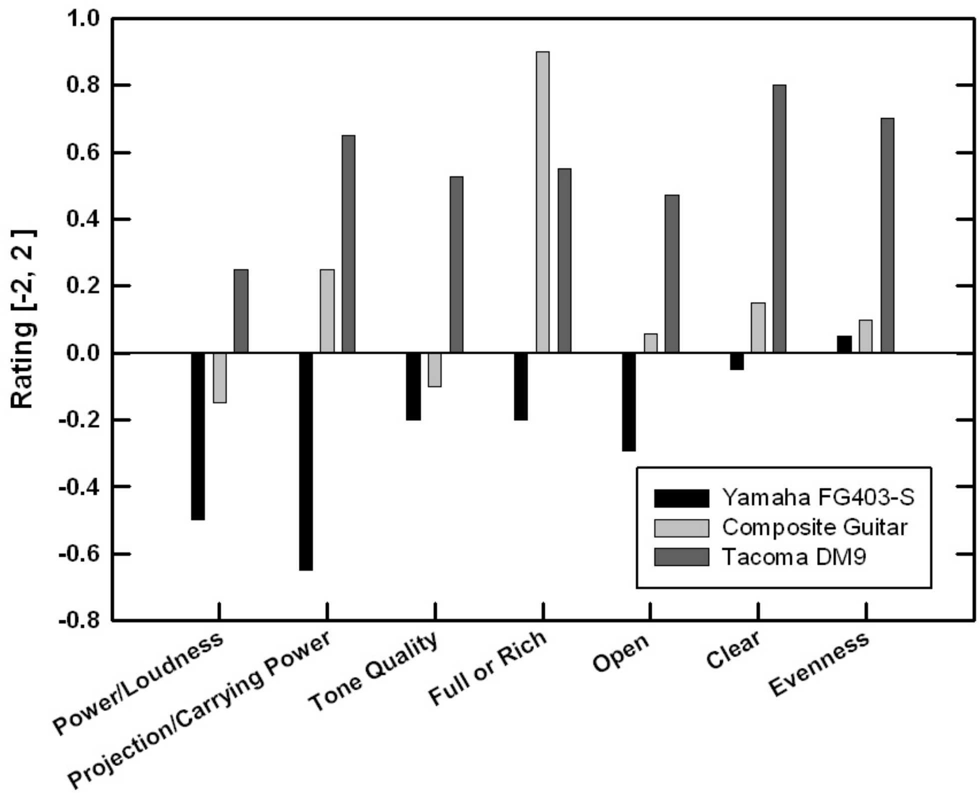

Figure 6.1. Guitar ratings from study participants with a musical background, the solid wood guitar is rated best and the laminate guitar worst with the composite guitar in between.

What is clear between the instruments is that there is not really a detection of the difference between the composite guitar and the other instruments. It doesn't really stand out in any category besides, perhaps, "Full or Rich." This shows at least that the sound of a guitar made from these foreign materials is not something very out of the ordinary to the human ear. No specific comments were made about this particular guitar, except that the guitarist after playing said that he thought it was the most responsive of the three.

7 Conclusions and Future Work

7.1 Conclusions

Carbon fiber-epoxy composites have been successfully used to manufacture the body of an acoustic steel-string guitar with the other pieces of the guitar being built out of wood. The guitar sounds good to the average listener and has many advantages over traditional wood guitars. Using composites allows for more consistent design because it does not vary from one piece of material to the next the way wood does. In addition, the composite material is not sensitive to moisture, as wood is, which makes it more robust against damage and the geometry is less variable meaning it will stay in tune better and always sound the same.

7.1.1 Comparison with a Wooden Guitar

Comparing the vibrational characteristics of the composite guitar with a similar wooden guitar was important because the goal of the manufacturing was to match the lower mode vibrations of a wooden guitar. Comparing to the Yamaha FG403S which is a very similar body shape, the first six modes of the guitars measured on the guitar top plate are similar to between 0.9 and 15.7 percent of the measured values.

7.1.2 Finite Element Analysis

Using finite element analysis to model the composite guitar proved to be a difficult task. Something about the geometry the types of material models, or the material properties that were used did not model reality accurately. Literature shows that FEA has been used successfully with reasonably accuracy to measured data. The likely problem with FEM developed is the representation of the composite structure. Modeling woven fibers is a difficult task and the properties of these materials are hard to measure. Somehow modeling in more detail the orthotropic nature of the composite structure will hopefully give better results.

7.1.3 Psychoacoustic Analysis

Even though the composite and Yamaha guitar had similar modal frequencies, from the listening study that was done it seems that the composite guitar was preferred to its wooden counterpart. Still the composite guitar did not do as well as an all-solid-wood guitar, the Tacoma DM9. The study shows that the composite guitar is a viable design, but needs improvement. It also shows that measuring the quality of an instrument is not only based on its modal frequencies. It is suspected that a lot of the character of a guitar may be understood by study of the transient frequencies and response to input from the strings. With critique of the design and incorporating more ideas from the existing research, the composite guitar can be made to sound just as good as the solid wood guitar and even take on a new, unique character of its own.

7.2 Future Work

The guitar is a complex system that is manufactured in a hundred different ways. These differences in manufacturing reflect both the differences of musical style that exist in the world and also the creativity and innovation of the luthier. Composite stringed instruments are one of the unique innovations amongst luthiers and in order to harness the capability of this new innovation, more research along with understanding of existing research is needed.

One of the major differences between the composite guitar made for this thesis and wooden guitars is that wood is naturally orthotropic with a strength along grain that is ten or twenty times that of the cross-grain strength, while the composite guitar was made with a relatively symmetric layups that made it more isotropic. Composites of course are capable of designed orthotropy and varying this in the guitar by utilizing unidirectional fiber layers would perhaps better replicate a wooden guitar's sound.

To better understand the differences between wood and composite guitars, the mode shapes of the composite guitar needs to be mapped. It is a rough assumption that the mode order of the wooden guitar is the same as the composite guitar, and though this was verified by the finite element model, experiments should be done using modal analysis or some sort of holographic method to determine the precise shapes of the modes.

The vibration measurements that were made from the guitars were of the unforced response of the guitar. Though this gives a lot of insight into the guitars character, it is also useful to measure the sound pressure level of the guitar when it is played. Recording the SPL of the steady state and transient response with a high quality microphone in anechoic conditions for both the wooden and composite guitar will give a more full understanding of the differences between the wood and composite. This data is what can be used for better correlation to psychoacoustical data.

Finite elements has shown its worth as a way to replace many time consuming experiments with simulation. One a model is developed that is proven to model reality accurately, it is fair to modify that model to obtain trustworthy results with other parameters. Hopefully in the future models with be developed which accurately model the entire guitar, including the air and the strings such that the full guitar can be understood without dislocation of its constituent parts.

More psychoacoustic data is necessary to get a real measure of the guitar quality. The high standard deviations that plagued the existing listening study indicates that they group is not in agreement. In order to get better data, a discussion should ensue prior to a second study in which the audience can agree on the measures of an instrument’s quality. Also, having a group that is composed of professional steel-string guitarists would give more consistency as was seen in the small number of music majors that participated in the study in this thesis.

The most important need in this area is to make guitar research available to luthiers and develop tools that can be used. Replicating the qualities of great wood guitars and innovating with the versatility of composites requires study and experimentation. Numerical analysis with finite elements will continue to be a great tool to save time and generate a lot of useful data. Hopefully others who are passionate about guitars and engineering will continue to meld those passions with beautiful results.

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Appendix A: Guitar Machine Drawings

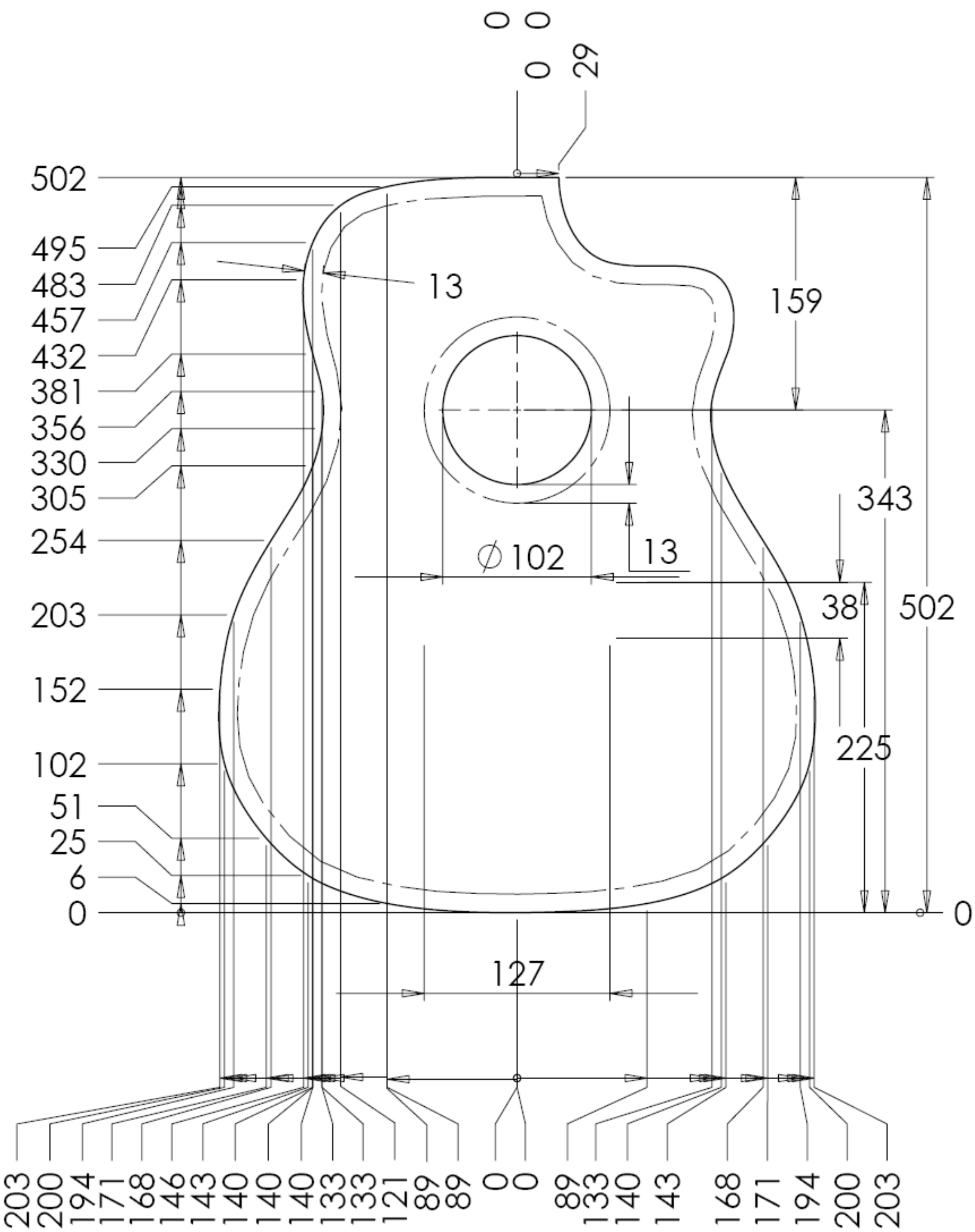

Figure A.1. Machine drawing of guitar top.

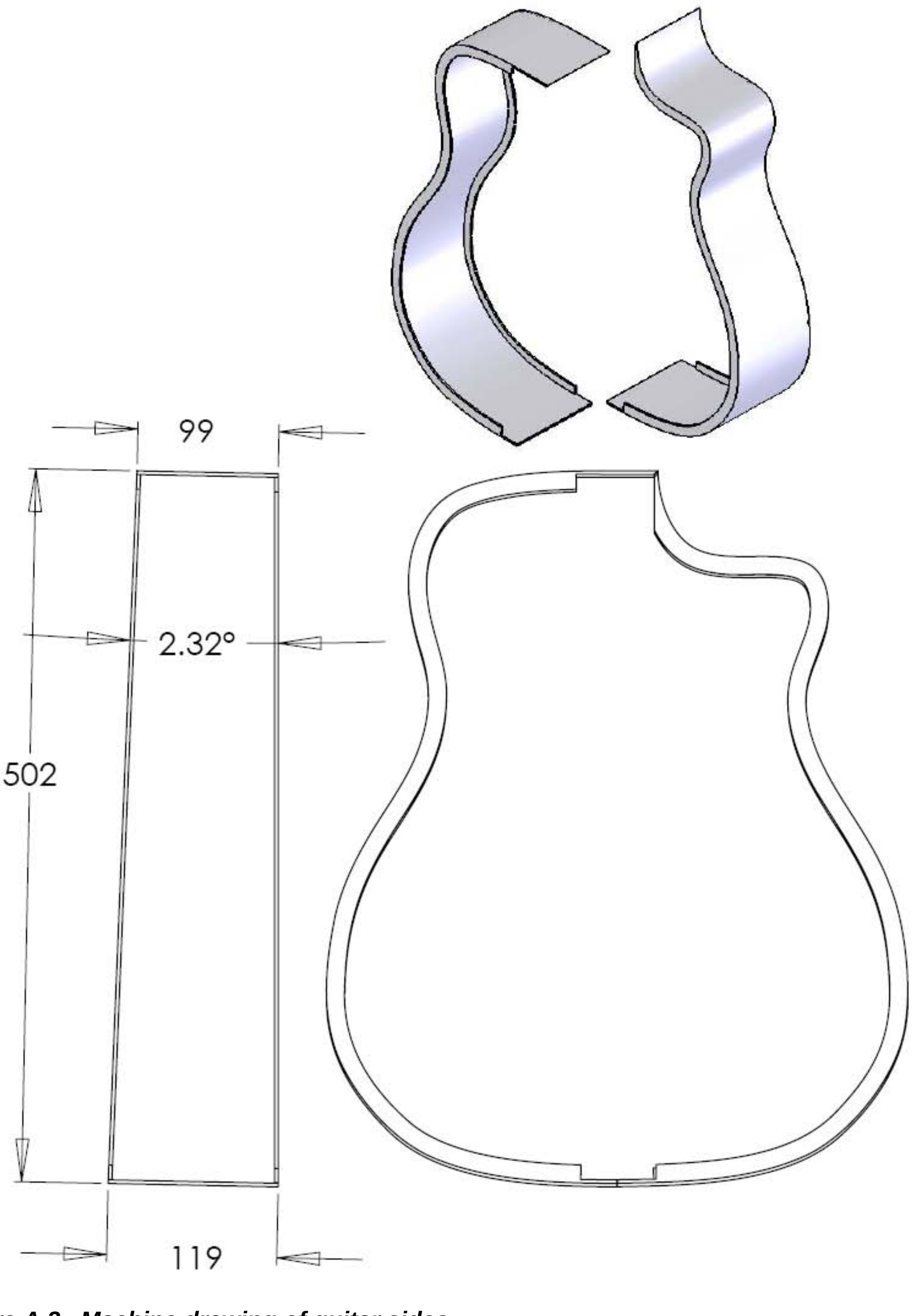

Figure A.2. Machine drawing of guitar sides.

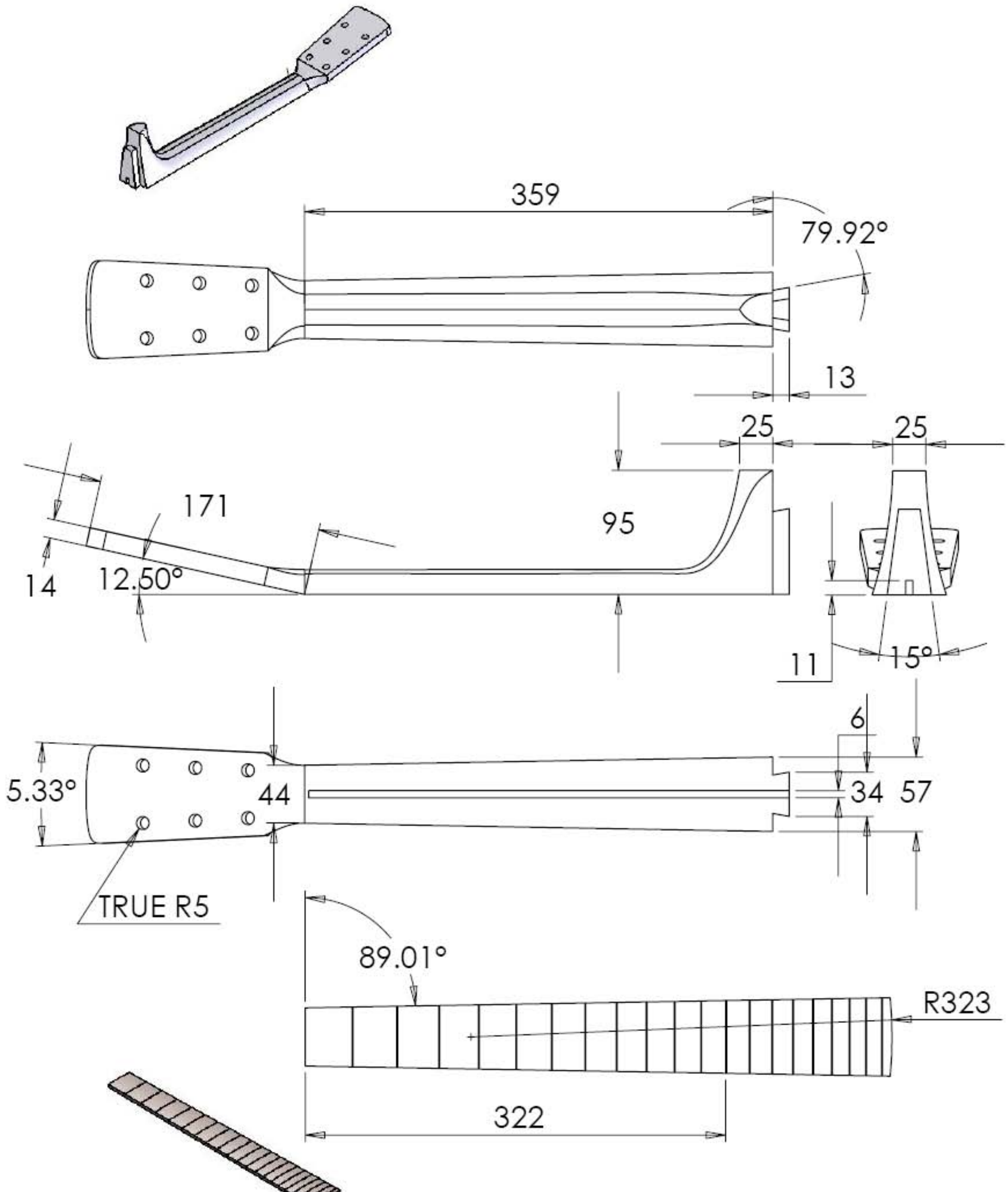

Figure A.3. Machine drawing of guitar neck and fretboard.

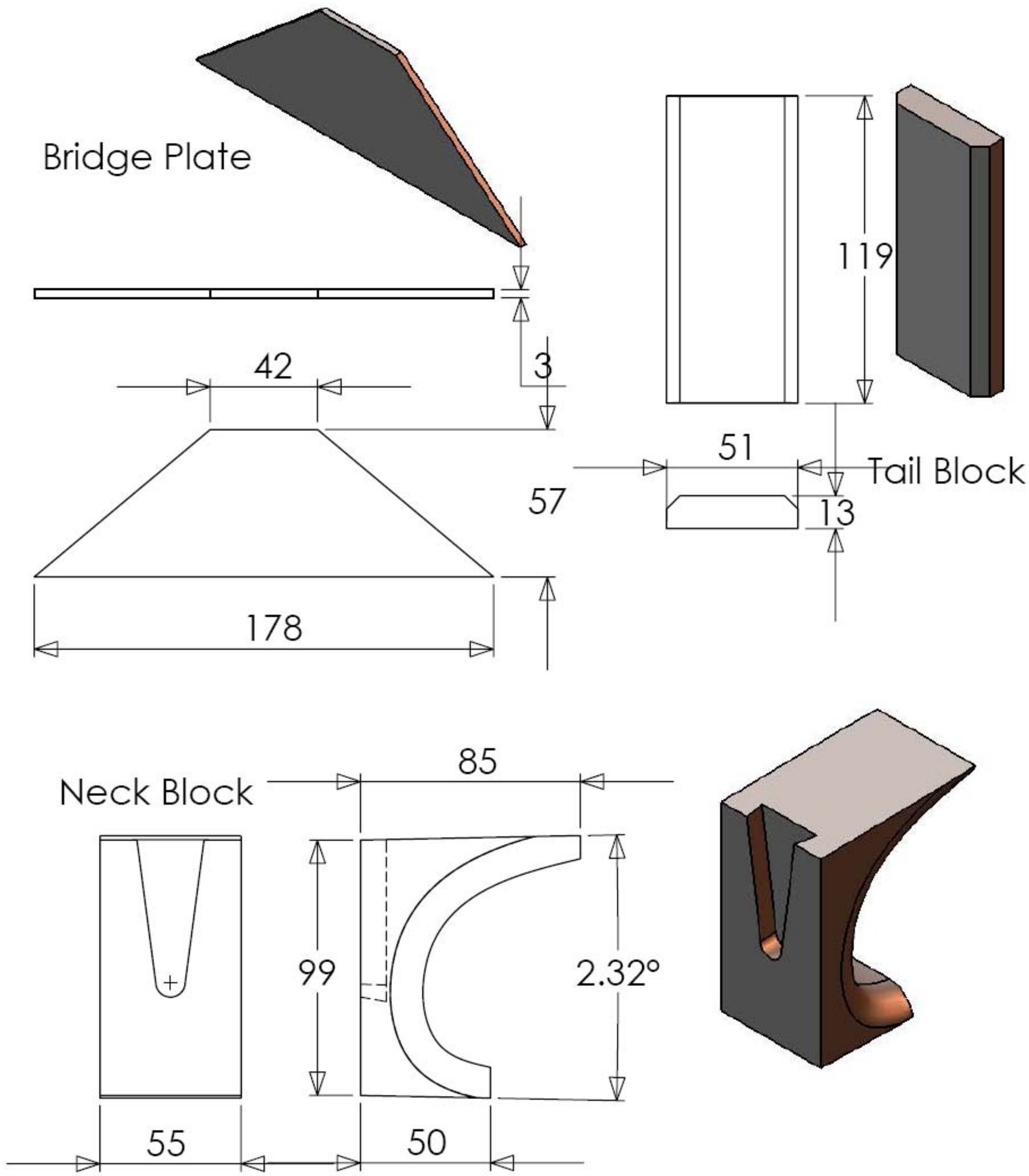

Figure A.4. Machine drawing of the bridge plate, tail block and neck block.

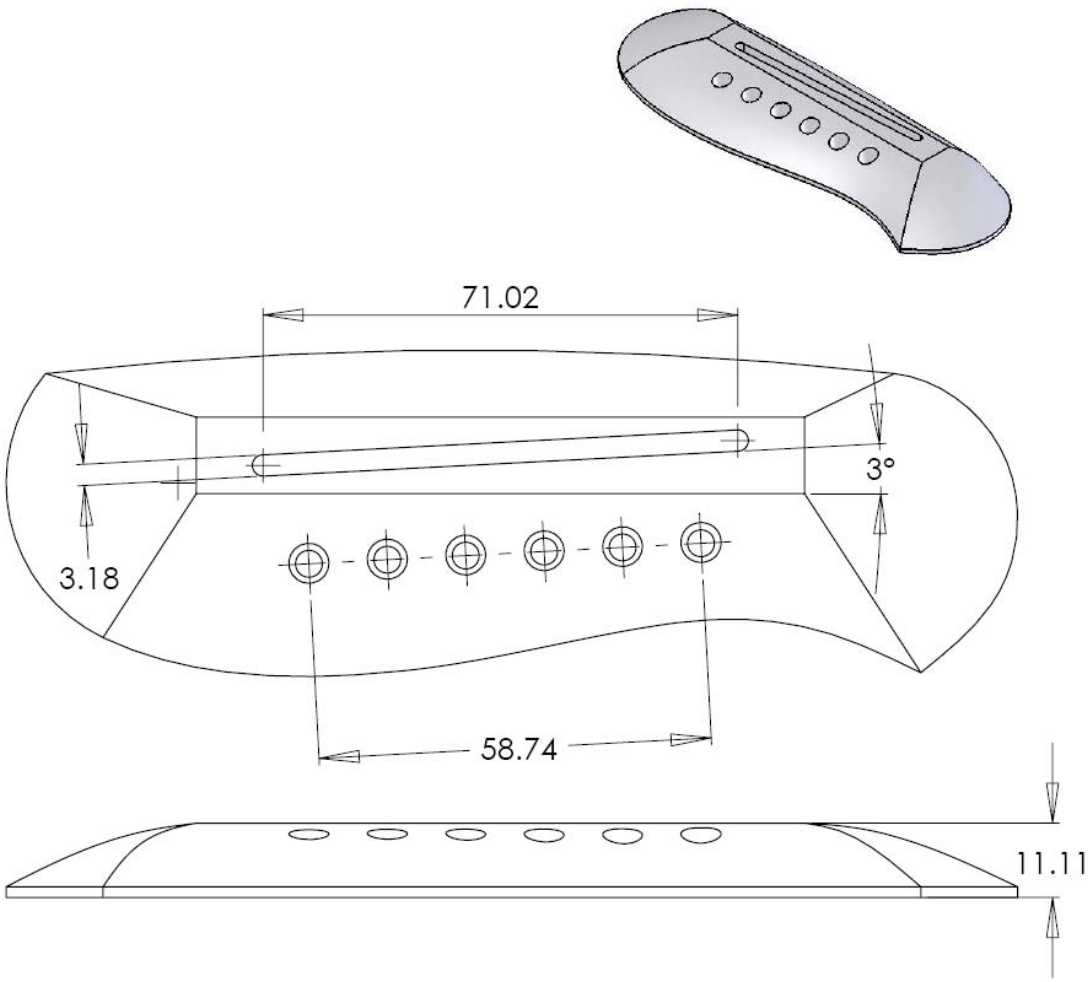

Figure A.5. Machine drawing of the bridge.

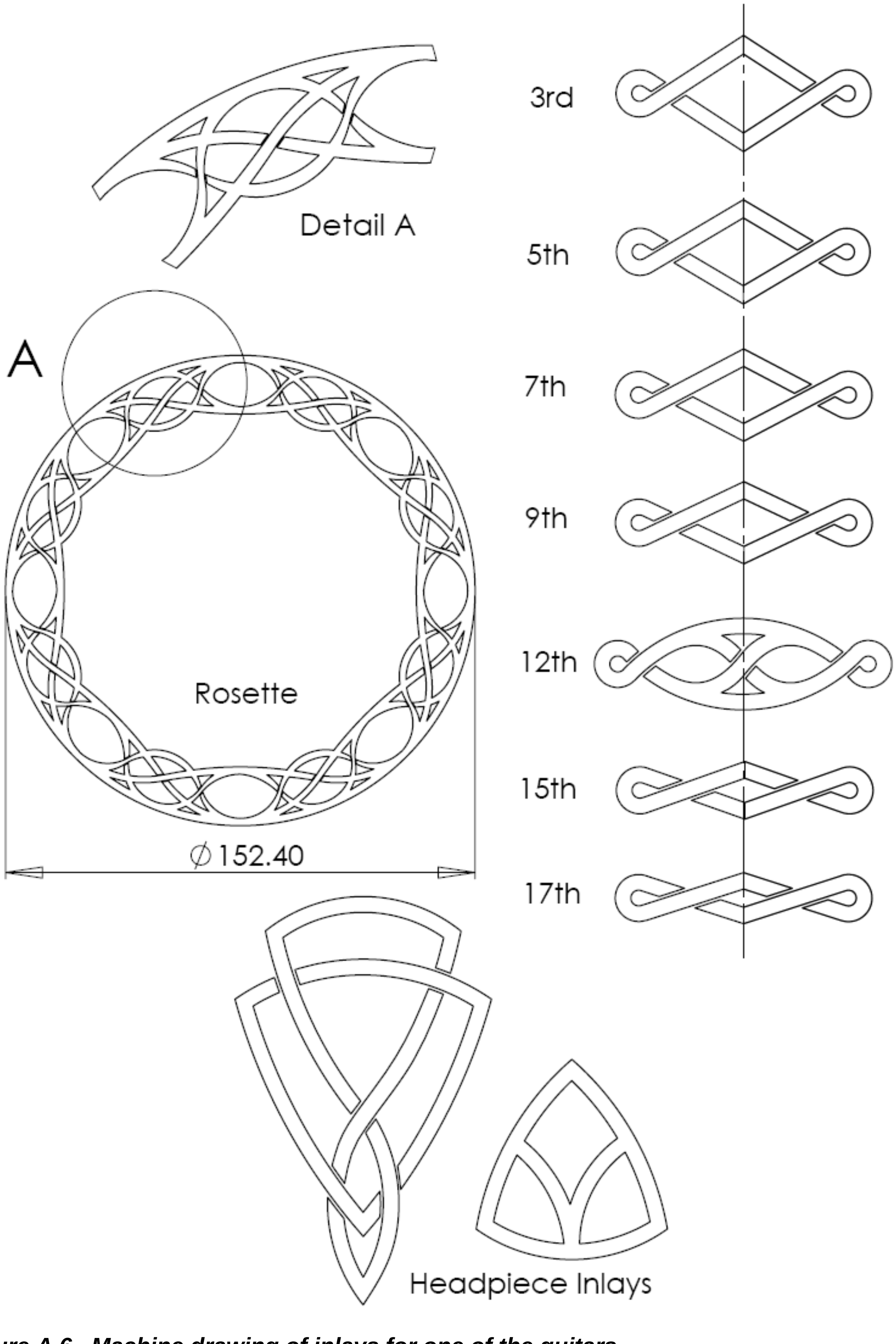

Figure A.6. Machine drawing of inlays for one of the guitars.

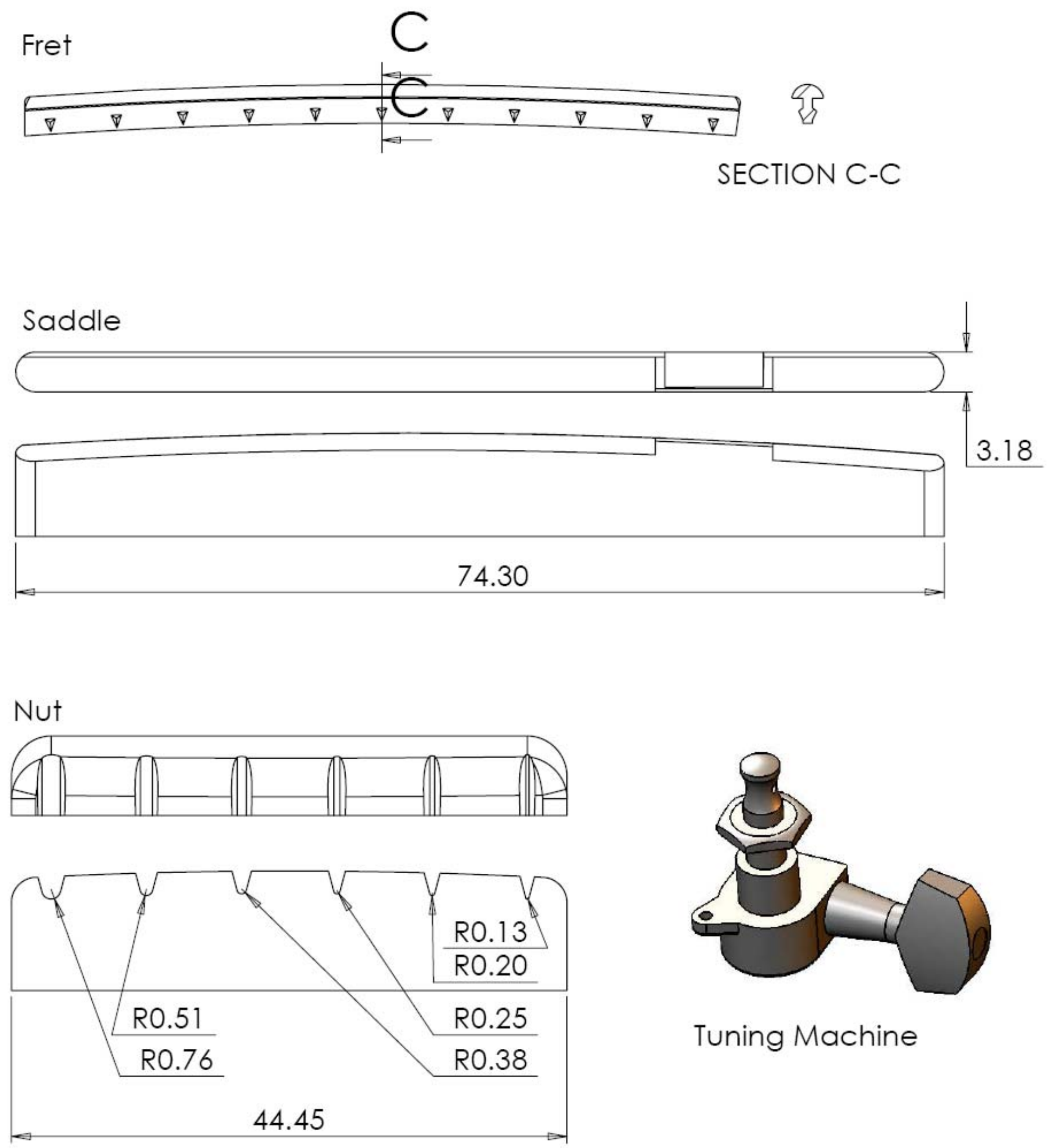

Figure A.7. Machine drawings of a fret, saddle, nut and tuning machine.

Appendix B: Tooling Machine Drawings

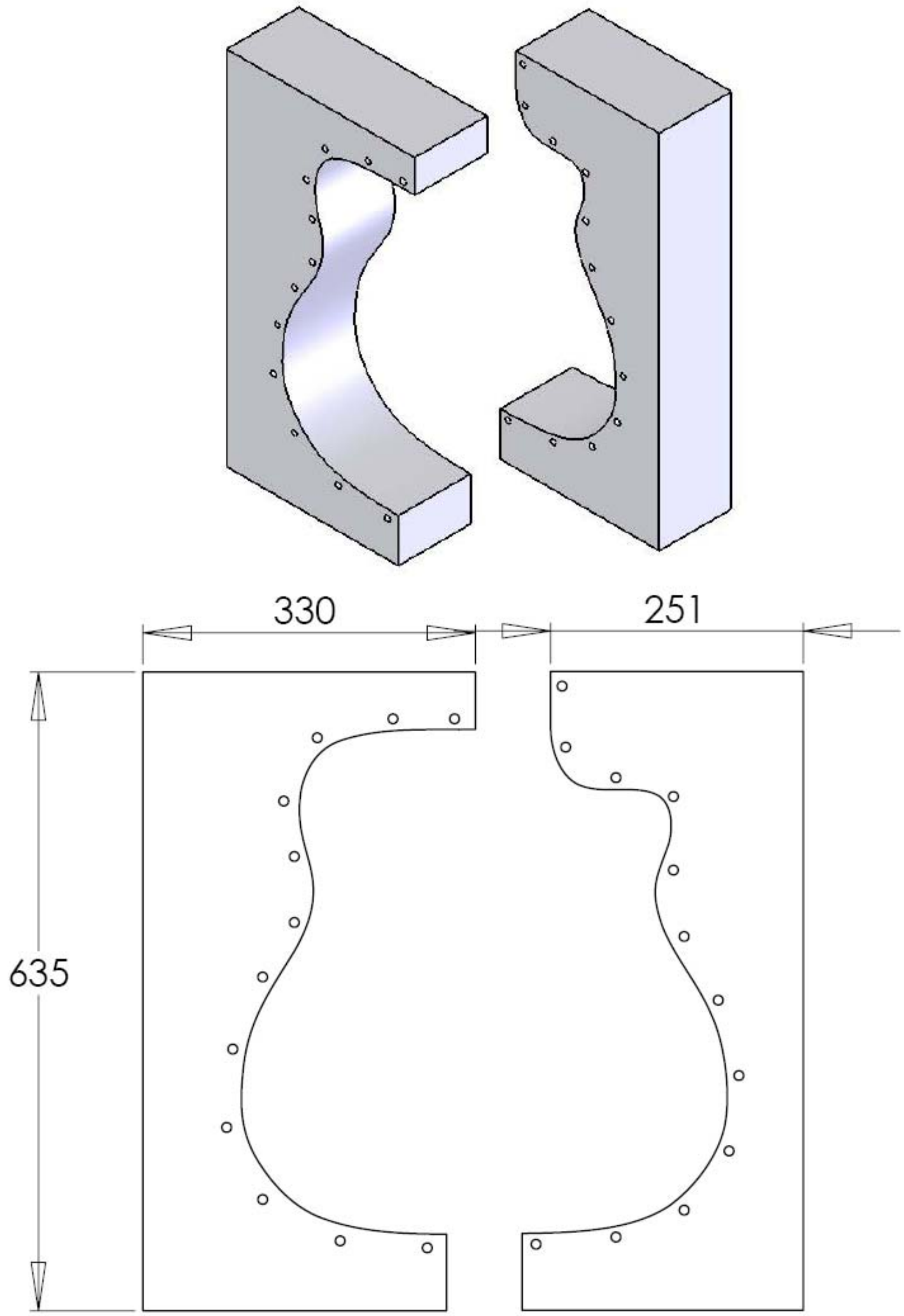

Figure B.8. Machine drawing of the side mold.

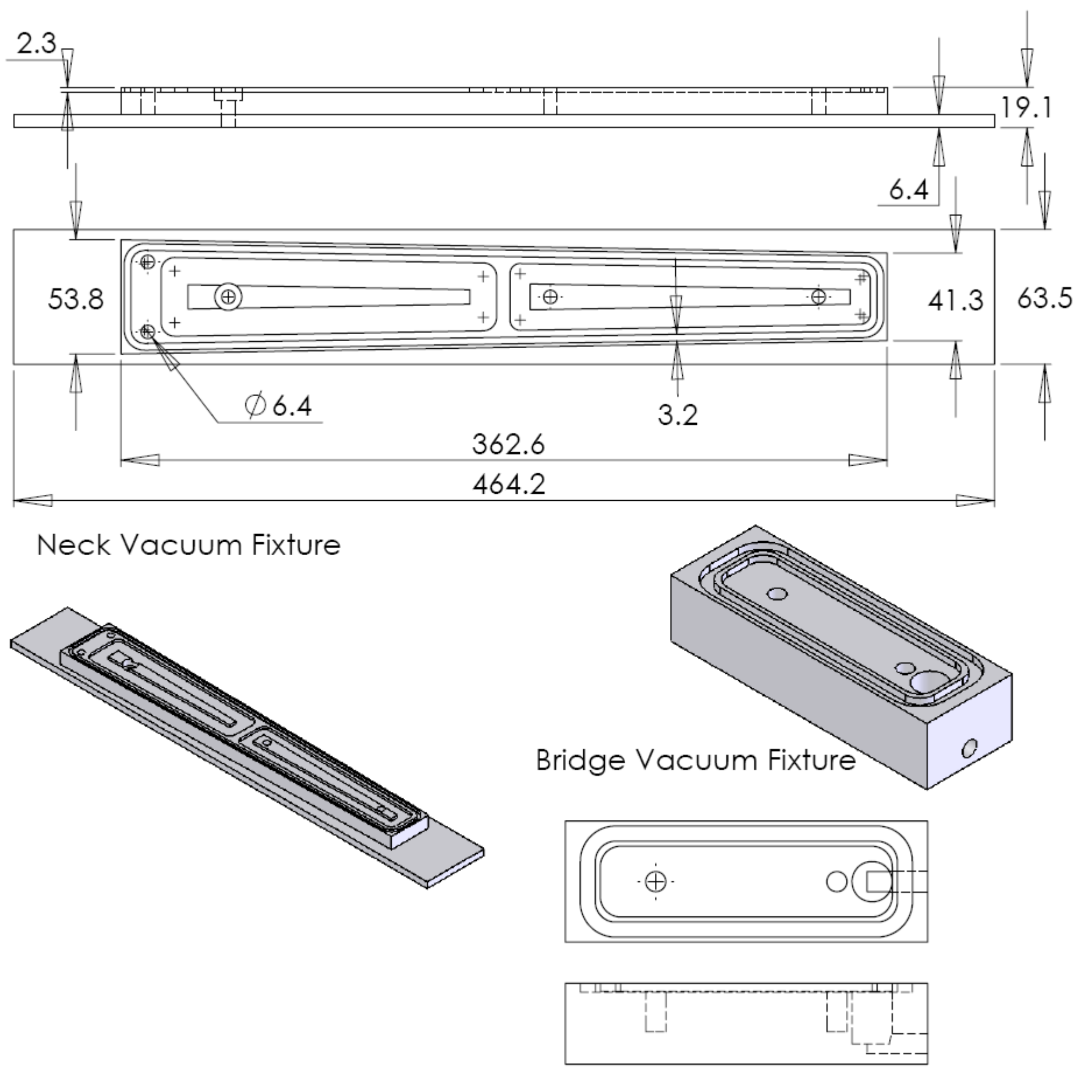

Figure B.9. Machine drawing of the neck and bridge vacuum fixtures.

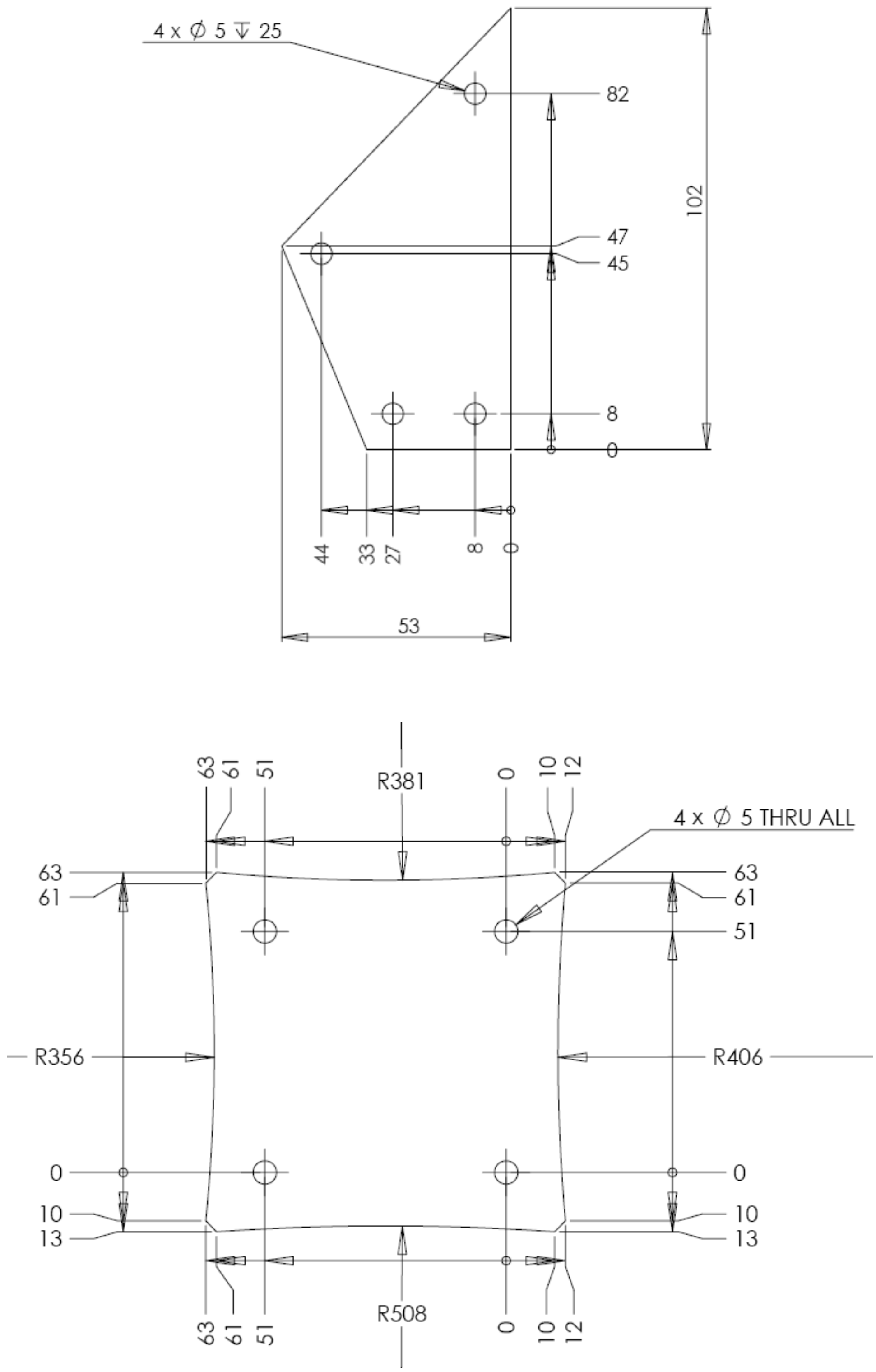

Figure B.10. Machine drawing of a fret rocker and a radius gauge.

Appendix C: Additional Frequency Response Curves

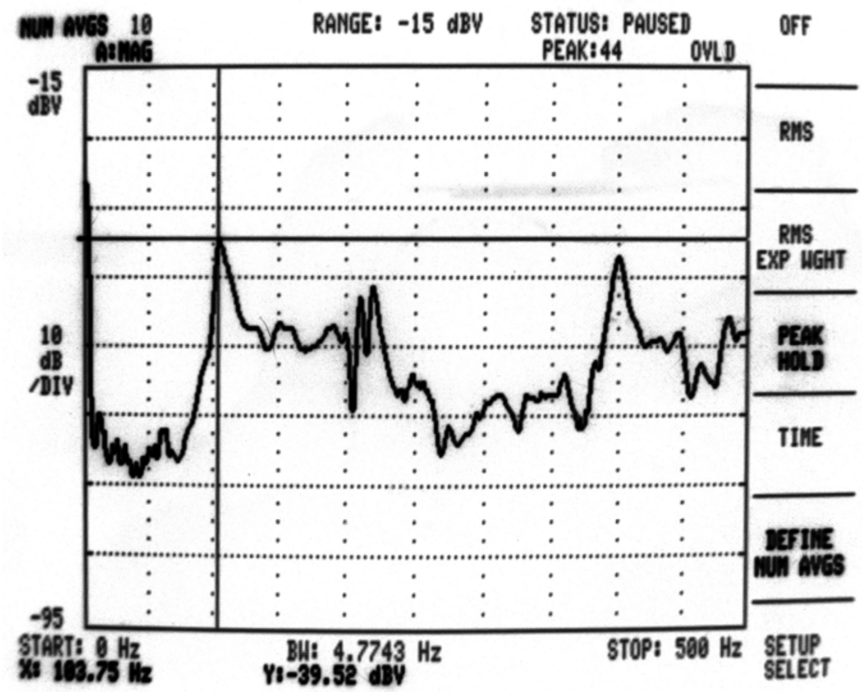

Figure C.11. Frequency response of a Yamaha FG403S to a 0-500Hz frequency modulation.

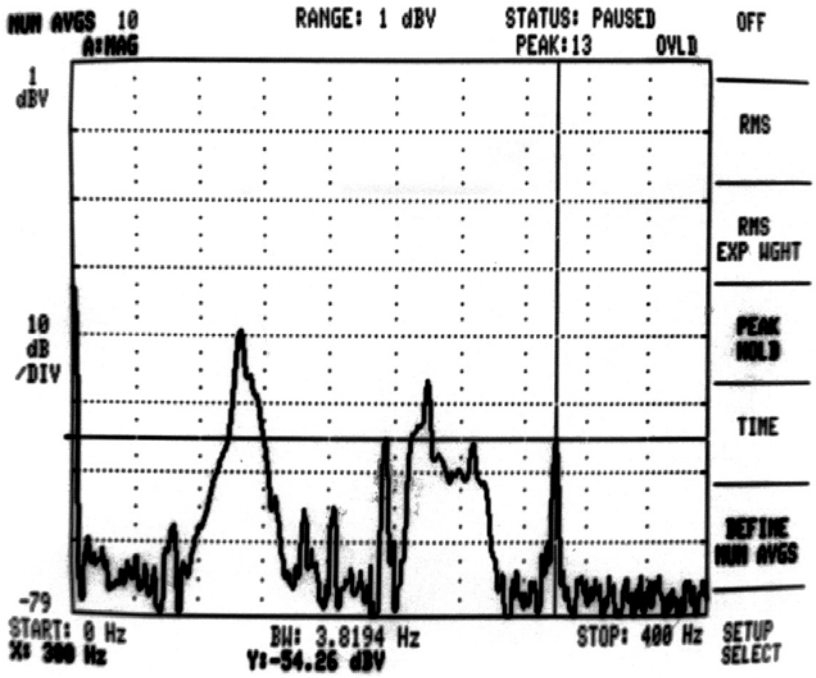

Figure C.12. Frequency response of a Yamaha FG403S to a 0-300Hz frequency modulation, scale is to 400 Hz, but frequency sweep was only to 300.

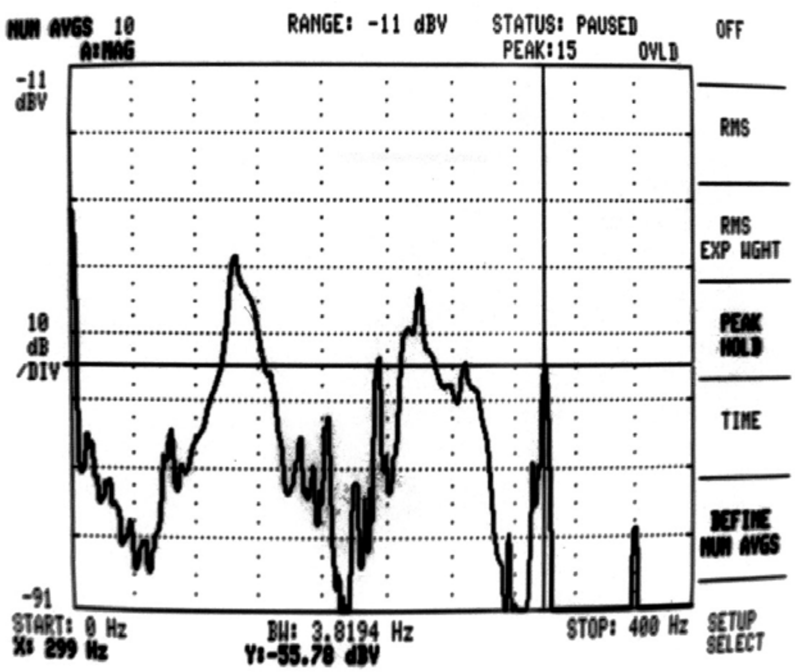

Figure C.13. Frequency response of a Yamaha FG403S to a 0-300Hz frequency modulation, scale is to 400 Hz, but frequency sweep was only to 300.

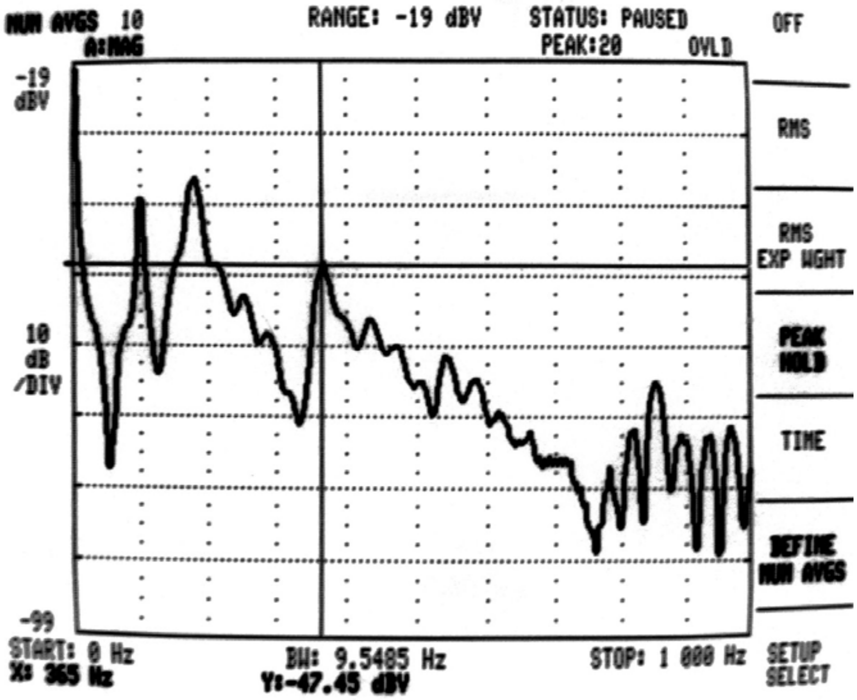

Figure C.14. Frequency response of the composite guitar to a 0-1kHz frequency modulation.

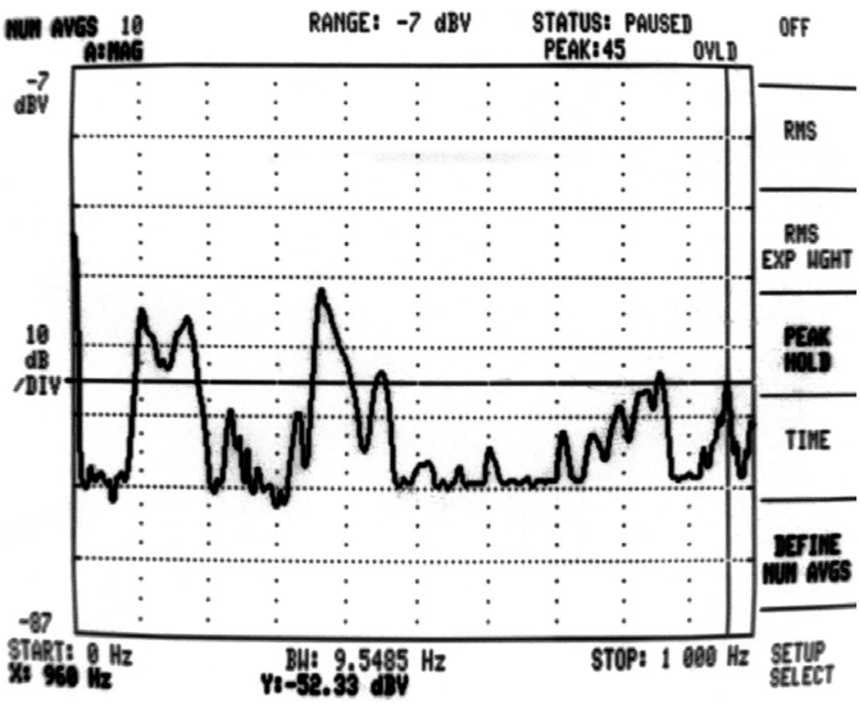

Figure C.15. Frequency response of the composite guitar to a 0-1kHz frequency modulation.

Appendix D: Vibration Testing Data

Table D.1. Vibration testing data for a Yamaha FG403S. Frequencies (Hz) and response (in dB) are given.

freq.	dB	freq.	dB	freq.	dB	freq.	dB	freq.	dB	freq.	dB	freq.	dB	freq.	dB
103.5	-25.5	145	-41.8	206	-28.2	396	-36.2	442	-50.5	475	-53.5	595.5	-49.5	861	-55.9
104	-23.6	146	-40.6	207	-26.9	397	-35.1	443	-50.0	476	-53.0	596	-49.3	862	-56.2
104.5	-22.5	147	-39.5	208	-26.5	398	-34.0	444	-49.9	477	-51.8	596.5	-46.5	863	-56.0
105	-22.3	148	-39.5	209	-26.6	399	-32.9	445	-49.0	478	-51.1	597	-48.6	864	-57.9
105.5	-23.5	149	-39.1	210	-27.0	400	-32.1	446	-48.7	479	-50.1	597.5	-49.3	865	-55.7
106	-24.6	150	-39.6	211	-28.2	401	-32.6	447	-48.9	480	-49.3	598	-45.2	866	-55.4
106.5	-26.1	151	-39.6	212	-29.5	402	-33.2	448	-48.9	481	-54.0	598.5	-47.6	867	-55.5
107	-27.4	152	-40.4	213	-32.8	403	-34.2	449	-49.8	482	-47.3	599	-47.8	868	-55.4
107.5	-28.4	153	-41.2	214	-39.0	404	-35.3	450	-60.2	483	-46.6	599.5	-47.5	869	-55.2
108	-29.3	154	-42.1	215	-42.3	405	-36.6			484	-46.3	600	-47.1	870	-54.6
108.5	-30.2	155	-45.6	216	-39.1					485	-46.2	600.5	-46.6	871	-54.5
109	-31.0			217	-37.5							601	-47.0	872	-54.8
109.5	-31.8			218	-35.9					484	-46.4	601.5	-46.9	873	-53.3
110	-32.1			219	-34.6					485	-45.9	602	-46.7	874	-55.1
				220	-34.1					486	-46.3	602.5	-46.7	875	-53.6
				221	-34.2					487	-46.7	603	-46.5	876	-55.9
				222	-35.3					488	-48.7	603.5	-47.2	877	-56.1
				223	-36.8					489	-47.9	604	-46.2	878	-56.5
				224	-38.2									879	-57.2
				225	-39.4							604	-45.9	880	-56.6
												604.5	-46.5	881	-58.2
												605	-46.6	882	-58.0
												605.5	-46.7	883	-58.2
												606	-46.8	884	-61.6
												606.5	-46.9	885	-55.1
												607	-46.9		
												607.5	-47.0	868	-55.5
												608	-47.3	868.5	-55.4
												608.5	-47.4	869	-55.2
												609	-47.2	869.5	-55.4
												609.5	-47.3	870	-55.0
												610	-47.5	870.5	-53.7
														871	-54.7
												604	-46.1	871.5	-54.9
												605	-46.8	872	-54.8
												606	-46.8	872.5	-54.1
												607	-47.0	873	-54.6
												608	-47.1	873.5	-54.7
												609	-47.2	874	-55.8
												610	-47.3	874.5	-54.8
												611	-46.8	875	-54.8
												612	-47.6	875.5	-54.9
												613	-47.8	876	-55.2
												614	-47.8		
												615	-48.7		
												616	-48.4		
												606	-51.5		
												607	-47.1		
												608	-47.3		
												609	-47.2		
												610	-47.8		
												611	-47.7		
												612	-47.7		
												613	-48.0		
												614	-48.0		
												615	-47.9		

Table D.2. Vibration testing data for the composite guitar. Frequencies (Hz) and response (in dB) are given.

freq	dB	freq	dB	freq	dB	freq	dB	freq	dB	freq	dB	freq	dB	freq	dB	freq	dB	freq	dB	freq	dB	freq	dB
97	-35.2	174	-29.6	228	-48.6	329	-45.1	359	-34.7	443	-44.9	529	-51.2	710	-48.9	748	-56.3	790	-51.9	815	-51.1	958	-54.4
97	-34.9	174	-29.1	229	-47.5	330	-44.4	359	-33.3	443	-44.9	529	-50	710	-48.6	749	-56.9	791	-50.5	816	-50.4	958	-53.3
98	-33.7	175	-28.5	229	-47.1	330	-44.6	360	-32.3	444	-45	530	-50.1	711	-48.2	749	-56.4	792	-50	817	-50	959	-52.9
98	-32.7	175	-28.1	230	-46.9	331	-43.9	360	-31.3	444	-44.9	530	-48.4	711	-47.9	750	-56.2	793	-49.6	818	-49.7	959	-52.8
98	-31.5	175	-27.6	230	-46.8	331	-44.1	361	-30.4	445	-45.5	531	-47.8	712	-47.9	750	-55.5	794	-49.9	819	-49.2	960	-52.7
98	-30.6	175	-27.5	231	-46.9	332	-44.9	361	-29.4	445	-45.4	531	-46.7	712	-48	751	-55.9	795	-49.8	820	-48.8	960	-52.6
99	-29.1	176	-27.6	231	-47.1	332	-45.1	362	-29.1	446	-45.1	532	-45.6	713	-48.2	751	-52.9	796	-49.6	821	-48.3	961	-52.7
99	-28.2	176	-27.8	232	-47.3			362	-28.7	446	-45	532	-44.3	713	-48.4	752	-56	797	-49.8	822	-48	961	-53.5
99	-27.2	176	-28.4	232	-47.5	326	-48.1	363	-28.9	447	-45.5			714	-48.5	752	-56.1			823	-47.8	962	-54.1
99	-26.9	176	-28.9			327	-47.8	363	-29.3	447	-46.6	531	-45.5	714	-48.8	753	-55.8	796	-49.6	824	-47.7	962	-54.4
100	-27.2	177	-29.6			328	-46.8	364	-30.2	448	-45.2	532	-45.4	715	-49	753	-55.4	797	-49.6	825	-47.7	963	-54.6
100	-27.5	177	-30.2			329	-44.6	364	-31.7	448	-45.3	532	-45.3	715	-49.3	754	-57.9	798	-48.8	826	-47.6	963	-54.9
100	-28.4	177	-31.1			330	-44.2			449	-45	533	-44.9			754	-51.7	799	-50	827	-47.8		
100	-29	177	-31.6			331	-44.2			449	-43.2	533	-44.9			755	-55.3	800	-50.2	828	-47.9		
101	-29.9	178	-32.5			332	-45.5			450	-44.2	534	-45.5			755	-55.5	801	-50.9	829	-48.3		
101	-30.5	178	-33			333	-47			450	-44.7	534	-45.3					802	-51	830	-48.4		
101	-31.3	178	-33.7			334	-48.3					535	-45.3			748	-56.4			831	-48.5		
		178	-34.3			335	-49.9			442	-44.9	535	-46.3							832	-48.7		
		179	-35							443	-45.1	536	-46.6			749	-55.3			833	-49		
		179	-35.5			329	-44.6			444	-45	536	-47.7			750	-56.3			834	-49		
		179	-36.1			330	-44.5			445	-44.7	537	-48.3			750	-56.9			835	-49.1		
						330	-43.9			446	-44.7	537	-50.7			751	-52.4			836	-48.9		
						331	-43.6			447	-44.6					751	-56.2			837	-49		
						331	-43.7			448	-44.8					752	-55.9			838	-48.3		
						332	-43.9			449	-44.5					752	-55.7			839	-49.3		
						332	-44.6			450	-44.6					753	-55.8			840	-55.3		
																753	-55.5			841	-49.2		
						330	-43.8			442	-46.9					754	-55.6			842	-49.4		
						331	-43.9			443	-46.7					754	-55.6			843	-49.3		
						331	-44			444	-46.1					755	-55.7			844	-49.3		
						331	-44			445	-45.7					755	-55.8			845	-49.2		
						331	-44			446	-46.1									846	-49.3		
						332	-44.3			447	-45.4									847	-49.4		
										448	-44.7									848	-49.9		
										449	-45.1									849	-49.8		
										450	-45.5									850	-50.6		
																				851	-50.6		
										442	-46.7									852	-50.8		
																				853	-51.4		
										444	-47.3									854	-52.2		
										445	-46									855	-53.3		
										446	-45.8									856	-52.3		
										447	-45.7									857	-55.5		
										448	-45.6									858	-56.6		
										449	-45.3									859	-57.2		
										450	-45.1									860	-58.4		
										451	-45.1												
										452	-46									840	-49.2		
																				840	-49.1		
										448	-45.7									841	-49.2		
										449	-45.3									841	-49.4		
										449	-45.3												
										450	-45.3												
										450	-45.3												
										451	-45.1												
										451	-45.1												
										452	-45.1												
										452	-45.5												
										453	-45.8												
										453	-46.2												

Appendix E: Guitar Rating Form

Guitar Rating Form

This study is voluntary, therefore if you do not wish to participate you may hand in a blank form. If you need any assistance in filling out the form, please ask for help. No personally identifying information will be collected for this study.

For each guitar you hear, if you are impressed by any of the properties listed below please write a +1 in the corresponding box; if the impression is strong, write a +2. If the guitar is lacking in any of the properties, then write a -1, and if it is strongly lacking, write a -2. Place a 0 in the box if you feel that the guitar is average or normal for a given property. Please include any comments about your impression of each guitar's sound.

Property	Guitar A	Guitar B	Guitar C	Comments
very powerful/loud +2 Power or Loudness very soft -2				
carries/projects very well +2 Projection/Carrying Power does not carry/project well -2				
very bright +2 Tone Quality or Timbre Bright (Dull or Muted) very dull/muted -2				
very full/rich +2 Full or Rich (Shallow) very shallow -2				
very open +2 Open (closed or boxy) very closed/boxy -2				
very clear +2 Clear (muffled) very muffled -2				
very even +2 Evenness very uneven -2				

Other Information

Please provide your age, major, and musical background below. This information will only be used to for correlation with the responses of the group.

Age: ____________________

Major: ____________________

Musical Background ____________________

Figure E.16. Guitar rating form for listening test.

Appendix F: Guitar Rating Raw Data

Table F.3. Guitar rating data for Guitar A (Yamaha FG403S).

Age	Major	Musical Background	Power/ Loudness	Projection/Carrying Power	Tone Quality	Full or Rich	Open	Clear	Evenness	Comments
18	Music	Trombone, Piano, Composition	0	0	-1	1		1	0	
22	Music (Piano performance)	~ 17 or 18 years, mostly with classical music	-1	-1	-1	-1	0	-1	0	I don't know a lot about guitar
18	Music	Piano/guitar	-1	-1	1	-1	-1	-1	0	
38	General Studies	30 years experience	-2	-2	-2	-2	-2	-1	-1	I think the playing was not very consistent
19	Physics	Played violin 8 years	-1	-1	0	1		0	1	
18	Chemistry/Physics	violin 6 years/ 2 years viola	0	-1	-2	-1	0	-1	1	
28	Intended major of Dx Arts	12 years guitar, mostly electric	0	-1	1	-1	-1	1	2	
18	Acoustical or Aeronautical Engineering	6 years low brass and bass guitar	1	-1	-1	1	0	0	-1	
19	Architecture	9 years piano	0	0	0	-1		-1	0	
18	International Studies	Trumpet and guitar in ensembles for 10 years	-1	-1	-1	0	-1	0	0	
19	Pre-English	violin 8 years, piano 6 years	-1	-1	-2	1	1	-1	0	
18	Neurobiology / Economics	4 years guitar, 8 years piano	0	1	2	1	-1	2	1	
26	Cinema studies	10 years guitar, 6 years singing	1	-1	1	1	0	0	0	
19	Accounting, finance, economics	2 years piano, 7 years trombone	-1	-2	0	-1	-1	0	-1	
20	English	Trumpet 10 years, guitar 3 years	-1	0	1	-1	-1	-1	0	
19	-	Guitarist (electric)	-1	0	-1	-1	1	1	-1	Lacking in bass (A)
19	Biology	6 years of choir	0	0	2	1	-1	1	1	
20	Journalism	Guitar player	0	0	-1	-1	0	-1	-2	
24	Art and Art History	Bass guitar in middle school, 2 years guitar lessons in high school.	-1	0	0	0	1	0	0	I play guitar for fun
19	English	guitar, drums, vocal experience	-1	-1	0	0	1	1	1	Self taught
22	Physics (Astro)	I play guitar, drums badly	-1	-1	1	0	1			
22	Film	Violin	-1	-1	-2	-2	-2	-2	-2	
22	European Studies	Middle school band trumpet	-1	-1		0	0	1	1	
20	Pre-major	Little/record music	0	0	2	-1	2	1	-1	
64	Math	Used to play saxophone and clarinet	0	0	0			0		
21	Linguistics	Play piano (badly)	-1	-1	0	0		0		significant difference between picked and strummed
70	Post graduate	Amateur- singer	0	1	2	1	2	2	2	
23	Mathematics	A/N	-1		0	1		-1		
20	Geography	none	0	0	1	0		0		
22		none	0	-1	0	-1		-1	-1	
18	Undecided		1	1	0	0	1	-1	-1	
19	Mechanical Engineering	none	0	0	-1	-2		-1		
19	Marketing		2	2	1	2	2	2	2	

Table F.4. Guitar rating data for Guitar B (composite guitar). This table continues from the previous page with the participants in the same order as before.

Power/ Loudn ess	Project ion/Ca rrying Power	Tone Quality	Full or Rich	Open	Clear	Evenn ess
-2	-1	-1	0		0	-1
-2	-2	-2	0	-1	0	0
0	0	1	1	1	1	0
-2	-2	-2	0	0	0	0
0	1	-1	2		0	1
2	2	2	2	1	2	1
-1	0	-1	1	0	0	1
-1	1	1	0	0	-1	0
1	1	0	1		-1	0
2	1	1	2	0	1	-1
-1	0	1	1	-1	0	-1
0	0	-1	0	1	0	-1
0	0	0	1	1	1	0
-2	-1	1	1	0	1	0
1	2	0	2	0	1	1
0	1	0	1	1	0	1
0	1	1	1	1	-1	1
1	1	0	2	0	1	1
0	0	-1	-1	-2	-1	-1
1	0	-1	1	-1	-1	0
1	1	0	1	0		
-2	-2	-2	-2	-2	-2	1
-2	1		2	-2	-1	
1	1	1	1	0	0	0
-1	-1	-1			0	
0	0	1	1		-1	
-2	-1	-1	-1	-1	-1	0
-2		-1	2		-1	
1	1	0	1		0	
1	1	1	1		1	0
2	0	1	1	-2	1	0
1	1	1	0		0	
2	2	-2	1	-2	-2	

Table F.5. Guitar rating data for Guitar B (composite guitar). This table continues from the previous page with the participants in the same order as before.

Power/ Loudness	Projection/Carrying Power	Tone Quality	Full or Rich	Open	Clear	Evenness
-1	-1	0	1		1	1
0	2	1	1	1	2	-1
0	0	2	1	1	1	0
0	0	1	1	1	1	1
-1	-1	1	-1		-1	-1
1	1	1	1	-2	1	2
-1	0	0	-1	-1	2	0
1	1	-1	-1	0	-1	1
1	2	1	2		1	1
1	1	0	0	0	1	1
0	0	0	0	0	1	0
0	0	0	0	1	1	2
2	2	1	2	1	1	2
0	1	-1	2	1	2	1
0	1	2	-1	1	1	1
0	1	1	1	0	0	0
0	0	0	0	1	0	0
0	1		1	0	1	0
1	1	1	1	2	1	1
1	1	0	1	1	0	2
0	0	-1	-1	0		
0	0	1	2	1	1	2
-1	1			-2	-2	-1
1	1	1	2	1	0	0
0	0	0			0	
1	0	1	1		1	
0	-1	0	0	0	0	-1
0		1	2		-2	
-1	-1	1	0		0	
2	1	1	2		2	1
1	1	1	1	-1	1	0
2	2	2	1		1	
1	1	2	1	-2	1	