Composite Acoustic Guitar Project

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ME 495 Final Report
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1) Introduction:

Winter quarter has seen significant progress in the composite acoustic guitar project. Although slightly behind the schedule laid out at the beginning of the year, there was enough slack scheduled for spring quarter that completing the guitars by summer should be easily possible.

Many test lay-ups and experiments have take place, from which we have determined an optimal laminate pattern for the guitar bodies. Material tests were performed on this sandwich structure, and the results were then fed back into ANSYS in a tightening decision loop. Based on our final tests, static FEA results were off by less than 7% (typ 4%) and dynamic results (modal frequencies) erred from 1 to 14%.

In addition, an accurate CAD model of the guitar has been created in Solidworks to finalize geometries. From this, CNC technology is incorporated into machining parts associated with the body shape and the neck. A thorough survey of guitar parts and material suppliers was also completed, and all the necessary hardware, wood, tools, and finishing materials were purchased.

2) Material Testing:

In order to accurately model the behavior of composite structures, both in the static and dynamic regimes, it is necessary obtain accurate material properties. Unlike homogeneous metals, for which material properties can be closely obtained from literature, the properties of composite structures depends on many variables. These include the number of layers, laminate directions, number of strands/tow, type of weave, type and amount of resin used, presence and properties of a core material, processing, and many others.

Because there is currently no accurate way to include all these factors in calculating composite structure properties, material tests were conducted for different lay-ups that were in the range needed for an acoustic guitar. For static and modal analysis, the density, elastic modulus, and Poisson's ratio of the final composite structure are needed.

Density:

In the most rudimentary form, our density tests simply consisted of weighing a finished composite specimen of known dimensions. However, the percent (by weight) of carbon, foam, and resin is useful in determining whether the specimen is as light as possible and matches values published in literature. Because the resin adds very little mechanical strength or stiffness (properties desirable in a guitar body), it is desirable to minimize the % resin (by weight) to less than 40%.

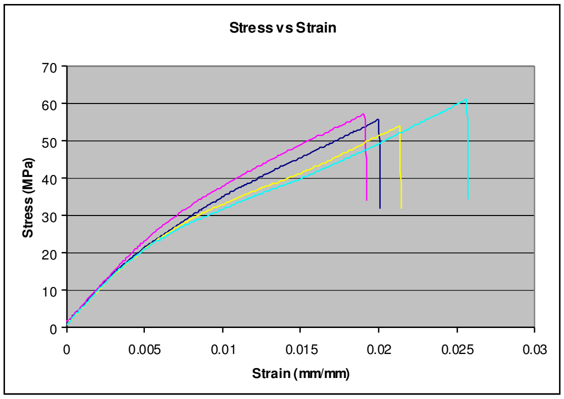
To calculate this, specimens of 1/8" foam core material and raw carbon cloth were massed per unit area. By subtracting these two area densities from a total density, the area density of resin (and thus its percentage by weight) can be easily determined. Our first square test layup was more than 50% resin by weight, which was unacceptable. On subsequent layups, using a spreader to minimize epoxy pockets between each layer resulted in much lower epoxy percentages, consistently in the 35-38% range. Calculations and data are shown in Appendix A.

Elastic Modulus:

Besides density, the elastic modulus (or stiffness) of a material plays a critical role in its dynamic behavior. In order to measure the elastic modulus of the laminate, dog-bone specimens of the finished composite were prepared for tensile testing. The tests were performed on an Instron 5585H, as shown in Figure 2.1.

Figure 2.1: Carbon fiber specimen undergoing tensile testing

Two different laminates were tested: one woven ply on each side of the core [0/90, core, 0/90] and two woven plies [+/- 45, 0/90, core, 0/90, +/- 45]. The carbon cloth is a 0/90 degree fine over-under weave with 3000 strands/tow. Core materials is 1/8" rigid PVC foam (91 Kg/m^3) from General Plastics. Figures 2.2a and 2.2b show the stress-strain plots (Figure 2.2b is a detail of the linear regime) for 4 specimens of the 1-ply lay-ups. The plots are roughly bi-linear, where the change in slope likely occurs when the fibers begin slipping within the matrix.



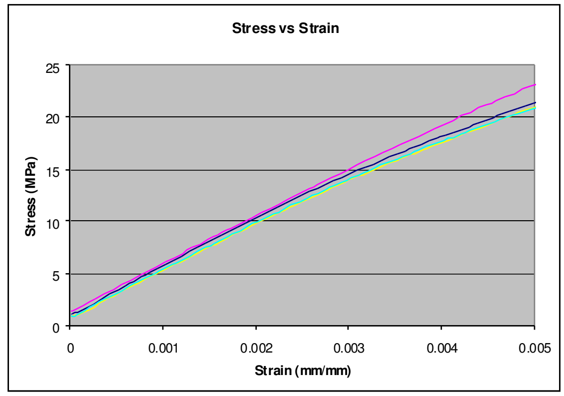


Figure 2.2: Stress/strain plots for 1-ply sandwich lay-up. (right: linear portion)

Since the linear region is slightly curved, the elastic modulus is calculated for the first 10, 20, 30, and 40 data points (40 data points is about 0.35% strain). Since the result drops off evenly, the average value for the first 10 data points was used. Data is shown in Table 2.1.

Table 2.1: Elastic moduli of 1-ply lay-ups (4 specimens)

Data pts	"1-1"	"1-2"	"1-3"	"1-4"		Average
	Mpa	Mpa	Mpa	Mpa		Mpa
10	**4607.584**	**4604.108**	**4663.186**	**4762.405**		4659.32
20	4588.04	4561.244	4649.441	4734.185		
30	4503.477	4477.701	4598.113	4647.839		
40	4348.917	4337.466	4531.83	4478.438		

Figures 2.3a and 2.3b show the stress-strain plots (Figure 2.3b is a detail of the linear regime) for 4 specimens of the 2-ply sandwich lay-ups. The results display a distinctly tri-linear (steep – shallow – steep) pattern. The first steep region is before any yield, the shallower region is when the fibers are slipping within the matrix, and the late increasing slope is when the fibers have all shifted as far as they can (I.E. "scissored": all the slack is taken up in the individual fibers). In the case of our guitar, the initial linear slope is all that will be needed, since none of the stresses will approach the yield point.

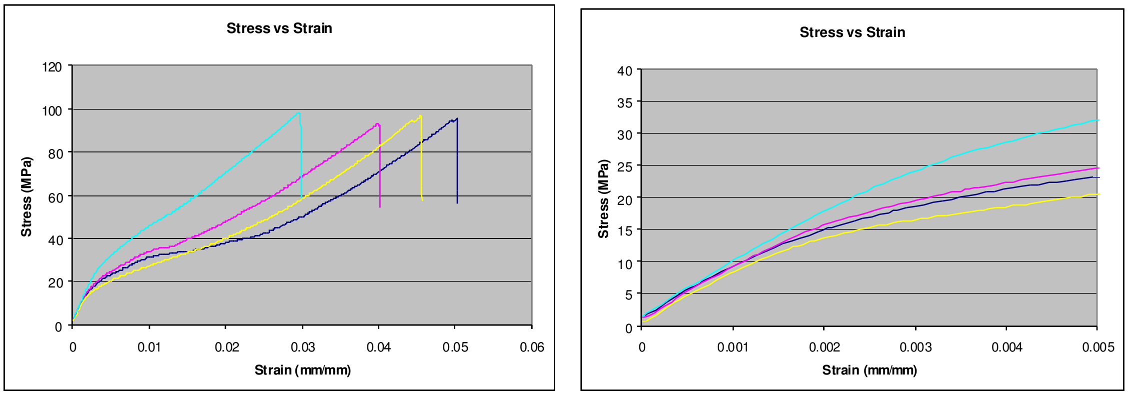


Figure 2.3: Stress/strain plots for 2-ply sandwich lay-up. (right: linear portion)

Again, the "linear" portion is slightly curved, so an equivalent method is used as above. Classical lamination theory was also used to approximate the overall properties, but lack of accurate data about the raw carbon fiber and a lack of ways to account for the weaving led to less than optimal results. (See Table 2.3) Although the minimal weight of the 1-ply sandwich is desirable, the stiffness and strength of the 2-ply sandwich is necessary for application as an acoustic guitar top (see FEA section), so a 2-ply sandwich was selected for use.

Table 2.2: Elastic moduli of 1-ply lay-ups (4 specimens)

Data pts	"2-1"	"2-2"	"2-3"	"2-4"		average
	Mpa	Mpa	Mpa	Mpa		Mpa
10	**8604.616**	**7867.267**	**8604.616**	**7993.266**		8267.441
20	8246.401	6984.797	8246.401	7007.439		
30	7785.531	5711.126	7785.531	5945.787		
40	7027.18	4449.557	7027.18	4839.426		

Poisson's ratio:

Poisson's ratio is the only other material property (besides density and stiffness) that significantly affects the modal analysis. Poisson's ratio plays only a small role though, so it was estimated from classical lamination theory using the lay-up parameters. FEA has verified that small changes in Poisson's ration make insignificant changes to the modal analysis, so no further experimentation was conducted.

Damping ratios for that material were not measured, because transient and forced response cases were not included in this analysis (due to the relatively limited scope of this project.

Table 2.3: Comparison of calculated and tested material properties

Material	E11	E22	v12	G12	density	thick
	GPa	GPa		GPa	kg/m^3	mm
CLT Calculations						
45/-45/0/90/45/-45/core/S	33	33	0.336	17.8	610.8	4.975
45/-45/0/90/core/S	19.4	19.4	0.245	7.8	475.1	4.375
0/90/core/S	14.4	14.4	0.34	2.08		
Tested						
0/90/core/S - trial 1	**4.75**	4.75	**0.34**		**354**	**3.785**
0/90/core/S - trial 2	**4.66**	4.66	**0.34**		**280.6**	**3.785**
45/-45/0/90/core/S - trial 2	**8.27**	8.27	**0.245**		**418.5**	**4.14**

3) FEA/Experimental comparisons:

FEA was used autumn quarter to determine the approximate material properties needed for an acoustic guitar, which provided the baseline data to select lay-ups to further test. Once all the relevant material properties for the actual lay-ups have been determined and/or well approximated, these values can were then fed back into the finite element program (ANSYS) to yield results which should compare reasonably closely to reality. Both dynamic and static cases were explored for both modal analysis and static deflection.

Dynamic:

First, it is necessary to demonstrate through actual tests that the FEA results agree with reality. In order to demonstrate this, several 12" square lay-ups were created. By using a simple square lay-up, modes are easily identified by location the sample point. (See Figure 3.1) A Polytek OFV 2600 laser vibrometer was used to measure velocity vs. frequency of specific points without changing the response at all.

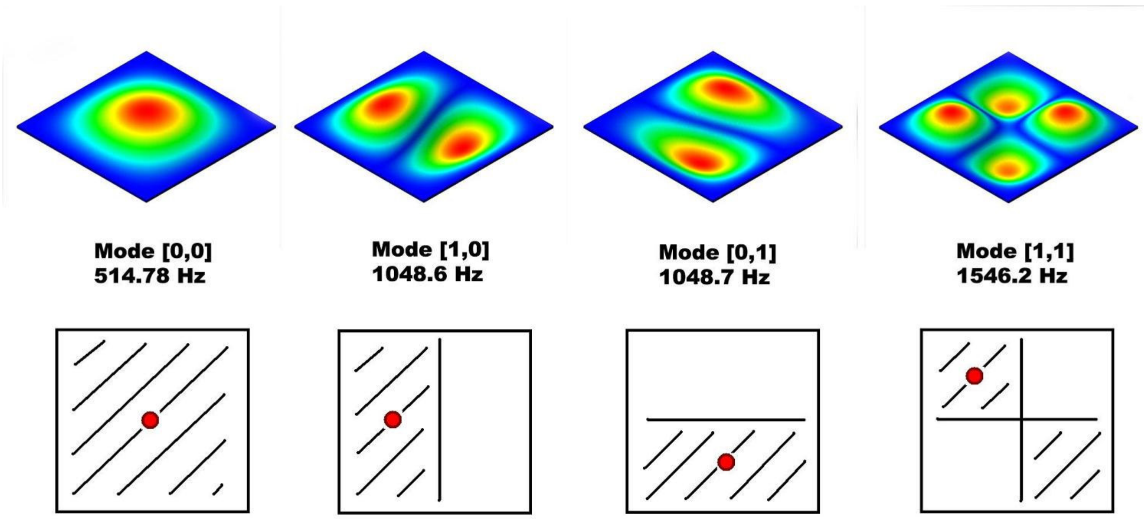


Figure3.1: Lowest 4 modes of a square plate & laser locations to measure each.

Using the laser vibrometer, the simple lower frequency modes are easily measured and identified by physical excitement of the plate with a rigid object and careful positioning of the measurement point. For instance, Figure 3.2 shows the response of a square plate with the laser pointed very near the center. This should be at a node for the mode (0,0) and antinodes for the 2nd-4th modes. Indeed, one large peak was observed at 150 Hz.

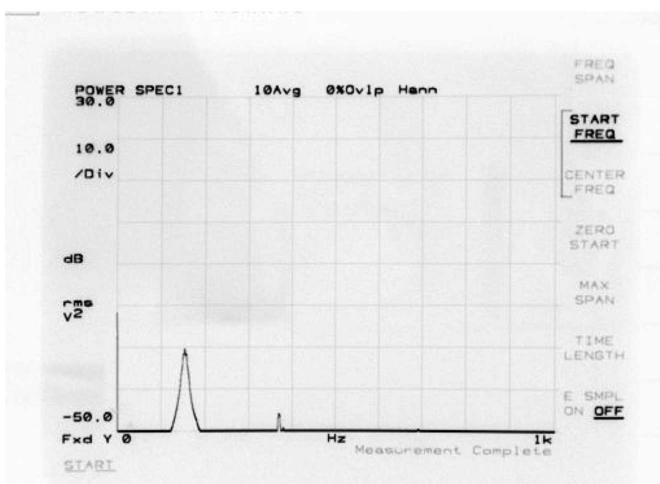


Figure 3.2: Square plate response measured roughly at center

Next the laser point was shifted to the center of one of the halves of the plate (See Figure 3.1, 2nd and 3rd modes). A smaller peak should be present at the fundamental (0,0) modal frequency determined above, and a large peak should now be present at a higher frequency, representing the 2nd and/or 3rd mode. Indeed this is the case, with the 2nd/3rd modes at around 375 Hz. (See Figure 3.3)

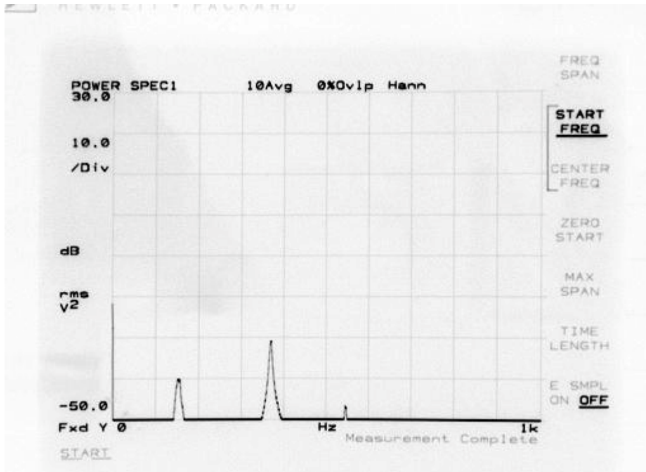


Figure 3.3: Square plate response measured at center of ½ the plate.

Then, the laser point was located in the center of one of the quadrants (See figure 3.1, 4th mode). This now should pick up the first, second, and third modes as well as a new peak at the 4th mode, higher than the 2nd/3rd modes. Again the predictions are correct, as shown in Figure 3.4, with the 4th mode at 550 Hz. One interesting note is that the 2nd and 3rd modes are not at exactly the same frequency, presumably because the plate was not exactly square and/or homogeneous.

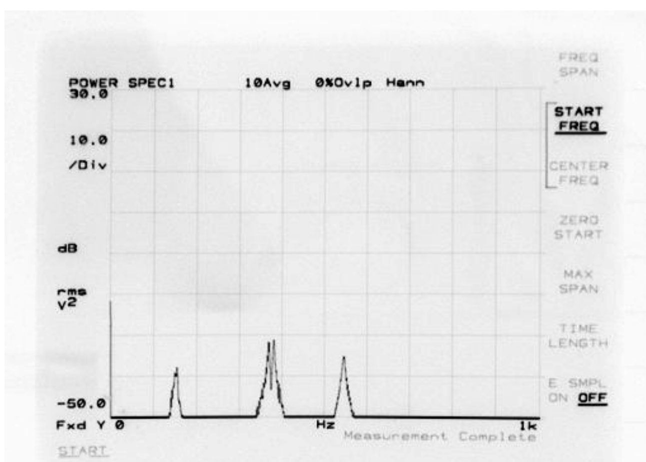


Figure 3.4: Square plate response measured at center of quadrant.

Using fixed boundary conditions proved troublesome in comparing to FEA, so the plates were analyzed with free edges. For a 2-ply sandwich layup, the mode frequencies agreed well (0-13% error) for the first 7 modes. (See Table 3.1) From this, the conclusion was drawn that the modal analysis of ANSYS compared well enough to real life to attempt to define the mode frequencies of a guitar body. This method of identifying modes will be used to experimentally determine the exact modal frequencies of the guitar, although it will be somewhat more difficult due to the more complex mode shapes.

Table 3.1

2 ply square, FREE edges	Mode 1	2	3	4	5	6	7
	(Hz)	(Hz)	(Hz)	(Hz)	(Hz)	(Hz)	(Hz)
FEA	135.5	195.73	232.67	346.44	346.44	594.75	594.75
TEST	145	195	260	335	350	525	545
% difference	**6.55%**	**0.37%**	**10.51%**	**3.41%**	**1.02%**	**13.29%**	**9.13%**

In addition, comparison tests were done with a free-edged guitar back. However, the significantly more complex mode shapes and non-homogeneous nature of the folded edge style of lay-up led to greater error in trying to match up the modal frequencies in practice.

Static:

Out-of-plane stiffness is also very important for the functionality of a guitar, both on feel (solidness of the body) and in deflection of the soundboard under string tension. In order to determine the accuracy of FEA in predicting the out-of-plane deflection vs. force, another comparison experiment was set up. A guitar back lay-up was constrained by its edges and weights systematically added to the center of it (to create known out-of-plane force). A dial gauge was set up at a central location and deflection measured and recorded. An analogous situation was modeled in ANSYS and a non-linear analysis performed. Data are shown in Appendix E.

The initial stiffness was very similar between FEA and reality, as shown in Figure 3.5. However, once deflections neared 1 mm, the values began to deviate as non-linearities began to intrude. However, in subsequent FEA analysis, it was determined the top would deflect less than 0.5mm, so this deviation is insignificant to the analysis. Therefore, static FEA results in the out-of plane direction can be trusted.

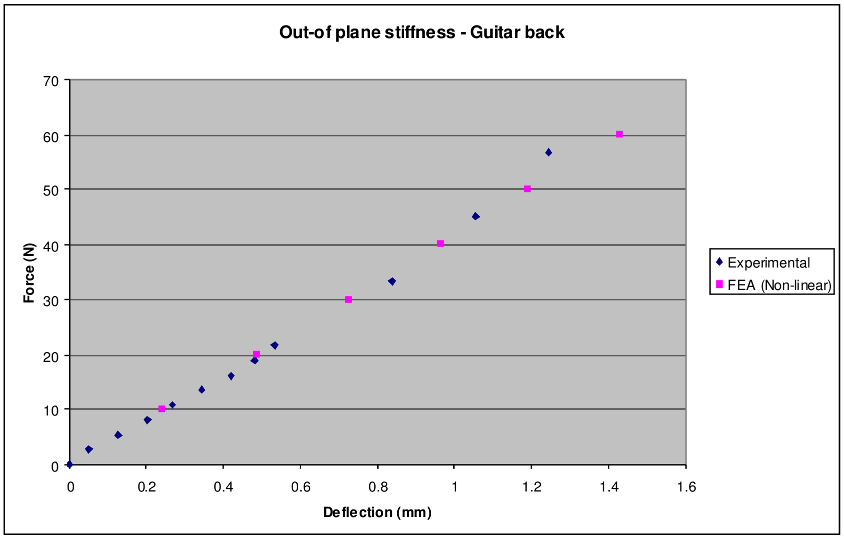


Figure 3.5: Out of plane stiffness comparison between FEA and experiment

4) Dynamic FEA:

The focus on our project regarding the tone of acoustic guitars is mostly focused on low frequency (<1000 Hz) modal analysis, although many other doubtless relevant factors (such as the relative strength of the modes, the higher frequency response, and the damping of the top) have been overlooked due to the limited scope of the project and limited time.

Once the actual material properties of the [2 woven ply/core/symmetrical] sandwich structure and the geometry of the guitar body was decided upon, a final run of FEA tests was conducted (many other FEA tests have taken place to guide the selection process in a non-qualitative way). However, the exact boundary conditions of the bonded interface between the top and the sides is a yet unresolved question. For the purpose of this analysis, the position (x, y, z) of the edge was considered fixed and the rotation (ux, uy, uz) of the edges was considered both in the free (unconstrained) and fixed (constrained) cases. Mesh and conditions are shown in Figure 4.1. In reality, the rotating boundary condition will be somewhere in between free and fixed, but to what percent is not known.

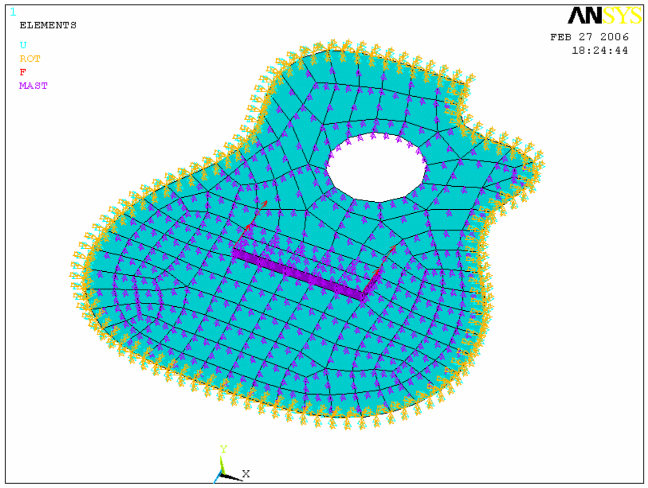
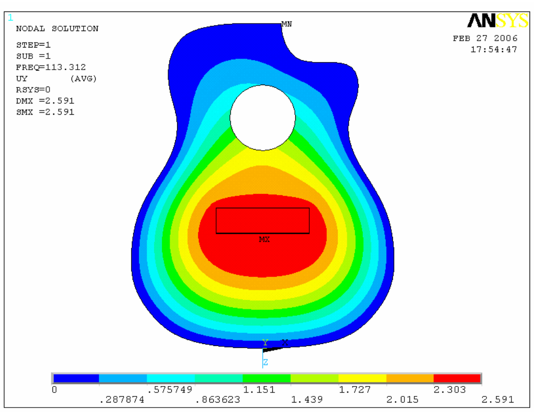
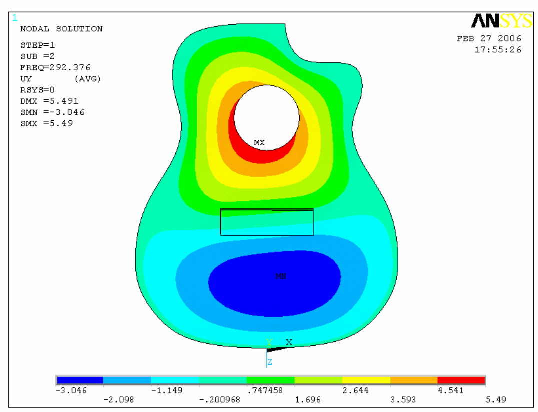


Figure 4.1: Mesh, constraints, forces, and DOF used for final top FEA.

To validate an accurate FEA analysis, a decreasing of mesh size was used with both 4-noded and 8-noded shell elements. Results were very consistent (within 2% for all cases), which is well within the error bounds of this analysis. In the hinged boundary conditions, the first 5 modes were found to be at about frequencies of 113, 292, 310, 455, and 635 Hz, whereas in the fixed conditions, they were 208, 445, 460, 690, and 850 Hz. (See Figure 4.3 - Complete data is included in Appendix B) The first 5 modes of the free conditions are shown in Figure 4. A complete index of the mode shapes can be found in Appendix C. This analysis included the mass of the bridge and the tension of the strings.





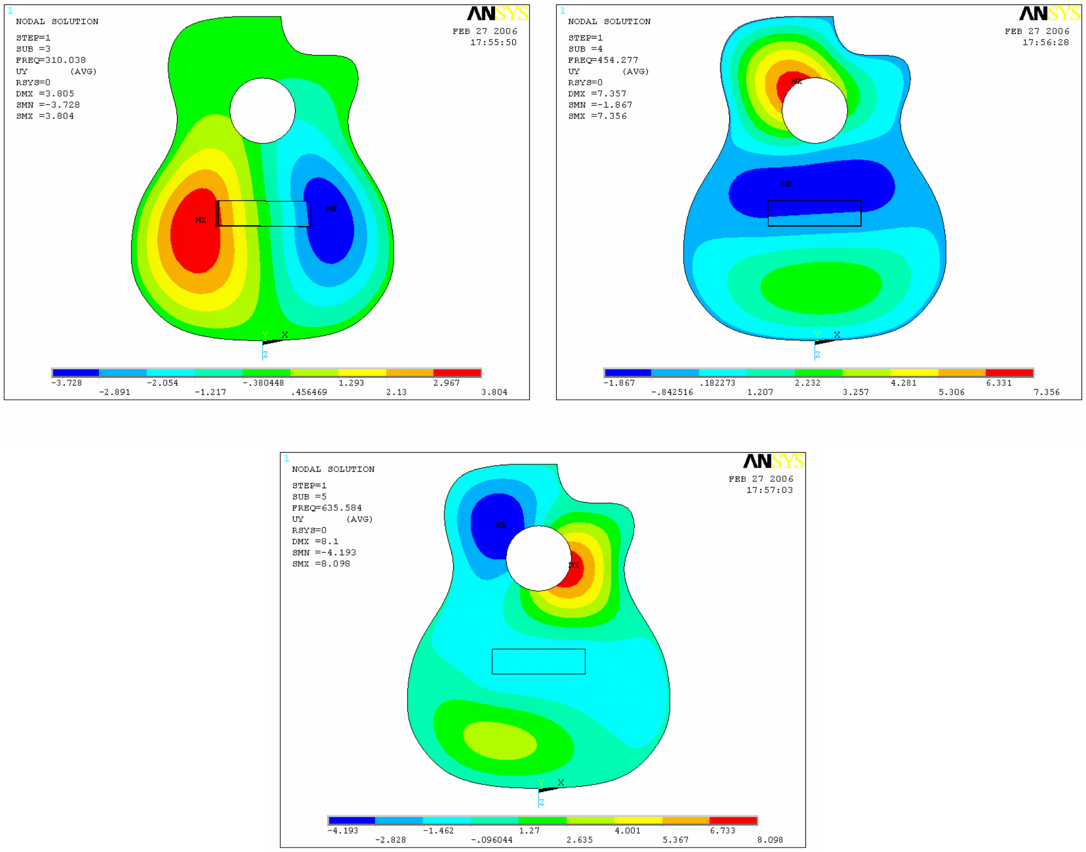


Figure 4.2: First 5 mode shapes of guitar top with hinged boundary conditions.

The lay-up for our guitar was selected to have the free and fixed rotational boundary conditions that roughly span modal frequencies of existing guitars. This is difficult though, because the bracing in conventional acoustic guitars changes the relative frequency of the modes, which makes even qualitative matching impossible between modes. However, variables were chosen such that differences were minimized.

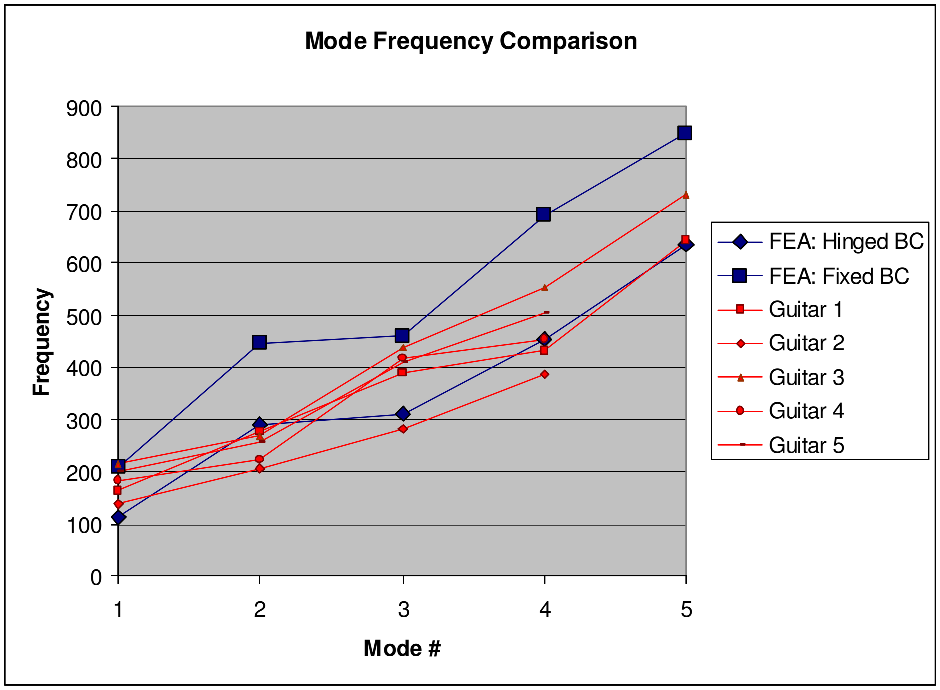


Figure 4.3: A comparison of modal frequencies between out FEA model and 5 actual guitars.

The modes of the back of the guitar were likewise determined using FEA and fixed boundary conditions. The back of the guitar plays a relatively minor role in the tone of a guitar, so little optimization was done here. Modal frequencies were 312, 536, 662, 824, and 1040 Hz. Mode shapes are shown in Appendix D.

In addition, the coupled modes of the top and the back of the guitar were explored in ANSYS with meshed air inside the cavity. Good results were hard to obtain, but the main "breathing" mode (where the mode (0,0) of the top and the back are moving out of phase with each other and air is forced in and out of the soundhole) was calculated to occur at 205 Hz, and the second mode (top and back fundamental modes moving in phase) occurred at about 250 Hz.

5) Static FEA:

One important aspect of an acoustic guitar is that the top must be stiff and strong enough to undergo the constant string tension (163 lbs for Diaddario light strings) without long term yielding or unacceptable amounts of deflection (which would affect playability of the guitar). The most critical deflection is in the out-of plane direction of the top. This should be kept to a minimum (under 0.5 mm) to not affect the playing action on the fretboard.

The mesh & conditions and out-of-plane deflection (in m) for the top plate is shown in Figure 5.1 under full string tension. The maximum deflection of the top is 0.4mm, but the deflection of the bridge at the location of the saddle is practically negligible (<0.1mm). Also, deflection in the string direction (which could cause intonation problems) is negligible, so we conclude that adding string tension will not adversely affect the geometry of the guitar.

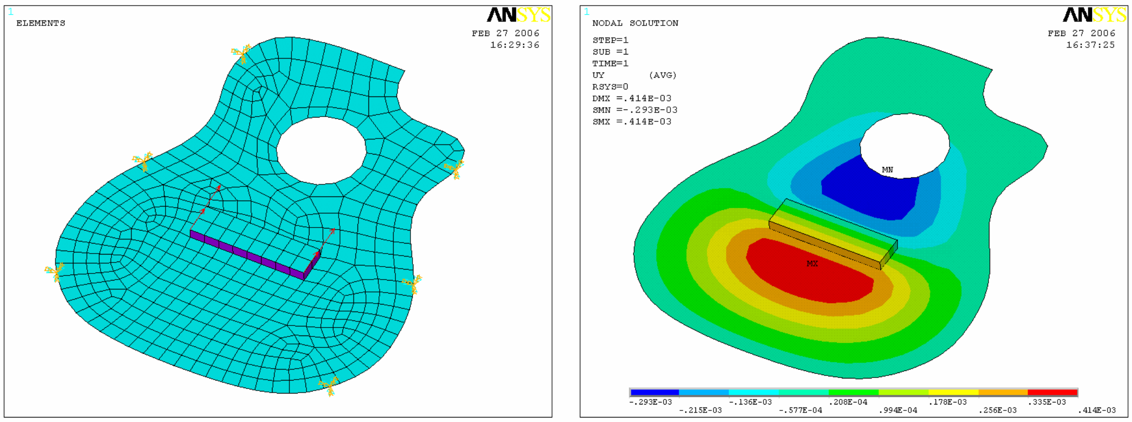


Figure 5.1: Static FEA mesh & conditions (left) and results (right).

6) Layups:

As alluded to above, the final laminates decided for the lay-up consists of +/- 45 degree and 0/90 degree woven carbon fiber fabric layers sandwiching a 1/8" rigid PVC foam core. This is laid up such that it is symmetric to avoid any warping during the cure cycle.

For the planar lay-ups, we use a sheet of glass as a mold because it is flat, glossy, can be re-used many times, and is relatively inexpensive. The side molds were machined out of high density rigid PVC foam on a Bridgeport 2-axis CNC mill and coated with polyester body putty and glazing compound before being machined to final specs. (See figure 6.1). The molds were then sprayed with primer, smoothed, and sprayed with a white paint coat which has been buffed to a high gloss. 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.

Figure 6.1: Side mold before final machining pass (left), side molds after spray-coating with primer (right)

The following is the process we have arrived at for doing lay-ups:

1) Prepare the surface to be laid up on such that it is smooth and glossy and free of any contaminates. This involves polishing the surface if glass, and possibly lightly sanding and buffing out a painted surface
2) Apply 4 coats of silicon-free mold release wax. Allow it to dry and buff out between each coat. Wait at least an hour between the 2nd and 3rd coats. (painted surface only)
3) Airbrush several coats of polyvinyl alchohol (PVA) mold release onto the surface. This will dry into a peelable ply. Allow to dry thoroughly (at least an hour)
4) Cut foam into correct shape using aluminum template for the top and back and straightedge for sides. For the top and back, bevel the edges back approximately 60 degrees to minimize unsightly fabric lift during curing. (Figure 6.2, 6.3)

Figure 6.2: Cutting foam core

Figure 6.3: beveling edges

5) Cut carbon fabric to size using 2^{nd} aluminum template and/or a straightedge for the sides to trace the shape of the top or back with chalk onto the fabric. (Figure 6.4)
6) Cut release cloth, breather cloth, and vacuum bag material to size, lay out sealant tape. (Figure 6.5)

Figure 6.4: scribing shape on carbon cloth.

Figure 6.5: Lay-up materials cut

7) Measure epoxy and mix thoroughly.
8) Put several small drops of epoxy onto the mold surface (to hold first layer of carbon fiber)
9) Carefully lay out first ply of carbon fabric and smooth carefully over the mold surface.
10) Using a plastic spreader, spread epoxy evenly over the fabric, allowing it to soak in against the mold surface. Eliminate pools of resin before adding next layer. (Figure 6.6)
11) Repeat with 2^{nd} carbon layer
12) Position the foam core and spread epoxy over it evenly
13) Repeat with top two layers of carbon fabric
14) Lay release ply on top, (avoiding wrinkles), then breather cloth
15) Position and seal the vacuum bagging. Connect to vacuum pump and slowly draw vacuum while checking for leaks. (Figure 6.7)

Figure 6.6: Spreading epoxy

Figure 6.7: Sealing vacuum bag

16) Hold at full vacuum for at least 8 hours (preferably overnight). (Figure 6.8)
17) Carefully remove lay-up materials and de-mold. Use wedges if necessary. Wash residual PVA off part. (Figure 6.9)

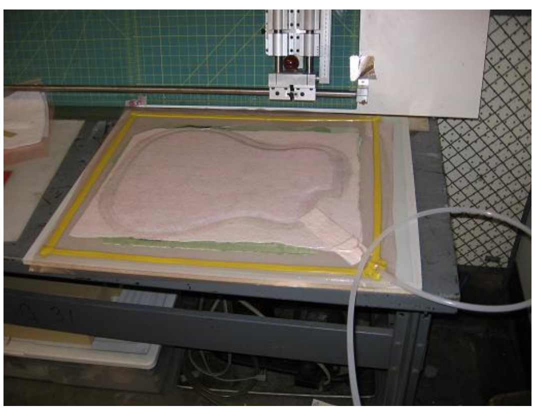


Figure 6.8: Under vacuum

Figure 6.9: Removing finished part from tool.

Examination of the finished composite structures was performed under a microscope. The epoxy wetted out the fiber well, but tended to leave small gaps in the cross-holes of the weave (figure 6.10). Although not structurally a problem, these gaps are unsightly and will be filled with sealer and/or lacquer during final processing if a technique is not figured out to eliminate them during the lay-up stage. The vacuum bagging resulted in good bonding between plies and the core. Figure 6.11 shows one edge of a cross section of a laminate with a single ply of 0-90 degree fabric against foam.

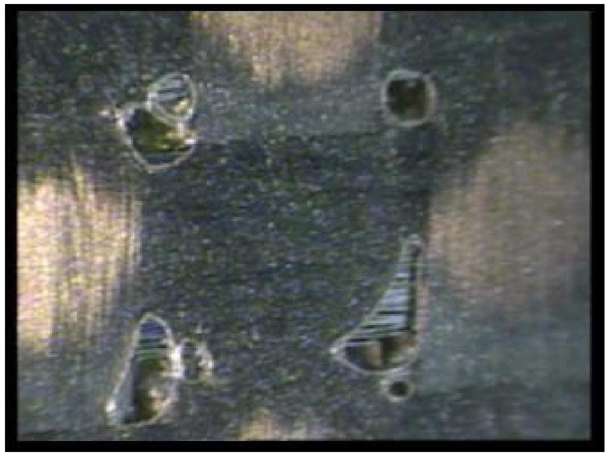


Figure 6.10: Epoxy voids (~40x Mag)

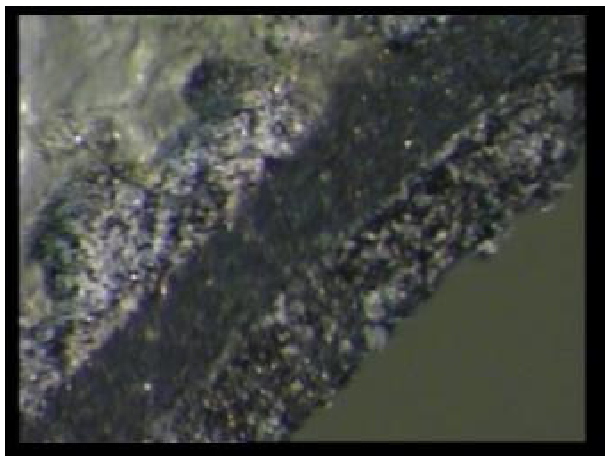


Figure 6.11: Cross section of fibers and foam (upper left). (~100 X mag)

7) CAD:

In order to accurately and precisely make other parts of the guitar, such as the neck and the reinforcing blocks, an accurate CAD model of the guitar was constructed in Solidworks, and all components modeled to actual tolerances. This allows parts to be designed and made that will position the neck, nut, saddle, and the bridge accurately in order to have a well-playing guitar.

From the CAD models, G-code has been generated to create much of the tooling for the creation of the actual guitars. This includes, the side molds, the side mold edge plates, aluminum templates for the body shape and foam core shape

The neck will also be 3–axis machined straight from CAD. In order to accommodate machining its back profile, a vacuum fixture was designed and created using locating pins and an O-ring as shown in Figure 7.1. This will allow one fixturing setup for the entire 3-axis machining step. A traditional dovetail joint (in conjunction with the neck block) will be used to attach the neck to the body securely.

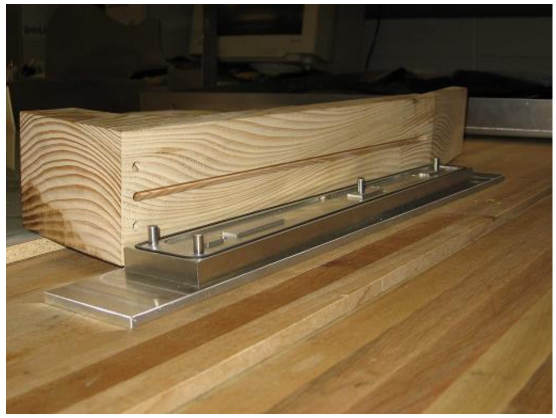


Figure 7.1: Vacuum fixturing for the neck milling

Screenshots of the CAD assembly are shown in Figure 7.2 and 7.3.

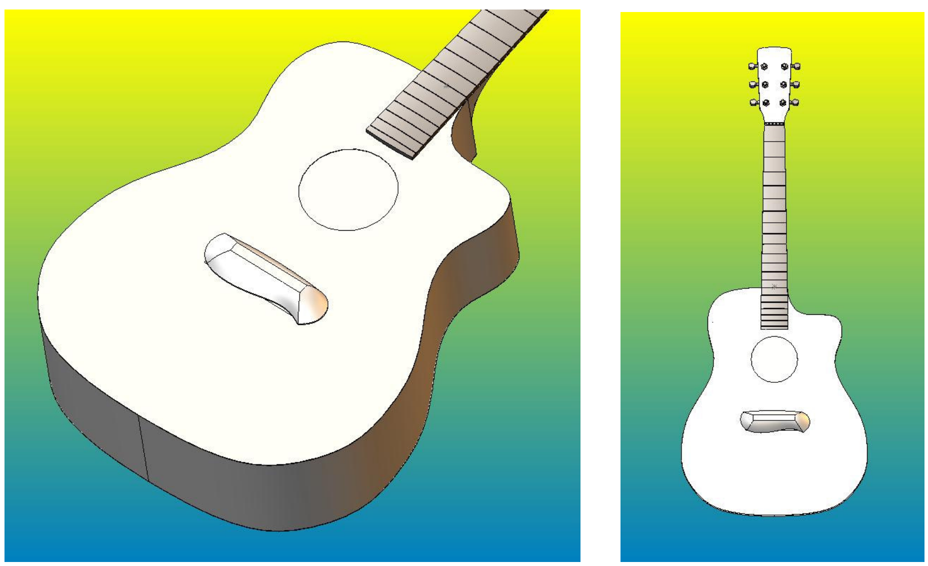


Figure 7.2 Body detail and whole guitar in Solidworks

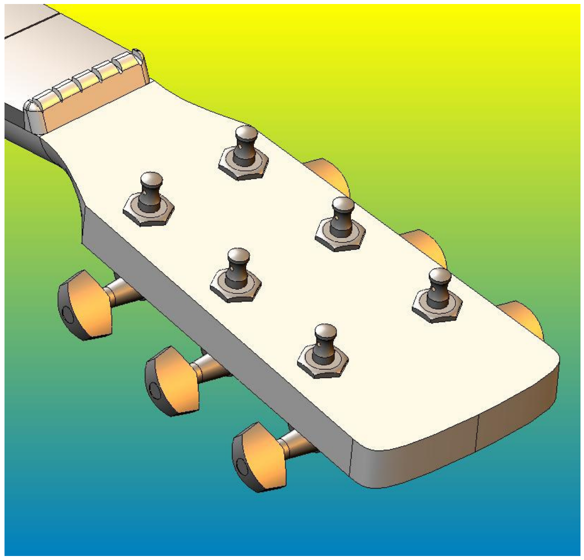


Figure 7.3: Headstock detail of CAD model.

8) Guitar Construction:

Much research has taken place this quarter in the methods and techniques of constructing conventional acoustic guitars. Although parts of this will translate directly into the construction of our guitars, the rest is just the groundwork for our experiments. Based on this research, all the guitar components and specific tooling that will be needed in constructing our guitars has been purchased. This includes hardware such as tuners, bridge and nut blanks, and bridge pins (Figure 8.1). Also purchased was mahogany for the necks, rosewood for the bridgeplates, ebony bridge blanks and fretboards, and mahogany for the body internals. A complete BOM and vendor comparison has been included in Appendix F.

Figure 8.1: Wood, hardware, tools, and finishing supplies

In addition, a fully ventilated spraybooth was constructed at my place of residence to paint the molds and lacquer the finished guitar, since there is nowhere on campus where one can legally spray paints and lacquers.

Also, we arrange and went on an unofficial tour of Gurian Instruments, Inc. located on a barge (!?) near the Ballard locks to gain some insight into what makes a "good" guitar. Michael Gurian (who personally showed us around!) is a legendary luthier who played a large part in defining the modern steel-string acoustic guitar. His valuable guitars made in the early 1970's are very sought after, but these days he is involved supplying the entire North American guitar-making market with high-end bindings, rosettes, bridge pins, end pins, veneers, and other assorted items from time to time. The visit was both interesting and informative, as we sought his advice on luthiership in general and heard his opinions on this project.

9) Conclusions:

By far the most prevalent conclusion that I have come to is this: Although it is an insane amount of work for two students to develop the infrastructure and tooling to make carbon fiber acoustic guitars from scratch on top of a full load of classes and work/other research, the experience and learning that is going on is irreplaceable. I am greatly enjoying the process of learning about the science and engineering that go into the acoustics and construction of an acoustic guitar, even as I struggle with getting good and accurate data and making time to do all the legwork of a project like this.

10) Acknowledgements:

Many thanks to out Sponsors Janicki Industries (Peter Janicki and John Weller) and 3M (Tim Shay), as well as the Mary Gates Research Scholarship. Thanks to Michael Gurian (Shop tour and excellent guiding advice), Travis Garrison (composites help and advice), Bill Kuykendall (material testing) and Prof. Reinhall for supporting this project!

Also:
-UW FSAE team for rigid mold foam
-UW Sub team for core material
-Russ Noe for shop help/advice
-Prof. Kumar

11) Appendecies:

Appendix A: Composite lay-up density data & calculations

Density Calculations									
	Meas X		**Meas Y**		**Meas Thick**			**Area**	**Area**
Raw materials	**in**	**cm**	**in**	**cm**	**in**	**cm**	**m**	**in^2**	**cm^2**
Actual carbon (0-90 cloth)	2.20	5.59	2.35	5.97	0.01	0.03		5.17	33.35
foam (UW Sub team: General plastics)	4.98	12.65	12.05	30.61	0.13	0.32		60.01	387.15
Laminates: reference									
rainsong					0.149-0.169	0.38-0.43			
First Layup									
small piece	3.36	8.53	10.00	25.40	0.15	0.38	0.0038	33.60	216.77
large square	13.75	34.93	13.75	34.93	0.15	0.38	0.0038	189.06	1219.76
-within frame	11.10	28.19	11.10	28.19	0.15	0.38	0.0038	123.21	794.90
Full sheet, trial 2	13.63	34.61	13.65	34.67	0.15	0.38	0.0038	185.98	1199.88
Full sheet foam dims trial 2	11.70	29.72	11.70	29.72	0.15	0.38	0.0038	136.89	883.16
Small section, 1 ply, trial 2	3.10	7.87	6.13	15.56	0.15	0.38	0.0038	18.99	122.50
small section, 2 ply, trial 2	3.10	7.87	6.10	15.49	0.16	0.41	0.0041	18.91	122.00

(ctd…)

Meas weight	**area dens**	**dens**	**dens**	**wt foam**	**wt carbon**	**(wt epoxy)**	**% foam**	**% carbon**	**%epoxy**
g	**g/cm^2**	**g/cc**	**kg/m^3**						
0.67	0.02	0.61	608.33						
11.23	0.03	0.09	91.36						
		0.25							
25.10	0.12	0.31	**305.95**	6.29	8.71	10.10	25.05%	34.70%	40.25%
155.00	0.13	0.34	**335.77**	26.95	49.00	79.05	17.39%	31.61%	51.00%
106.51	0.13	0.35	**354.04**	23.06	31.93	51.52	21.65%	29.98%	48.37%
118.06	0.10	0.26	**259.98**	25.62	48.20	44.24	21.70%	40.83%	37.47%
93.78	0.11	0.28	**280.59**	25.62	35.48	32.69	27.32%	37.83%	34.85%
13.62	0.11	0.30	**295.76**	3.55	4.92	5.15	26.09%	36.13%	37.78%
21.14	0.17	0.42	**418.53**	3.54	9.80	7.80	16.74%	46.37%	36.89%

Appendix B: Final guitar top FEA results

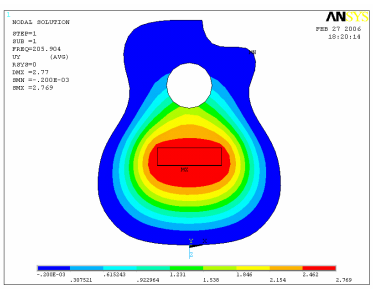
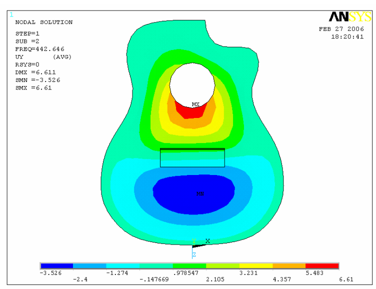
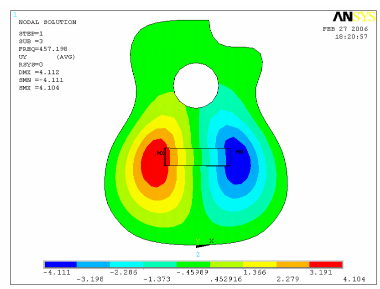
FINAL TOP FEA: (mode)	0,0	0,1	1,0
hinged BC, 10E9, .00414, .07kg bridge, .03 mesh, 4 node	114.51	294.47	311.37
hinged BC, 10E9, .00414, .07kg bridge, .02 mesh, 4 node	113.82	293.53	310.67
hinged BC, 10E9, .00414, .07kg bridge, .01 mesh, 4 node	113.31	292.38	310.04
hinged BC, 10E9, .00414, .07kg bridge, .03 mesh, 8 node	113.65	293.19	310.97
hinged BC, 10E9, .00414, .07kg bridge, .02 mesh, 8 node	112.68	290.15	308.75
Fixed BC, 10E9, .00414, .07kg bridge, .03 mesh, 8 node	208.05	447.68	462.01
Fixed BC, 10E9, .00414, .07kg bridge, .02 mesh, 8 node	205.9	442.65	457.2

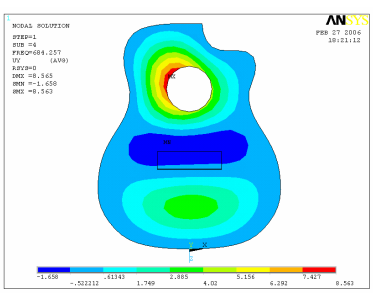
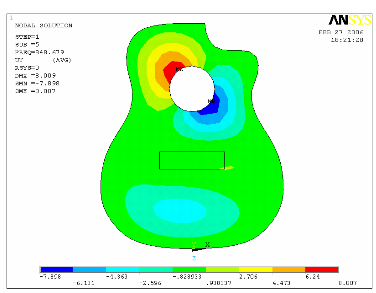
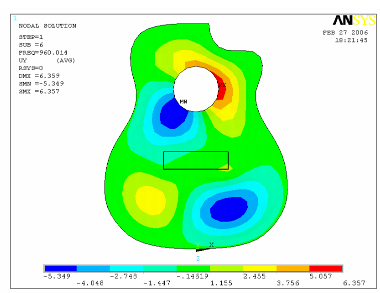
(ctd…)

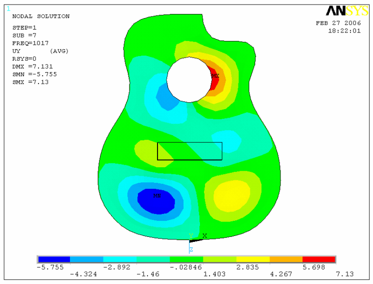
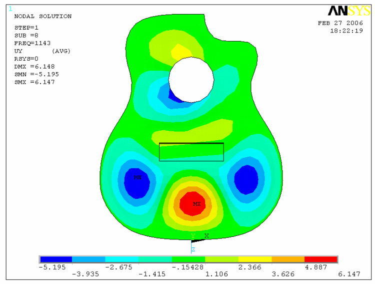
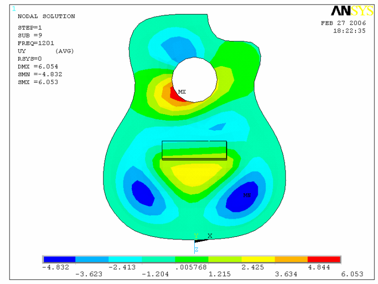
0,2	1,1	1,2?				
459.01	647.73	718.7	783.59	850.81	1002	1124
456.99	641.98	717.51	779.29	851.6	1001.9	1125.3
455.28	635.58	714.02	773.59	852.27	999.14	1125.4
454.61	633	717.28	771.66	853.28	1014	1126.2
449.62	627.62	707.53	765.41	847.54	992.85	1118
693.09	863.57	973.62	1027.3	1153.5	1223.4	1453.7
684.26	848.68	960.01	1017.1	1142.7	1201	1431.5

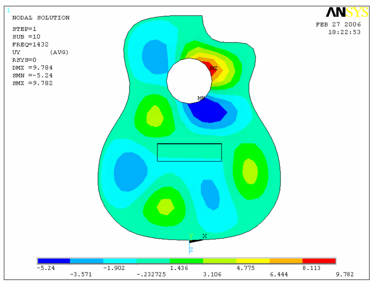
Appendix C: Mode shapes and frequencies for the top plate:

Fixed BC's:

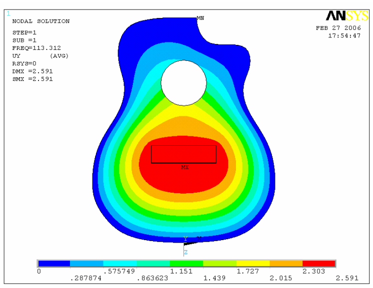
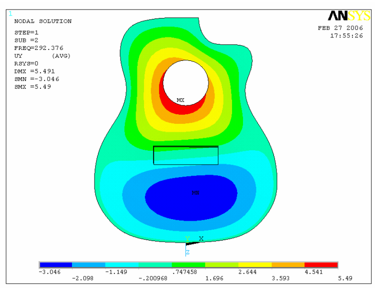
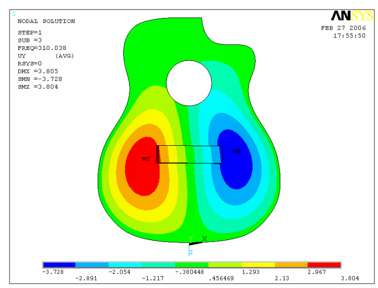




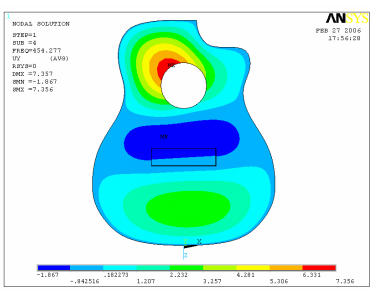
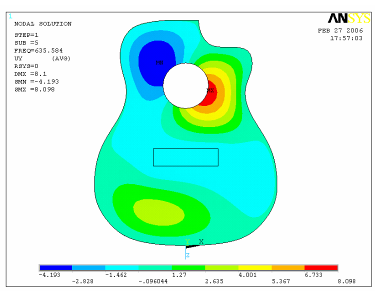
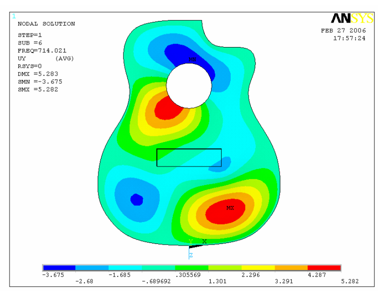




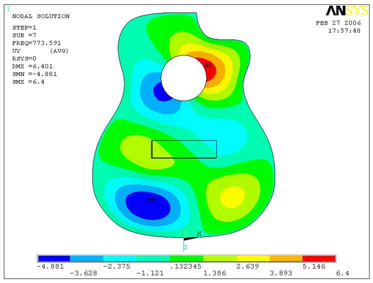




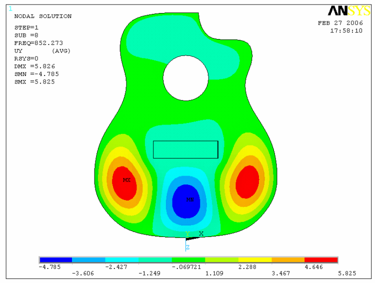


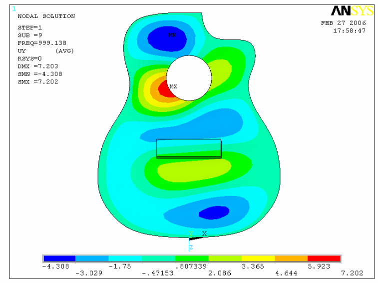
Hinged BC's:

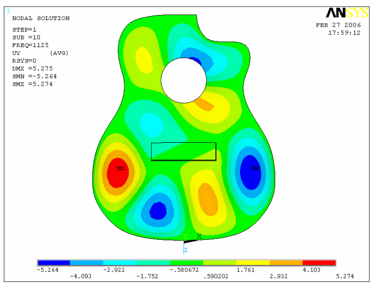




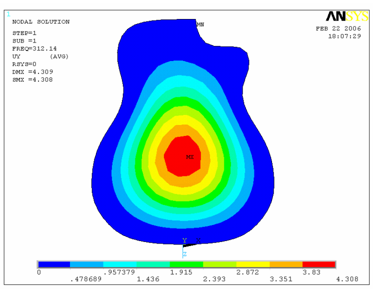


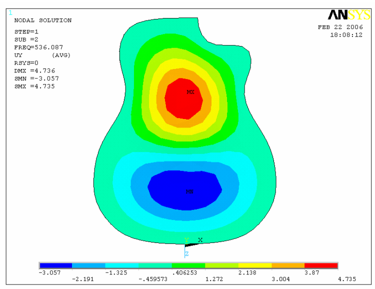


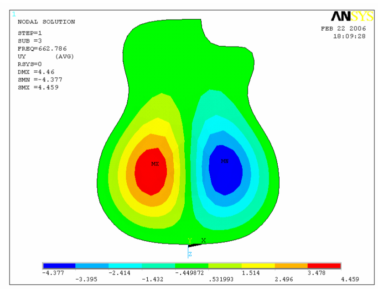


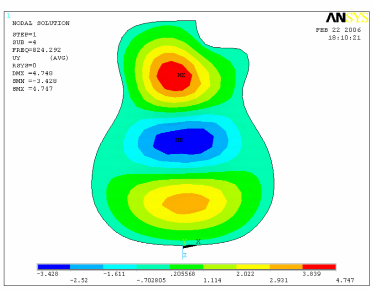


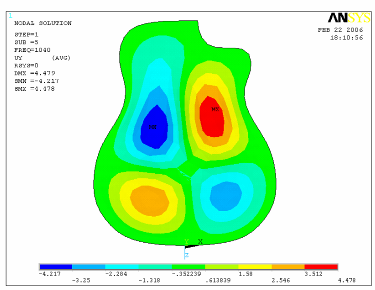
Appendix D: Guitar back mode shapes:











Appendix E: Out of plane stiffness experimental data

wt block =	276.12	g			
wt plate =	1194.75	g			
start position	0.0045				
total weight	deflection	deflection	FEA def	% difference	stiffness
N	in	mm	mm		KN/m
0	0	0			39.845
2.7087372	0.002	0.0508	2.121205		
5.4174744	0.005	0.127	5.303012	2.11%	
8.1262116	0.008	0.2032	8.484819	4.41%	
10.8349488	0.0105	0.2667	11.13633	2.78%	
13.543686	0.0135	0.3429	14.31813	5.72%	
16.2524232	0.0165	0.4191	17.49994	7.68%	
18.9611604	0.019	0.4826	20.15145	6.28%	
21.6698976	0.021	0.5334	22.27265	2.78%	
33.3903951	0.033	0.8382	34.99988	4.82%	
45.1108926	0.0415	1.0541	44.015	2.43%	
56.8313901	0.049	1.2446	51.96952	8.55%	
56	node				
Force per Node	FEA lines const	FEA E=10E9			
	mm	non-lin			
0.178571429	0.295	0.244			
0.357142857	0.591	0.487			
0.535714286	0.886	0.728			
0.714285714	1.181	0.965			
0.892857143	1.478	1.19			
1.071428571	1.773	1.43			
1.25		1.66			

Appendix F: BOM - Price/supplier comparison

CAG Project	**BOM- Price/Supplier list**			
Item	Specific	Price	price each	vendor
Raw Wood				
neck blank - mahog				
2	30x4x3 quartersawn honduran	$76.50	$38.25	LMI.com
3	23x4x3 quartersawn	$182.58	$60.86	stewmac
1	23x4x3 quartersawn	$67.60	$67.60	stewmac
2	3x4x30	$89.95	$44.98	grizzly.com
1	36x1x3	$31.99	$31.99	colonial tonewoods
2	28x4x3	$72.00	$36.00	alliedlutherie.com
Fretboard - ebony	Slotted? +$6 @ stewmac (25.4"), +$8 at LMI -- Rad? +$8 at LMI			
3	Madag. B grade	$38.85	$12.95	LMI
1		$13.65	$13.65	LMI
1	20x2-3/8x1/4	$24.83	$24.83	Stewmac
1	21x2.75	$16.50	$16.50	alliedlutherie.com
Bridge Blank - ebony				
1	7x1-7/8x1/16"	$7.13	$7.13	stewmac
1	"steel string"	$5.05	$5.05	LMI
Neck block				dunn?
Bridge plate?				
	Rosewood	4.05		LMI.com
	Maple	2.65		LMI.com
	Maple	3.25		Stewmac
Heel block				
	6x4x3" Mahogany	17.75		LMI.com
	12x3x1"	10.85		LMI.com
Hardware				
Tuners				
3	Gotoh - chrome large knobs	$85.50	$28.50	stewmac
1		$36.26	$36.26	stewmac
3	Gotoh - M6 chrome large knobs	$81.75	$27.25	LMI
1		$29.35	$29.35	LMI
3	Schaller 0643 chrome	$139.41	$46.47	stewmac
1		$52.64	$52.64	stewmac
3	Schaller SS	$120.60	$40.20	LMI
1		$44.25	$44.25	LMI
1	Schaller chrome standard	$42.00	$42.00	alliedlutherie.com
	ebay		20-30	
Nut				
	GraphTech, slotted	$8.99		musiciansfriend.com
	Bone, unslotted	$5.11		stewmac
	Bone, unslotted	$3.25		LMI
Saddle				

	1/8" thick	$4.82		stewmac
	bone, shaped	$3.20		LMI
Bridge pins	(6 pack)			
	cream plastic	$1.30		LMI
	cream plastic w/ black dot	$1.75		LMI
	Ebony with MOP/abal. dot	$6.75		LMI
end/neck pin				
	Ebony with MOP/abal. dot	$2.05		LMI
Truss rod				
	14-1/4" length Hot Rod 1/8" allen	$14.26		stewmac
	double action welded nut, 14.5"	$22.75		LMI
Strings				
fret wire				
70ft	Medium/medium (18% NiAg)	$35.28	$0.50	stewmac
2ft	Medium/medium (18% NiAg)	$2.52	$1.26	stewmac
4ft	hard (18% NI-Ag)	$4.30	$1.08	LMI
100ft	hard (18% NI-Ag)	$49.95	$0.50	LMI
12ft	hard (18% NI-Ag)	$10.65	$0.89	LMI
Acoustic pickup				
1	LR Baggs I-Beam, w/ endpin preamp+soundhole volume control	$139.90	$139.90	Stewmac
1	Fishman Natural I or II	$118.95	$118.95	Stewmac
1	Highlander Pickup (with preamp)	$179.75	$179.75	LMI
Acoustic preamp				
Other materials				
Inlay materials				
1	paua abalone microveneer (.15mm) (3x5")	$12.50	$12.50	inlayusa.com
1	paua abalone microveneer (.15mm) (5x9")	$34.00	$34.00	inlayusa.com
1	paua abalone top-strat (.05") (3x5")	$22.50	$22.50	inlayusa.com
1	paua abalone (.05") (2.5x4.5)	$45.95	$45.95	customluthier.com
side dot material				
pickguard: 0.005" mylar				
Finishing				
FB dye				
1	4oz	$5.61	$5.61	stewmac
1	.5oz (makes 8 oz w/ alcohol and shellac	$5.90	$5.90	LMI
Stain				
1	ColorTone, black, red, whatever (2oz)	$16.45	$16.45	stewmac
nitrocellose lacquer				

	1 quart Behlen	$15.18		stewmac
polishing compounds				
lacquer thinner				
	thinner 1 qt Behlen	$8.48		stewmac
grain filler				
	1 pint, clear	$14.65		stewmac
	1 pint, brown	$18.50		stewmac
sealer				
	1 qt, behlen	$13.78		stewmac
Tools				
HVLP system		$500.00		
fret files				
	3-in1 fret file for crowning	$36.75		LMI
fret end dressing file				
	um. Yeah.	$12.36		stewmac
fretting hammer				
	brass/plastic	$15.95		stewmac
	brass/plastic	$15.10		LMI
radius sanding block				
	16" radius x 7"	$14.45		LMI
slotting saw?		not needed		
miter box?		not needed		
fretboard guards				
	set of 6	$9.25		Stewmac
precision straightedge				
	24" AL 0.005"	$33.12		McMaster
	24" tool steel accurate to .001"	$48.00		Mcmaster
	24"	$55.90		stew mac
bridge saddle locator				
	saddlematic	$29.95		stew mac
clamps:				
threaded rod				
10	3' 14-28 SS threaded rod: pn 98837A029	$0.93	$9.30	McMaster
circle saw	Borrow			
washers				
	1/4" ID zink plated steel washer pk 100 pn:98023A029	$4.80	$4.80	Mcmaster
wingnuts				
	1/4-20 wingnut pk 100: pn 90866A029	$8.38	$8.38	McMaster

dremel tool		Have		
dremel router		not needed?		
inlaying bits		not needed?		
inlaying knife?		not needed?		
nut files				
	set of 8 Ibanez	$90.35		LMI
dovetail router bit				
	10 deg? With 1/2 " bearing	$25.90		stewmac
2-flute by 5" ball nose				
	3/4" by long enough: pn 3046A46	$50.40		mcmaster
bridge pin hole reamer				
	5 deg	$44.90		stew mac
	HAVE ONE (6.2 deg)	FREE		
7/32" cutter (truss rod)				
	double ended: pn 3049A43	$12.12		mcmaster
buffing wheel for spindle				
	12"dia 3/4" shaft	$13.58		stewmac
	12"dia 3/4" shaft	$12.40		lmi
Misc				
Case				musicians friend
wood glue				Hardware store
hide glue				
8oz	franklin hide glue	$9.15	$1.14	stewmac
	granular (1 lb) = 2 pts	$14.82		stewmac
	granular (1 lb) = 2 pts	$9.75		lmi
	Rough subtotal for first order:	$1,211.00		