AC 2008-354: TEACHING BASIC MATERIALS ENGINEERING DESIGN TO ENGINEERING TECHNOLOGY STUDENTS USING STRINGED INSTRUMENT TOP DESIGN

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Teaching Basic Materials Engineering Design to Engineering Technology Students Using Stringed Instrument Top Design

Abstract

During the past five years, we have transformed our basic Introduction to Materials Engineering course from a passive lecture only course to a learner-centered and concept based course. It is known that teaching any course in multiple ways, especially in ways which build scaffolds from the students' previous knowledge base, can prove to be very effective for a wide range of learners. One of the activities used in the course in this category which has proven useful and effective involves the use of stringed instrument design. This paper describes the selection of alternative materials for the design of soprano ukulele tops to teach materials engineering fundamentals such as the elastic constant, specific stiffness, density, bending stress and deflection. An inexpensive ukulele kit ($25) is used to construct the instruments with the alternative materials to illustrate the results of implementing the key design parameters on the sound of the instrument. The paper delineates the design parameters and equations needed for the ukulele tops so that other faculty members can easily use these concepts as an active learning tool. The paper also describes in detail how to construct the instruments with the new tops and how the tonal effects can be measured. Although mahogany and koa woods are the traditional choices for ukulele tops, a wide range of materials can be used such as natural materials like spruce and balsa wood to synthetic materials such as acrylic and carbon fiber reinforced plastics. It is very easy to demonstrate why some materials make superior instruments, while other materials produce mediocre instruments. One need not make careful measurements on some of the instruments produced as the tonal effects are dramatic and easy to hear. The geometry of the soprano ukulele is straightforward and its size is small, so this instrument is a good choice for in-class demonstrations, but the principles could be used to design acoustic or classical guitar tops or mandolin tops. The paper concludes with our initial assessment data, including lessons learned from pre- and post-class questionnaires, and actions that are planned for the future for this class for its continuing improvement.

Introduction

During the past five years, we have continuously transformed and improved our Introduction to Materials Engineering course with the overall goal of improving student learning by creating an active, learner-centered environment. By placing complex concepts, such as the anisotropic behavior of materials, in familiar contexts, students seem to become more engaged in and more excited about their own learning. In addition to formal and informal information that has been gathered based upon observing students and measuring their learning outcomes, several research investigations, such as a recent report from the National Research Council (NRC), have confirmed that it is important to build upon the "conceptual and cultural knowledge that students bring with them to the classroom"[1]. It is known that teaching any course in multiple ways, especially in ways which build scaffolds from the students' previous knowledge base, can prove to be very effective for a wide range of learners[1-7]. Several of the activities and strategies for this course have been reported and described elsewhere [8-10]. One of the strategies used in the course which has proven useful and effective involves the use of stringed instrument design. This particular paper describes the selection of alternative materials for the design of soprano ukulele tops to teach materials engineering fundamentals such as the elastic constant, specific stiffness, density, bending stress and deflection. An inexpensive ukulele kit ($25) from Grizzly Industrial (Bellingham, WA) is used to construct the instruments with the alternative materials to illustrate the results of implementing the key design parameters on the sound of the instrument.

Also described in detail here is how to construct the instruments with the new tops and how the tonal effects can easily be measured. Although mahogany and koa woods are the traditional choices for ukulele tops, a wide range of materials can be used such as natural materials like spruce and balsa wood or synthetic materials such as acrylic and carbon fiber reinforced plastics. It is straightforward to demonstrate why some materials make superior instruments, while other materials will produce mediocre instruments. One need not make careful research level measurements on some of the instruments produced as the tonal effects are dramatic and easy to hear. The geometry and design of the soprano ukulele is straightforward and its size is small, so this instrument is a good choice for course work, but the principles could be used to design acoustic or classical guitar tops, with classical guitar tops having the next level of complexity.

Grizzly Industrial sells several inexpensive stringed musical instrument kits that are all mostly suitable for these exercises, although they vary in complexity from a course objective standpoint: ukulele ($25), classical guitar ($80), and Western steel string ($90). All of these kits contain all the parts necessary to assemble the instrument and, most importantly for course objective purposes, an already assembled instrument body. Also at Grizzly Industrial, the steel string body can be purchased separately for $50. For those so inclined, Stewart-MacDonald (Athens, Ohio) sells complete kits where the body has to be assembled, but the kits contains higher quality wood components. The kit costs are much higher: ukulele ($100), Dreadknought ($395 - $475), and Triple-O ($395 - $475). Martin guitar kits range from $400 - $630 depending on the wood and style selected, and the body has to be assembled. In the Stewart-MacDonald and Taylor kits, the side pieces are pre-bent. For these kits, the tops would not have to be removed from the pre-assembled instrument. While the more expensive kits will produce superior results for experienced builders, the inexpensive kits from Grizzly Industrial can easily provide the appropriate materials engineering design experiences and illustrate the materials properties necessary for class purposes for a very reasonable cost per instrument ($25). In addition, the ukulele is a relatively simple design system in that the top and back plates of the Grizzly kit are flat, simply braced (one beam brace, plus a bridge plate), fit on 8.5 x 11 inch pieces of graph paper, and the strings are made from nylon of uniform diameter. As the size and complexity of the instrument increases, it makes it more difficult to teach conceptual design and materials properties as the complexity itself draws attention away from conceptual thinking and principles. Thus, the active learning exercises in materials engineering described here use the simple, soprano ukulele kits.

Discussion

The Grizzly kits contain all the parts necessary, including an assembled body, to make a finished instrument. The steps to assembled the kits are relatively straightforward: attach the fingerboard to the pre-shaped neck, glue the neck assembly to the body, attach the nut, bridge and tuners, and string the assembled instrument. Care should be taken to make sure the saddle on the bridge to nut distance is equal to the intended free length of the instrument (about 340 mm) with a small adjustment for fretting distance (1.5 – 3 mm). Do not put any finish on the instruments if you want to focus on the materials and the materials properties used to construct the instrument.

It is also relatively straightforward to teach the students about string design for a simple instrument. Once a particular string is selected, the students should compare the stress on each string to the yield or breaking stress of the material. In the case of ukuleles and classical guitars, the strings are made from nylon. Although nylon is certainly not one material, a student designer can choose to use the typical values for each material, which is widely available in text books and on http://www.matweb.com [11]. The free portion of matweb.com is an extremely valuable source of materials properties for design and research activities in materials engineering.

Typical values for extruded Nylon 6 are: density = 1.16 g/cm^3; Ultimate Tensile Strength = 102 MPa; Yield Strength = 79.0 MPa; Flexural Yield Strength = 151 MPa; Flexural Modulus = 3.61 GPa; and Elastic Modulus = 2.57 GPa (all values[11]).

The necessary tension in musical strings to produce a particular frequency can be calculated using the following equations:

$$f_n = \frac{n}{2l}\sqrt{\frac{T}{\mu}} \qquad (1)$$ [12]

where f_n is the desired frequency in Hertz, l is the free length of the instrument in meters, T is the required tension in N, and μ is the mass in Kg per unit length, kg/m, n = 1 for the fundamental frequency.

$$\mu = \pi r^2 \rho \qquad (2)$$ [12]

where r is the radius of the string in meters and ρ is the density of the material in kg/m^3 and μ is in kg/m.

Table 1. Measured Ukulele String Parameters

Note	**String Frequency**	**Measured Mass/Length**	**Diameter**	**Calculated Tension ***	**Measured Density**
	Hertz	**Kg/m** [12]	**mm** [12]	**Kg** [12]	**g/cm^3**
A4	440.0	0.000234 – 0.000503	0.53 - 0.71	2.17 - 4.66	1.06 - 1.28
E4	329.6	0.000579 - 0.000984	0.81 - 1.04	3.01 - 5.12	1.06 - 1.28
C4	261.6	0.000685 - 0.000984	0.86 - 1.04	2.24 - 3.23	1.06 - 1.28
G4	392.0	0.000328 - 0.000505	0.64 – 0.71	2.41 - 3.70	1.06 - 1.28

*Note that string tensions are commonly given in Kg by string manufacturers and instrument makers. Tension values are, of course, more properly in Newtons (N).

The total calculated force on the ukulele top from string forces ranges from 96.5 N – 163.9 N for the tuning listed in Table 1. Note that an alternative and common tuning for soprano ukuleles is: B4 - 493.9 hertz, F4# - 370 hertz, D4 - 293.7 hertz and A4 - 440 hertz. This raises the overall tension in the instrument to the 126.1 N - 206 N range (a 25 - 30 % increase).

The stress on any particular string is given by equation (3).

$$\sigma = \frac{F}{A} \qquad (3)$$

where σ is in Pa, F is in N, and A is in m^2.

Table 2. Calculated String Stresses

Note	String Diameter	Calculated Tension	Calculated String Stress	Percent Ultimate	Ultimate Strength
	mm[12]	**Kg**[12]	**MPa**	**%**	**MPa**[11]
A4	0.53 - 0.71	2.17 - 4.66	96 -115	69.5 - 83.3	82.7-138
E4	0.81 - 1.04	3.01 - 5.12	57 - 66	41.3 - 47.8	82.7-138
C4	0.86 - 1.04	2.24 - 3.23	33 - 41	23.9 - 29.7	82.7-138
G4	0.64 – 0.71	2.41 - 3.70	74 - 92	53.6 - 66.7	82.7-138

The A4 string has more than three times the stress as the C4 string, despite an effort on the part of string makers to make the force and stress as uniform as possible across the bridge. This difference is quite apparent on the ukulele itself. Also, given that there is a strong body resonance near the C4 string on the ukulele body, it is easy to understand why the C4 strings sound quite different than the other strings. Further refinement for ukuleles in this respect is possible.

The next logical step in understanding ukulele design from a materials engineering point of view, is to understand how sound waves are propagated in solid materials. Equation (4) shows that the velocity of the longitudinal sound waves travel is controlled by the specific stiffness of the material in question (specifically the square root of that ratio). Understanding conceptually the specific stiffness of a material is very important for introductory students. Often, the students tend to focus on one particular property rather than consider the specific stiffness or the specific strength to solve design problems. The students seem to easily grasp the basic concept that it is not just the elastic constants for any material for an instrument top that control the vibrations, but the density or weight of the top would also play an important role (in addition to geometric considerations, of course).

Longitudinal sound waves travel as speed ν:

$$v = \sqrt{\frac{E}{\rho}} \qquad (4)^{13}$$

where E is the Elastic Constant in N/m^2 and ρ is the density in kg/m^3.

Similarly, the longitudinal frequencies of a cylindrical rod are:

$$f_{nl} = n\frac{v}{2L} \qquad (5)^{13}$$

where f is in hertz, ν is in m/sec and L is in meters

An example problem and active exercise would be to calculate the longitudinal speed of sound in aluminum, point out the E/ρ is also the specific stiffness of a material, and then demonstrate how easy it is to initiate both the longitudinal and transverse waves in a rod by hitting them with a hammer (a rubber mallet) parallel and perpendicular to the end of the aluminum rod[14]. The typical speed of sound in aluminum is 5150 m/s while in steel it is about 5100 m/s.

$$v = \sqrt{\frac{2.84x10^9\,N/m^2}{1.18x10^3\,kg/m^3}}$$ = 1551.4 m/s (Average Values, Extruded Acrylic[11])

$$v = \sqrt{\frac{12.0x10^9\,N/m^2}{0.35x10^3\,kg/m^3}}$$ = 5855 m/s (measured values, soundboard Engelmann Spruce)

The calculated speed of a longitudinal wave in a typical extruded polycarbonate is approximately 1400 m/s, while in a typical balsa wood sample, it would be 4200 m/s.

The fundamental frequency of the transverse wave in a cylindrical rod is:

$$f_t = \pi K m^2 \frac{\sqrt{E/\rho}}{8L^2} \qquad (6)^{12}$$

where K is the radius of gyration, a/2, a is the radius in meters and m = (2n+1), but m = 3.011 for the fundamental.

In terms of longitudinal frequency, f_l, the frequency of the transverse wave (f_t) is much lower:

$$f_t = 3.011^2 \frac{\pi a}{8L} f_l \qquad (7)^{12}$$

where a and L are in meters and f is in hertz.

For a 1 meter long aluminum rod that has a radius of 5 mm, $f_t = 0.018\ f_l$, which means the transverse frequency is much lower and, thus, it is very easy to hear the difference in the two frequencies during an in-class demonstration.

The next step in understanding a soundboard is to examine the properties of the top plate more carefully. An easy way to illustrate the basic design concepts for the ukulele is to disassemble the instrument body and show the components to the class. Figure 1 shows the top of the ukulele removed and flipped over to show the internal bracing for both the top and the back. The pdf of assembly manual for the Stewart-MacDonald ukulele kit is available on their website and also shows a somewhat similar bracing pattern for the ukulele. There are many different bracing patterns that can be used for the ukuleles.

There are two methods that are effective for removing the top of the assembled ukulele bodies. Figure 1 shows the easier of the two methods where continuous ¼ inch holes were drilled near the edge of the top allowing easy removal of the center of the top. Since the edge of the top is glued to the body with brittle glue, it is relatively easy to snap off the remaining edge material. Often, as in Figure 1, the remaining edge comes off in one piece. The other method involves using a router to remove part of the top material, but this to be much more time consuming and unnecessarily complex. It is not difficult to remove the top from the body.

Figure 1 also reveals a problem observed in some of the ukulele edge bindings. Sometimes removing the top splits the binding away from the edge, or sometimes the edge lining isn't glued to the body in all locations or sometimes the edge lining runs down the side of the body at an angle. It is important that the lining be firmly attached to the body and be parallel to the tope edge, so the top can be reattached properly to the body. If the lining is not attached to the body in all locations, it should be re-glued to the body (see Figure 2). Superglue or quick setting epoxy with many small clamps affixed to the circumference of the body works very well.

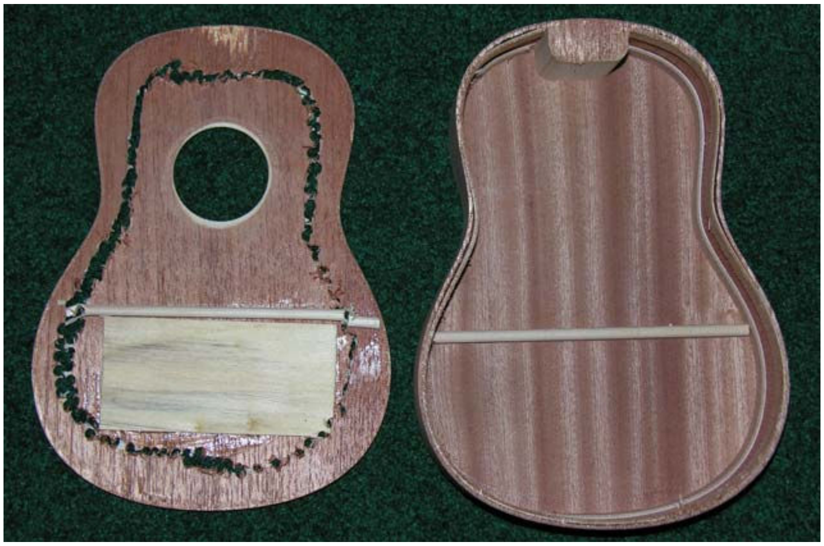

Figure 1. A Ukulele Body with its Top Removed to Show the Internal Design Features of the Instrument Body

A typical solid mahogany ukulele top is 1.75 mm – 2 mm thick and weighs about 40g, while the Grizzly kit top (mahogany veneer) is slightly thicker (about 2.75 mm) and heavier, about 60 g with bracing. The bridge plate is about 110 mm by 55 mm x 3 mm (with several mm of variation depending on the particular body). The top and back braces are about 5 mm by 7 mm x 160 mm. The ukulele bodies weigh about 200 g fully assembled; the necks are about 80 g; the fingerboards are about 20 g; and the bridge is about 5 grams, with a 1 g saddle. There is considerable variation (measured) in the assembled body weight (182 g – 202 g).

Figure 2. Gluing the Edge Lining to the Ukulele Body

Figure 3. Chladni Patterns for Body Resonances. Frequencies: 507 hertz, 545 hertz, 483 hertz, 510 hertz (left to right)

The differences in the assembled bodies are clearly evident in the frequencies of similar body resonances shown by Chladni patterns (see Figure 3).

You can create Chladni patterns of ukulele bodies with a speaker that is reasonably inexpensive, the Megawork® THX 2.1 250D, from Creative Labs ($150). The small size (a 3.5 inch driver) of the powerful satellite speakers, their high power (75 watts per speaker), their powerful subwoofer (150 watts), and their combined frequency response of 25 hertz to 20,000 hertz make the Megawork® system ideal for creating Chladni patterns. To create the pattern successfully, place the body as close as possible to the speaker, and wear ear protection as the speaker has to be very loud to produce an acceptable pattern. Larger bodies, such as those of classical and steel string guitars, need more powerful speakers of a few hundred watts to produce patterns. Small pieces of foam should be used to hold the body beneath a node. Chladni patterns are an interesting way to show the students that the shape of the pattern is largely determined by geometry, but the material type determines the frequency. Inexpensive Chladni pattern demonstration systems with plates can be purchased (Pasco Scientific, for example) and several web sites have images of various Chladni patterns, some for musical instruments[15].

The next design consideration is to choose a material for the top plate. Equation (3) can be used as a guide if the tradition of using a variety of spruce is used as a starting point. Calculations illustrated above, show that Engelmann spruce has a longitudinal velocity of sound of approximately 5855 m/s. We deliberately chose to make tops for some of the ukuleles with acrylic (speed of sound, about 1550 m/s) and polycarbonate because of the very poor matches of these materials to the traditional spruce top. An illustration of the poor acoustic signature of the polycarbonate instrument is shown in Figure 8.

To correctly design the top, the concept of anisotropy must be introduced at this time. Norway spruce is the traditional material for tops of violins and has been extensively characterized[16-20]. An average E_l is about 14.8 GPa and the average E_r is about 0.7 GPa (where l is the longitudinal direction and r is the radial direction)[16]. Soundboards are quarter sawn and are chosen to have straight grain in the longitudinal direction and without any major flaws. Since wood and advanced materials like carbon fiber composites are anisotropic and have such a large range of E_l and E_r values, it is difficult to use a literature values for these elastic constants. Thus, they should be estimated from measurements. However, it is not trivial measuring the E values of wood or composites and the measurements vary according to the measurement method (static, resonance or ultrasonic)[16-21]. Hurd suggests a relatively straightforward method of estimating both E_l and E_r from the FFT analysis of certain tap tones for luthiers[21]. Hurd's method is based on the work of Caldersmith[22], which built upon much previous research [23-26] and much more sophisticated analyses has followed[27-40]. However, for the conceptual exercises used here, good estimates and relative values of E_l and E_r are all that are needed.

The tap tone method is based on finding three mode frequencies of rectangular plates that will be used to construct the ukulele tops: the first tap tone - $f_{0,2}$; the second tap tone- $f_{0,2}$

and the third tap tone - $f_{1,1}$ [21]. Chladni patterns of the plates can easily be used to find the distinctive patterns. The Chladni patterns of the first tap tone produce 2 horizontal lines at approximately one-quarter and three-quarters across the plate (the plate has the longitudinal direction oriented top to bottom, with the long edge up). The Chladni pattern of the second tap tone is similar, but the two lines are now vertical. The Chladni pattern of the third tap tone has one line running down the middle of each side. The first tap tone can be produced by holding the plate in the middle of the top line and tapping at the center of the plate. The second tap tone is produced by holding the plate in the middle of one of the vertical lines and tapping in the middle of the plate (or you can turn the plate 90°). And, the third tap tone is produced by holding the plate as in the first tap tone, but tapping the plate in the lower right or lower edge[21]. Record the taps with either a measurement microphone or any microphone with a flat response in the necessary range (a few hertz to a couple hundred hertz). A free software program called Audacity can be used to examine the FFT of the signal. The FFT feature of an older version of Adobe Audition is used to find the tap tone frequencies. The tap tones are straight forward to identify (especially with a little bit of practice and with some knowledge of the Chladni patterns of rectangular plates).

Equations (8) and (9) are used to find good approximations of E_l [21-22].

$$D_l = \frac{E_l}{(1-\nu_l \nu_r)}$$

(8)[22]

where E_l and D_l are in N/m^2 and $\nu_l\nu_r$ (Poisson's ratios) are unitless.

$$D_l = \frac{f^2{}_{0,2}\,\rho L_l{}^4}{1.05h^2}$$

(9)[21,22]

where D_l is in N/m^2, L and h are in meters, and ρ is in Kg/m^3.

For many woods and other anisotropic materials used in acoustic soundboards, $\upsilon_x\upsilon_y$ is small, so D_l is a reasonably good approximation of E_l for the design of musical instruments. For example, for Sitka spruce, literature values for $\upsilon_x\upsilon_y$ are 0.37 and 0.029, respectively[19]. So, the quantity $(1- \upsilon_l\upsilon_r)$ in equation (8) is 0.989 which is close enough to 1 for our conceptual exercises. One can also use a static method to approximate E_l and E_r. Similarly, D_r and $D_{l,,r}$ (the twisting modulus) can also be found with this method. See equations (10) – (12).

$$D_r = \frac{E_r}{(1-\nu_l \nu_r)}$$

(10)[22]

where E_r and D_r are in N/m^2 and $\nu_l\nu_r$ (Poisson's ratios) are unitless.

$$D_r = \frac{f^2{}_{2,0}\rho L_r{}^4}{1.05h^2} \qquad (11)^{21,22}$$

where D_r is in N/m^2, L and h are in meters, and ρ is in Kg/m^3.

$$D_{l,r} = \frac{2.43 f^2{}_{1,1}\rho L_l{}^2 L_r{}^2}{h^2} \qquad (12)^{21}$$

where $D_{l,r}$ (the twisting modulus) is in N/m^2, L and h values in meters, and ρ is in kg/m^3.

$$D_{l,r} = D_l \nu_r + 2G \qquad (13)^{22}$$

where $D_{l,r}$ and G are in N/m^2 and ν is unitless.

For one Engelmann spruce soundboard with dimensions 330 mm x 229 mm x 3.175 mm, with a measured density of 0.35 g/cm^3, the following modes were measured using the tap tone method with FFT analysis using Adobe Audition: $f_{0,2}$, = 174.3 hertz, $f_{2,0}$ = 106.9 hertz and $f_{1,1}$ = 61.5 hertz. The resulting values of D_l and D_r compared well with literature values, where D_l measured was 11.9 GPa and D_r measured was 1.04 GPa (which are in good agreement with the range of values for these constants in the literature)[16-20].

For one carbon fiber epoxy soundboard with an bi-directional weave with dimensions 300 mm by 210 mm by 1.6 mm, with are measured density of 1.67g/cm^3, the following modes were again mesured using FFT analysis: $f_{0,2}$, = 98.1 hertz, $f_{2,0}$ = 208 hertz and $f_{1,1}$ = 143.5 hertz. The resulting values of D_l and D_2 compared well with literature values, where D_l measured was 48 GPa and D_2 measured was 50 GPa (which are also in good agreement with the range of values for these constants in the literature)[11]. Using equation (4), the velocity of sound in the longitudinal direction in Engelmann spruce would be approximately 5830 m/s, while the carbon fiber composite material would be approximately 5360 m/s (about an 8% difference).

The final topic in the design of musical instrument top is bracing. This is a perfect opportunity to cover bending stress and deflection with the students (a topic always covered in the mechanical properties section of materials engineering text books). Braces in ukulele approximate beams or plates. In the Grizzly ukulele, there is one beam brace on the front and one on the back plus one plate bridge brace/reinforcement (see Figure 1). Other ukuleles have completely different bracing patterns. Of course, the goal of bracing is to provide adequate stiffness, without adding too much weight. Recall, that the overall longitudinal sound wave propagation is controlled by the square root of the specific stiffness.

For a rectangular beam, the three-point bending stress and the maximum deflection equations are:

$$\sigma = \frac{3FL}{2bd^2} \qquad (14)$$

where F is the load in N, L is the length between supports in meters, b is the width in meters and d is the height in meters.

$$y_{\max} = \frac{FL^3}{48EI} \qquad (15)$$

where F is in N, L is in m, E is in N/m^2, and I in m^4.

For a rectangular cross-section:

$$I = \frac{bd^3}{12}. \qquad (16)$$

where I is the moment of Inertia and b is the width in meters and d is the height in meters.

In order to minimize the deflection then, both E and I must be as large as possible. Since I is proportional to the height cubed, it is much more efficient then to add height than to add width to a brace. A ukulele brace can not be too thin though or the bridge would tend to deflect and possibly deform the top plate around it.

The existing braces are about 5 mm wide by 7 mm high by 160 mm long. Doubling the height of the existing bridge would change the I value from about 143 mm^4 to 1143 mm^4, but doubling the base would only change the I value from 143m^4 to 286 mm^4. Assuming that the brace is made from a material with a density of about 0.4 g/cm^3, the original weight is approximately 2.25 g. The brace with the height doubled would be 4.5 g, but the brace with the base doubled would also be about 4.5 g. This exercise clearly demonstrates the efficient use of materials for adding stiffness to any design.

The stress on the bridge brace can be roughly calculated by summing all the string forces and multiplying by the sine of the angle of where the strings are attached to the bridge. This is only an approximate value and doesn't add new material to the conceptual ideas presented elsewhere, so the topic is not covered.

After the top soundboard material is selected, and D_l and D_r measured, the bracing pattern decided based on the design principles listed here, the top can be cut to size, braced and then glued to the top. An Engelmann spruce top with its bracing pattern is shown in Figure 4.

Care should be taken when the new top is glued back onto the body. Care should also be taken so all the lining is firmly attached to the sides of the body. Violin clamps can be extended with longer screws and used to glue on the top or the clamps can easily be made in the shop (see Figure 5). A quick setting epoxy, superglue or wood glue can be used. If the top is to be removed, a hide glue should be used instead. Because of the low cost of the kits, it is probably not necessary.

Figure 4. Engelmann Spruce Top with Braces Attached

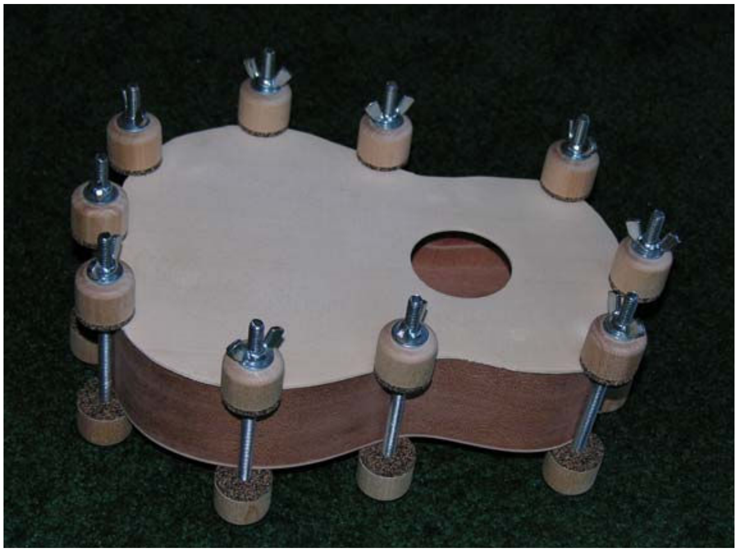

Figure 5. Carefully Clamp the New Top to the Body

Figures 6 and 7 show the assembled Engelmann spruce top ukulele and the acrylic top ukulele. The Engelmann spruce top instrument was intended to perform well, but the acrylic instrument was intended to demonstrate the dramatic effect than materials can have on the sound of the instrument. The sound quality of the ukuleles can be evaluated by playing them, of course. Since the ukulele is a simple instrument, it is easy to learn a couple of chords. Individual notes can be evaluated with FFT software. Figures 8 shows a comparison of the FFT of individual notes on two ukuleles – one with a spruce top and one with a polycarbonate top.

Figure 6. The Assembled Ukulele with an Engelmann Spruce Top.

Figure 7. The Assembled Ukulele with a heavy Acrylic Top.

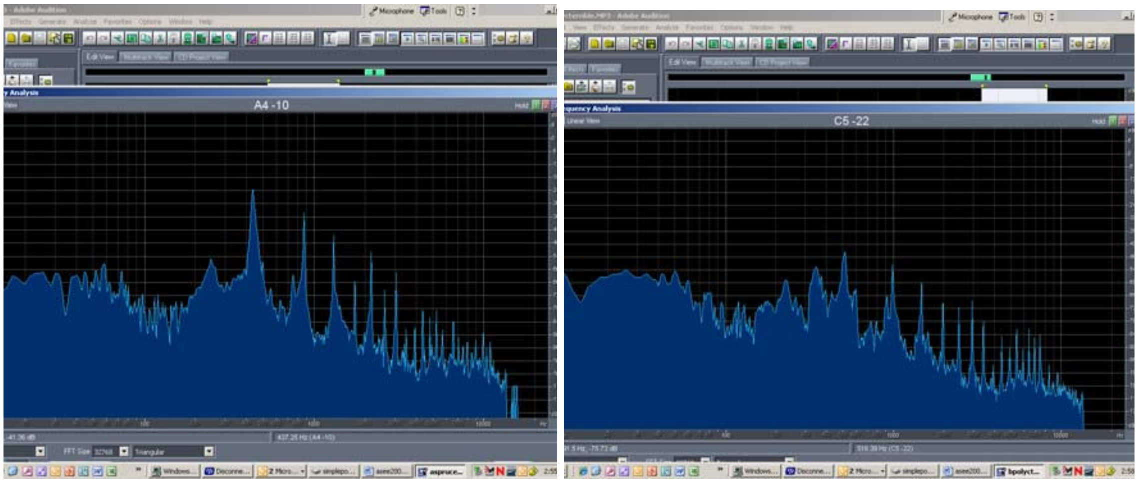

Figure 8. Clear Acoustic Signature on the Spruce top (Left) and "Muddy" Signature of the Polycarbonate Top (right)

Several finite element analysis (FEA) vibration mode models for several instruments have been generated. The vibration modes are correct in that our geometry accurately reflects the individual models (see Figure 9). Unfortunately, the frequencies are incorrect since we do not have methods to find all the materials constants necessary to model anisotropic materials, i.e. the Poisson's ratios. In these cases, we use the Chladni pattern method or use literature values.

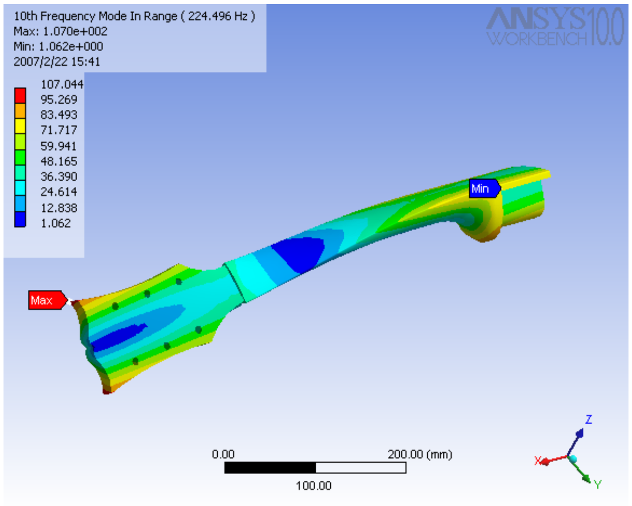

Figure 9. A Mode Shape of a Guitar Neck (Savage, J.)

Acknowledgements

Thank you to Eric McKell and Vincent Hill for their creative idea of making aluminum ukuleles for their metal forming project in their course. Also, thank you to Jesse Savage for working so hard for so many quarters with me trying to discover how precisely materials properties influence musical instrument construction and design. Also, thank you to Jesse for his skilled CAD modeling of instruments.

Conclusion and Future Directions

This academic year we added a pre-class and post-class assessment instrument into the agenda for the course (an approximately 100 students) to help us assess if the learning outcomes for the students are improved because of our many different active course enhancements. Assessment data based on improvements in traditional test scores on individual problems have been previously reported[10]. That paper shows that there is improved learning in this class based upon improving tests scores on traditional problems in several areas and that some of these improvements are improved because of this type of active work: the Elastic Constant, Anisotropic Properties of Materials, Tensile Strength, Elastic/Plastic Deformation, Yield Strength, Materials Selection for Designs, Safety Factors and perhaps how Materials Properties Change with Temperature.

The measurement threshold for those improvements was a ten percent increase in the number of students successfully completing a traditional question on midterms and the final exam. An example of a traditional problem is that the students need to be able to select a material for an application given the load and geometry constraints or to calculate the elastic constant from force and load data from a tensile test. In addition to that measurement, the students were able to complete a comprehensive design problem on the final exam that was much more rigorous and had more materials constraints after the active changes were made to the course. As an experiment this quarter, some active learning exercises were eliminated and more traditional lectures were given during the first part of the course. The average on the first exam dropped eight percent from the average of the more active terms, and the students were much less engaged in the course. This result seems to suggest the ten percent threshold previously used may have been too high. However, with only one data point, it is difficult to draw solid conclusions.

The initial pre-class and post-class questionnaires revealed some surprising information and also have provided additional data on which to make judgments about improvements in student learning. For example, it was surprising to find out that students did not know that copper would be bonded with metallic bonds, even though they have taken chemistry as a pre-requisite. The students believed that metals would be either covalently bonded or ionically bonded perhaps because of the emphasis upon those bonds in freshman chemistry. The pre-class questionnaire revealed that the students do not know about the anisotropic nature of materials and they can not distinguish between geometry effects and materials properties effects for a basic engineering design, such as a diving board. On the other hand, the post-class questionnaires showed that by the end of the term less than ten percent of the students could not distinguish between these effects.

Last term, in addition to writing research papers where the students answered important materials engineering questions, the students presented their work to each other during Poster Sessions. Peer grading rubrics were also used during the sessions (the students were provided with concept based grading guidelines). The students seemed to enjoy the sessions, but more importantly they gained valuable experience by communicating to each other why one material is used for a particular application. Their arguments had to be grounded in at least three materials properties, so the students had to have a conceptual understanding of these properties in order to persuade their peer audience their arguments were indeed correct. This quarter, the students will be allowed to choose to complete their research work on materials used in musical instruments as per past practice.

Assessing the conceptual gains made by the students because of the active, learner-centered environment has proven to be challenging. There are certainly improved scores on certain traditional test questions for most students[10]. And, the students are able to complete a much more challenging design problem by the end of the term where they have to select the "best" material for a basic design given safety factors, yield strengths, fatigue limits or strengths, creep strength, costs, weight, change in length or change in diameter factors. Each term, the final design problem is more challenging, yet the student performance on the comprehensive problem is better. The students rate the course higher and the involvement of the instructor higher even though the course challenge and rigor has been increasing. In the future, we anticipate that the pre-class and post-class questionnaires will help us further understand the conceptual gains of our course learning outcomes. However, truly assessing long-term student learning remains challenging and sorting out how each change affects different student learners is even more challenging. Musical instrument design will remain a part of the course, but this strategy is only one of many exercises used to enhance the learning environment of this course with the goal of creating a truly learner-centered environment for the students.

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