A Large New Set of Stiffness Data for Lutherie Woods, and a Proposed Standard Test Method

As I noted in *American Lutherie* #125 (Spring 2016), I have found very little hard data available for the stiffness and other properties of wood of interest to luthiers. In order to help remedy this, I decided to do my own testing of wood samples from species that are of interest to guitar makers. This article presents the first set of those data: For Sitka spruce (*Picea sitchensis*), European spruce (*Picea abies*), Honduran mahogany (*Swietenia macrophylla*), Indian rosewood (*Dalbergia latifolia*), Engelmann spruce (*Picea Engelmannii*), Western Red cedar (*Thuja plicata*), Mango (*Mangifera spp.*), Ebony (*Diospyros spp.*), and Purpleheart (*Peltogyne spp.*).

I am taking the following data for the wood samples; and this article will examine the relationships between them:

- Stiffness in bending (Young's modulus)
- Density
- Grain orientation (vertical vs. horizontal grain)
- Grain density (count/inch or count/cm)
- Species
- Hardwood v. softwood
- The presence of figure

There are many "old luthier's tales" out there about how these properties are related and how they affect guitar performance. I want to examine them in detail, using precise measurements to bring some real data to bear on these questions.

I plan to publish more data in *American Lutherie* as I create the additional data.

Test Results, First Data Set

My first set of tests included 192 softwood samples and 78 hardwoods samples, as shown in Table 1.

Table 1: Samples Tested for the First Data Set

Species	Type	Number of Samples
Sitka spruce (*Picea sitchensis*)	Softwood	80 samples
European spruce (*Picea abies*)	Softwood	52 samples
Engelmann spruce (*Picea Engelmannii*)	Softwood	25 samples
Western Red cedar (*Thuja plicata*)	Softwood	35 samples
Honduran mahogany (*Swietenia macrophylla*)	Hardwood	18 samples
Indian rosewood (*Dalbergia latifolia*)	Hardwood	17 samples
Mango (*Mangifera spp.*)	Hardwood	24 samples
Ebony (*Diospyros spp.*)	Hardwood	13 samples
Purpleheart (*Peltogyne spp.*)	Hardwood	6 samples

All of the softwood samples came from guitar top sets used to make guitars. This means they are very select wood samples. The Honduran mahogany samples came from high-quality boards purchased at a lumber yard and suitable for neck blanks. The Indian rosewood samples were from off-cuts from back sets used to build guitars. The ebony is off-cuts from fretboard blanks (high quality). The Mango was from back sets (select wood). The purpleheart is from selected boards from lumber yards intended for use as back and sides wood.

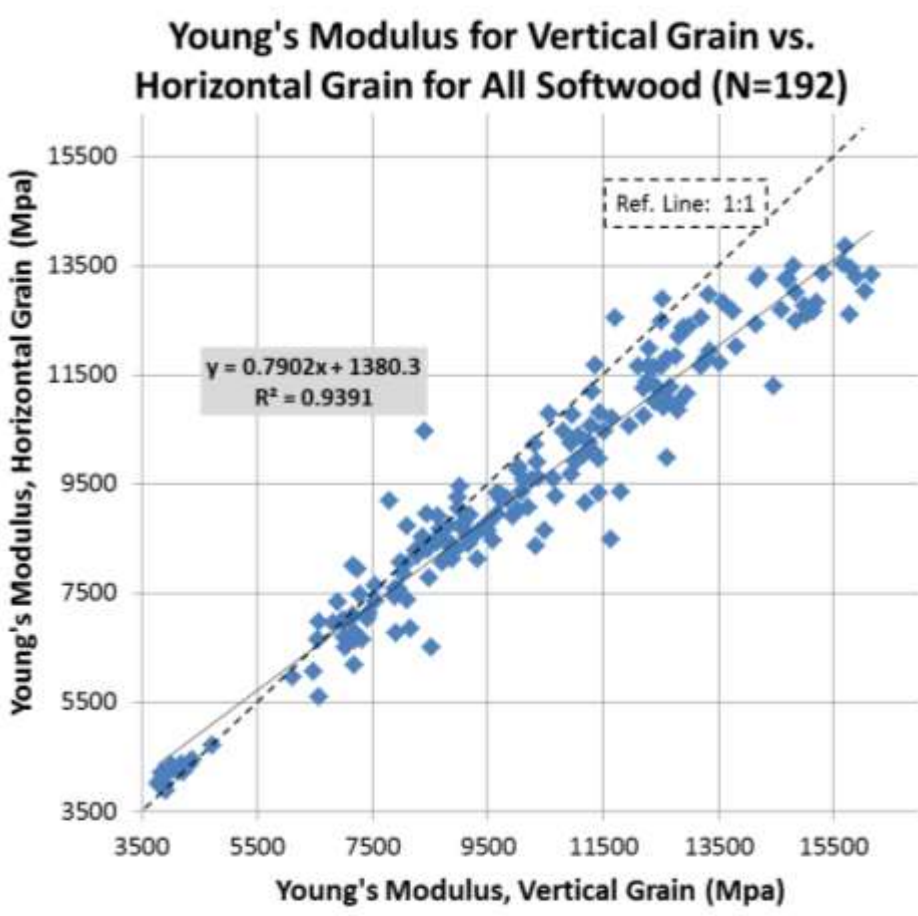
Does grain orientation matter for stiffness?

As it turns out, yes, it does matter, at least for typical softwoods used for guitar tops.

As you can see from Figure 1 and Figure 2, bending stiffness for the vertical and horizontal grain orientations does actually matter for softwoods. Precise measurement and correlating all properties from each sample to each other, this trend can be shown. In fact, for Sitka spruce, the trend is for bending stiffness with the grain oriented horizontally to be about 70% of the stiffness of the same wood oriented with the grain vertically: Vertical grain is stiffer (contrary my previous assertions in AL #100 and Mr. Somogyi's in AL #60) – at least for the softwood species studied here. For all softwoods considered together, the trend is for the stiffness in the horizontal grain orientation to be about 80% of the vertical orientation. The fit of the regression line is quite good too (R^2 = 0.94 is quite a good fit.)

A 20% reduction in stiffness is fairly significant.

As shown in Figure 3, the same holds true for the one hardwood species I was able to study[1] in this regard: Mango. Horizontal grain direction is about 73% as stiff as the vertical grain direction.



[1] For most of the hardwood samples, I could not confidently identify the grain directions on the small samples I used.

Figure 1 Bending Stiffness for All Softwood Samples (Horizontal vs. Vertical Grain)

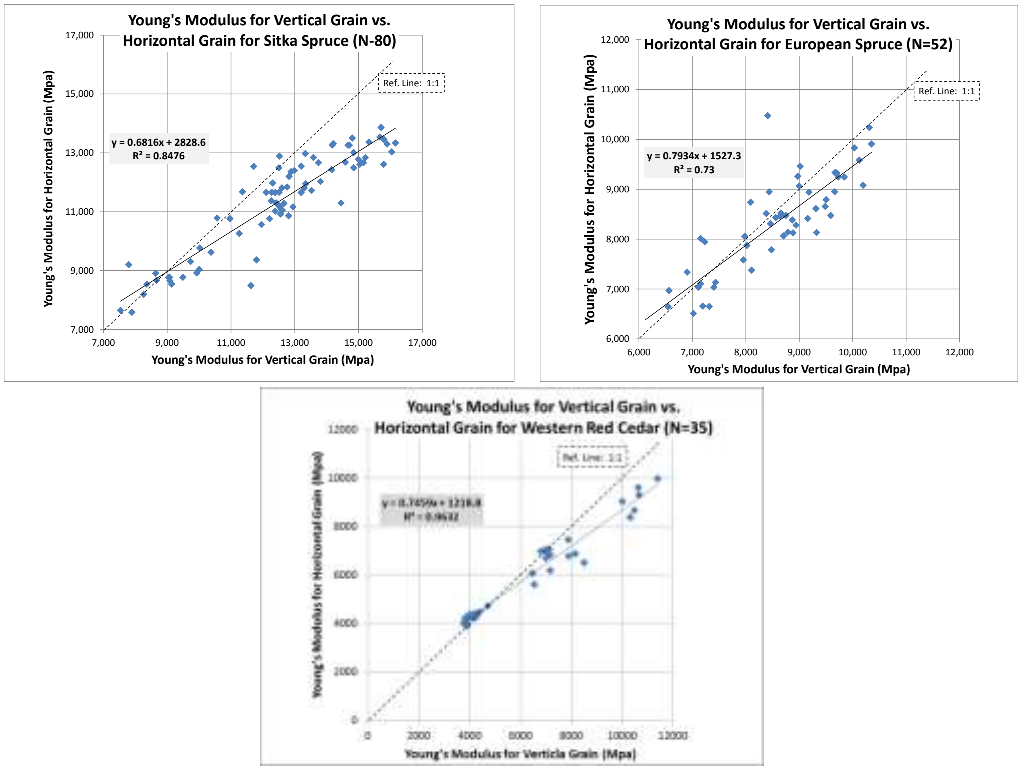


Figure 2: Bending Stiffness for Selected Softwoods (Horizontal vs. Vertical Grain)

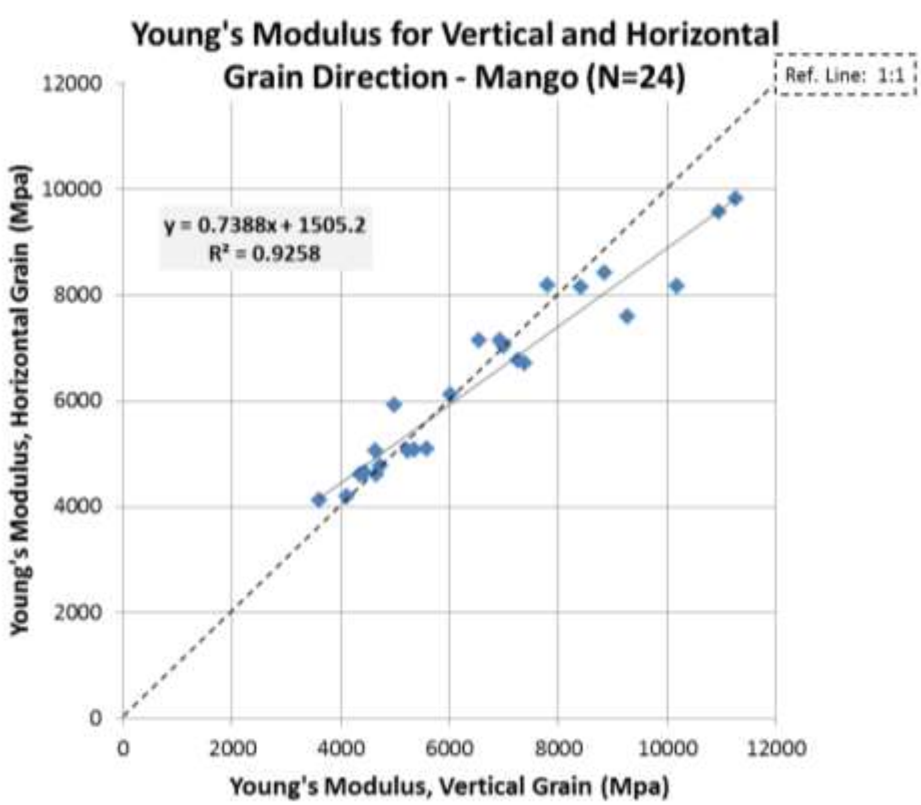


Figure 3: Bending Stiffness for Mango Wood (Horizontal vs. Vertical Grain)

Does grain density matter?

No, grain density (grain *count* per inch or per cm) does not matter. There is no relationship between grain density and stiffness or between grain density and wood density in the softwood species studied, as shown in Figure 4. The regression lines are essentially horizontal.[2] This shows that there is no trend for stiffness or density due to grain density. I strongly suspect that this is true for all softwood species. If you do the same analysis for each softwood species individually, the same pattern is shown (the species of softwoods studied do not differ in this respect).

Because of the different structure of hardwoods and because of the small size of my test specimens, I was not able to get meaningful grain counts on the hardwoods. In addition, because hardwoods vary so much in structure, it might be necessary to look at each species individually.

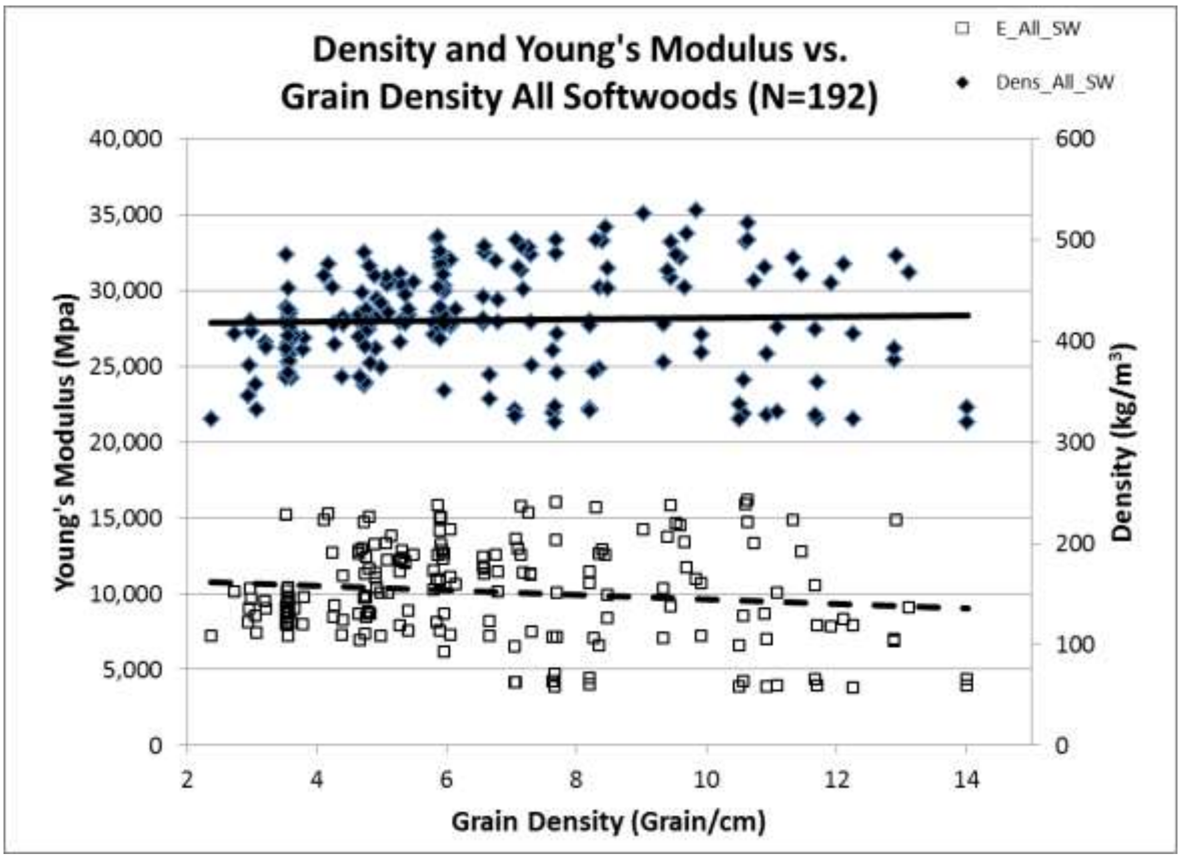


Figure 4: Grain Density vs. Stiffness and Density for Softwoods

[2] If stiffness or density increased with increasing grain density, then the lines would rise from left to right. If stiffness or density decreased with increasing grain density, then the lines would fall from left to right. The horizontal lines show that there is no relationship for stiffness or density with regard to grain density.

Does wood density matter?

Yes it does. As we showed previously[3], stiffness has a direct relationship to density. This latest set of data confirms what Alan's data showed. My data have a stronger trend in the hardwoods (they are in a more distinct grouping and show a clearer trend of stiffness increasing with density) but otherwise, the graphs look essentially the same. Refer to Figure 5 through Figure 7. There is almost perfect overlap in the stiffness of the group of all softwoods studied and the group of all hardwoods studied. But there is very little overlap in density for the same groups.

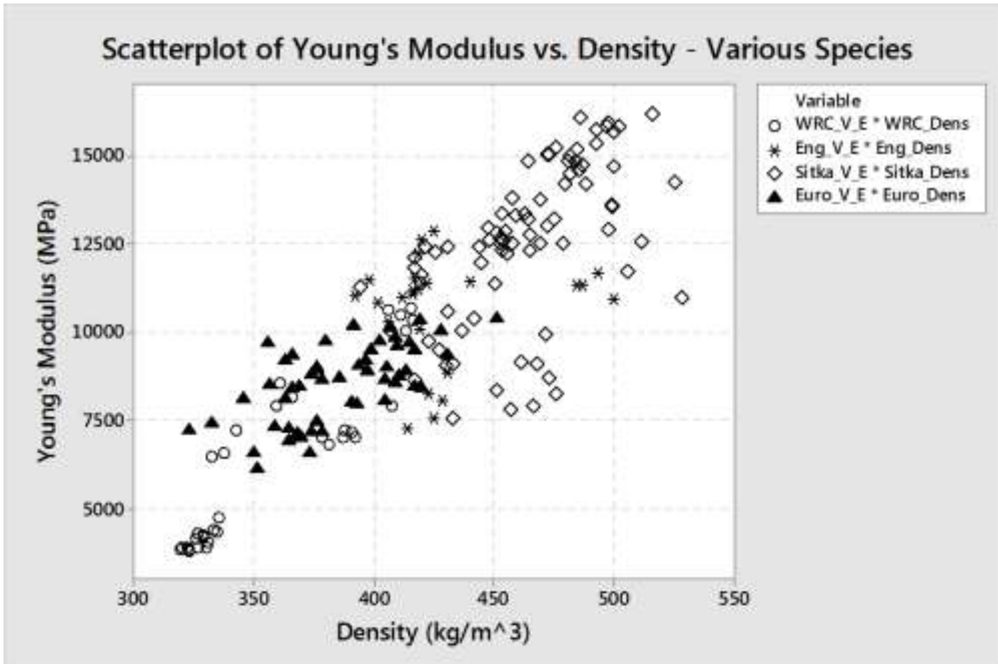


Figure 5: Stiffness vs. Density for All Softwood Species Studied (N=192)

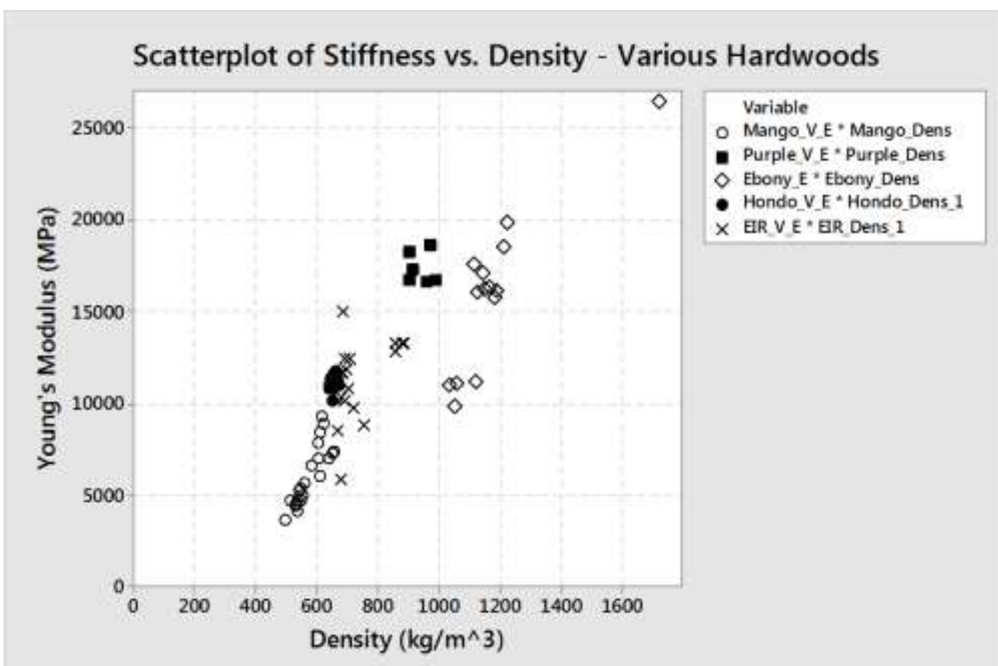
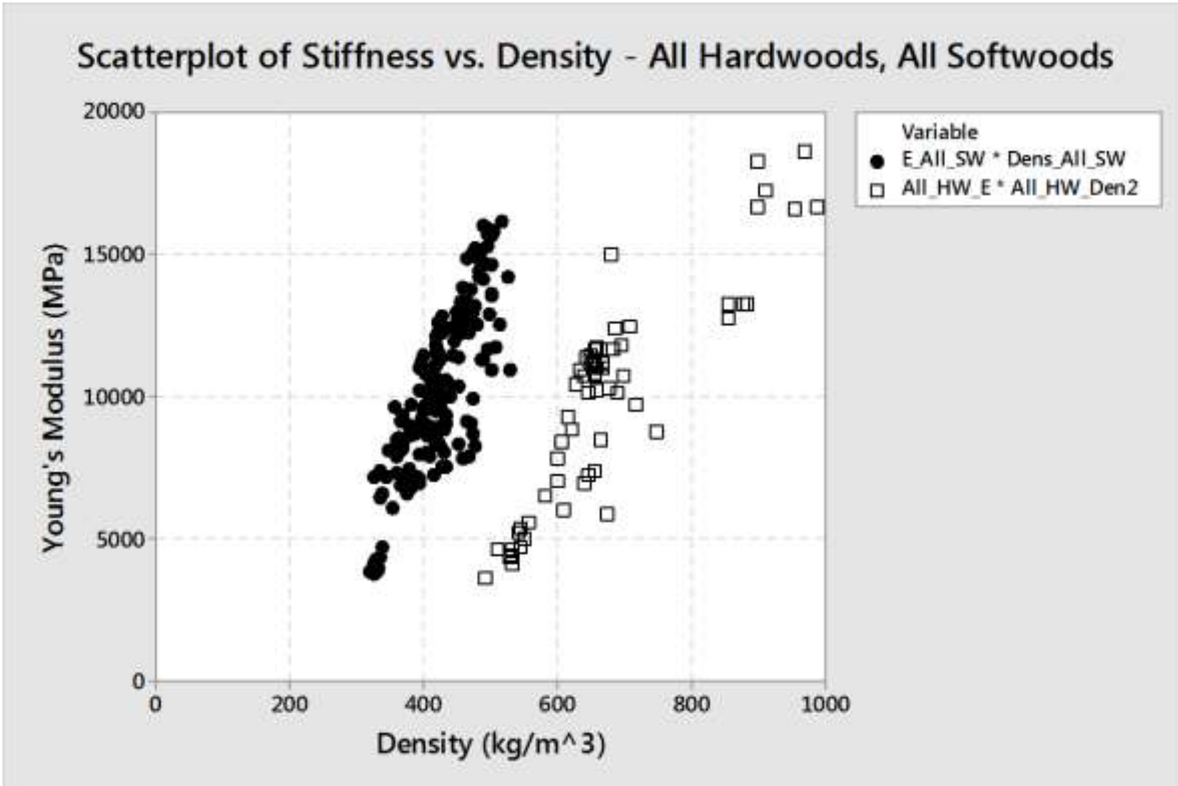


Figure 6: Stiffness vs. Density for All Hardwood Species Studied (N=78)

---

[3] *American Lutherie* #100 in my article, The Guitar as a Structure, and in *American Lutherie* #125, pp 20-23, with Alan Carruth's set of data on density and stiffness.



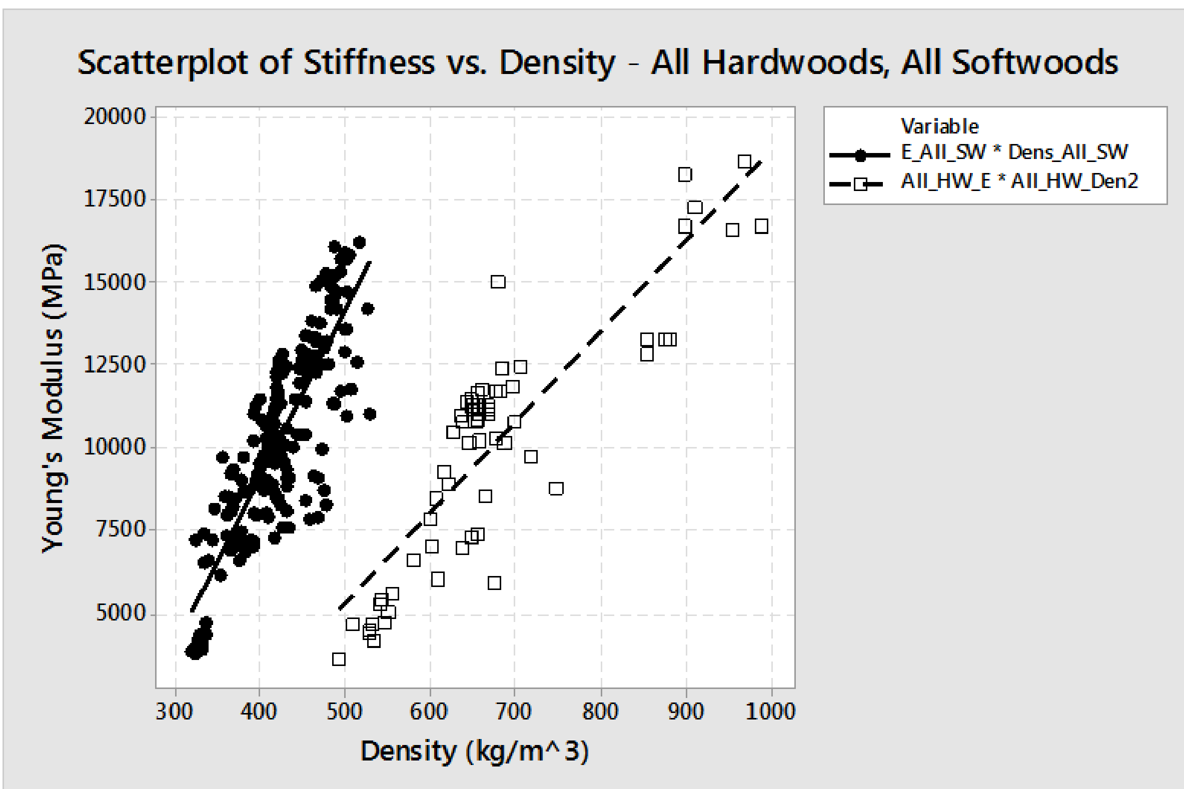


Figure 7: Stiffness vs. Density for All Hardwoods and Softwoods

Is species of wood significant?

Yes it is. Wood stiffness and density do vary from species to species, and especially between softwood and hardwood species (as already shown in the section above on the relationship between stiffness and density). But there is also plenty of overlap in these characteristics between species. Refer to Figure 8 through Figure 9.[4]

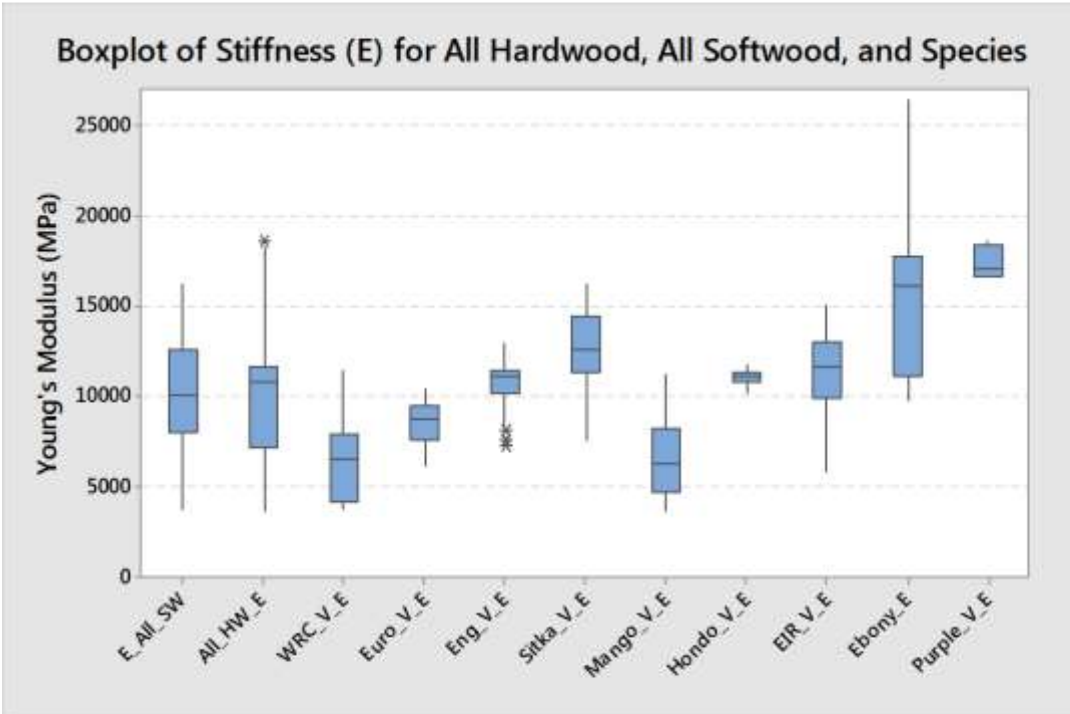


Figure 8: Stiffness of Softwoods and Hardwoods

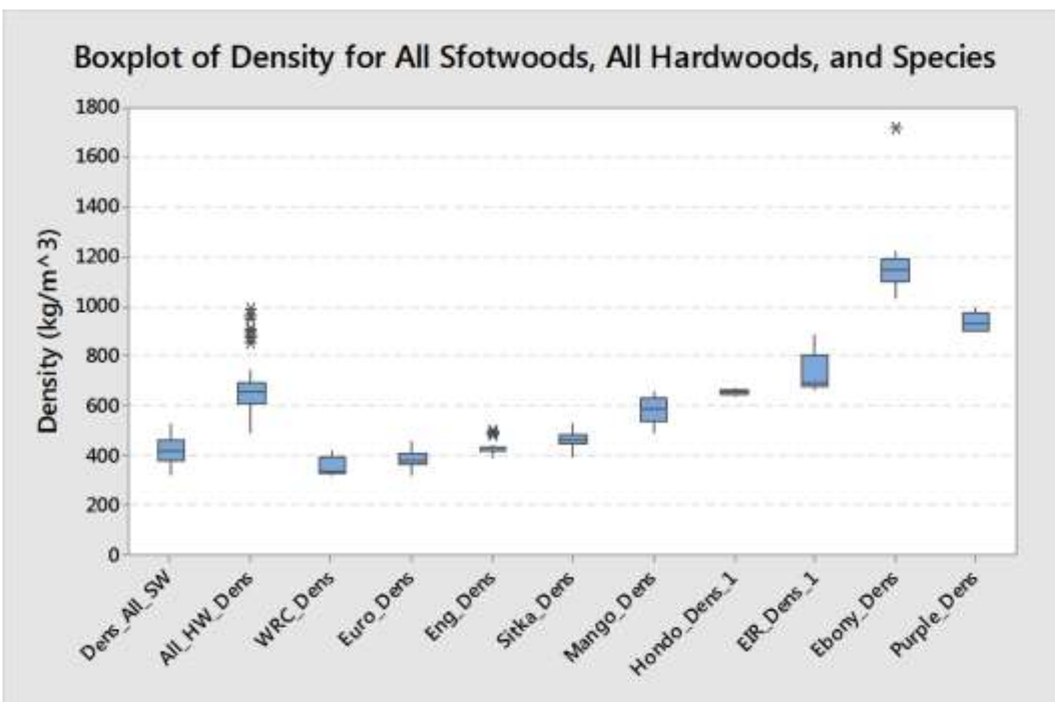


Figure 9: Density of Softwoods and Hardwoods

[4] There were very limited Honduran mahogany samples available for this study, hence the very tight distributions. More samples tested in the future will make the distributions look more like those of the other species.

Other Factors

I also wanted to study the effect of figure on softwood stiffness. I was only able to obtain 8 samples of bearclaw Sitka ("Bear") for testing. In addition, I had some Sitka that I purchased at a lumberyard (very nice stuff; but basically just lumber). The stiffness and density of these factors are shown in Figure 10 and Figure 11 ("Reg" is all the other Sitka samples tested). I did not shown any effect for the bearclaw figure (though it may have an effect on the cross-grain stiffness (radial grain direction)). The lumberyard Sitka ("Lumb") was at the low end in both stiffness and density. This is not surprising, given the highly select nature of guitar top wood (from which the other samples came).

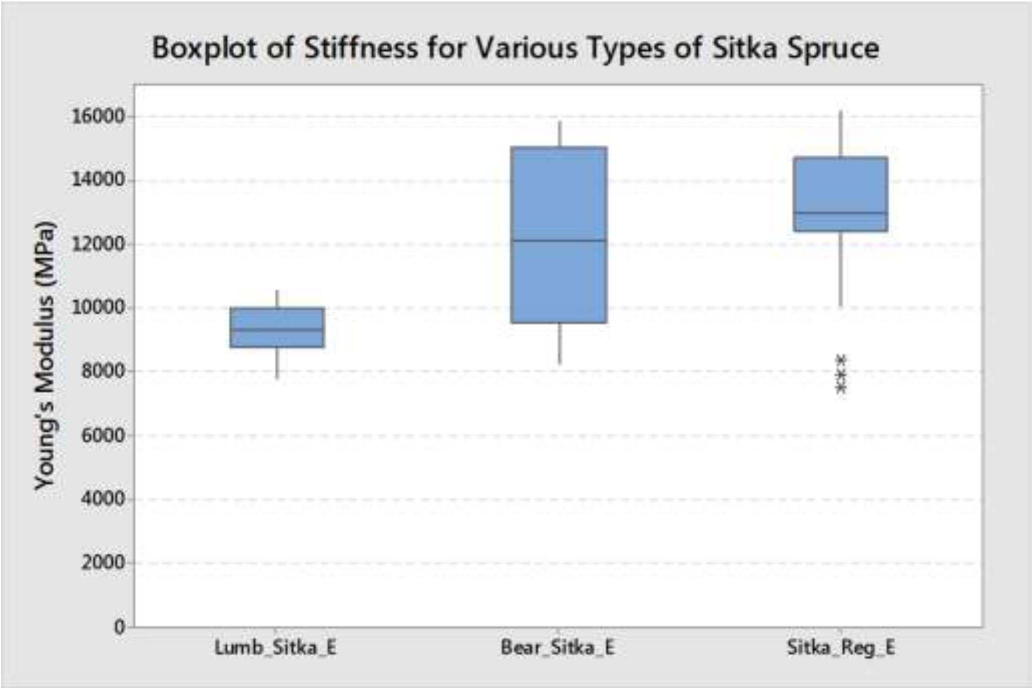


Figure 10: Stiffness for Three Categories of Sitka Spruce

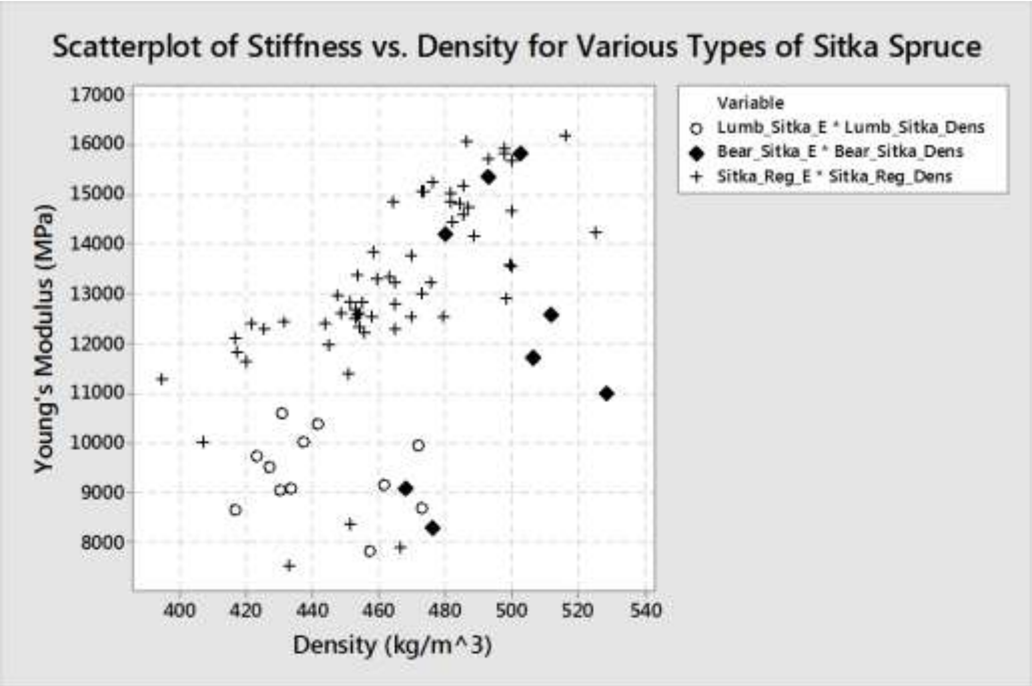


Figure 11: Stiffness vs. Density for Three Categories of Sitka Spruce

Making use of the data

So what does all this mean? My main conclusions are these, basically the same ones that Alan Carruth and I came to in *American Lutherie* #125:

1. Wood selection is very important. The data show that variation within a species is as great or greater than variation between species.
2. As wood gets more dense, it tends to get more stiff. This is true of almost all engineering materials.
3. By measuring your wood stiffness and mass (two key factors driving vibration response), and observing the results in the finished instrument, you may be able to more consistently create the sound you like.[5]
4. More data (larger samples sizes) means more accurate conclusions. The data characterize the overall population better. I encourage people to measure their wood and to share those data with the community.

In addition, because I measured the grain density and grain direction of my softwoods samples (and some hardwood samples), I make the following further conclusions:

5. Grain density is not significant for either stiffness or for density. (It may be important for esthetic reasons; but it has no *predictable* effect on stiffness or density.)
6. Grain direction does matter for bending stiffness in the species studied. The data for both softwoods and hardwoods support the conclusion that bending stiffness with grain oriented horizontally is only about 70% - 85% of the bending stiffness of the same wood with the grain oriented vertically.

Again, a few caveats

Again, as noted in *American Lutherie* #125 the data presented here do not cover the third important determinant of vibration response: The internal damping characteristics of the material. This article also does not address design. Design is a big part of why most of us do this: The satisfaction of designing an instrument that sounds good. However, data such as those presented here may help a builder be more consistent within a chosen design.

The wood tested in this article is carefully selected wood, intended for making high-quality guitars. Randomly chosen wood would likely show more random results.

All test systems have errors inherent to the system. Using consistent methods, ensuring consistent dimensions within a specimen, and gathering larger numbers of samples help reduce error. Wood is a notoriously variable material. The calculations assume that the material is uniform in its properties and in its dimensions. The dimensions are relatively simple to make uniform enough for our purposes. However, the variation in the wood is harder to determine and control. Using small specimens helps. Using high-quality, select wood helps. In the end, however, some error is introduced by the non-uniformity of the wood itself.

Sampling testing, such as the data presented here, provides an *estimate* of the characteristics of the full population. The more samples you test, the more accurate that estimate becomes.

---

[5] As I noted in my article, The Guitar as a Structure, in *American Lutherie* #100, vibration response (resonance) is driven by the stiffness and mass of the material. If you want something to vibrate at a higher frequency, make it lighter, stiffer, or both. If you want something to vibrate at a lower frequency, make it heavier, less stiff, or both.

Standard Method for Stiffness Testing

I am also proposing a standard method that can be easily applied by any luthier with the desire to find out more about the wood she or he uses. My proposed method is very simple to set up and perform. All you need are a few accurate instruments most of us already have: Steel scale, caliper, and a good scale for weighing your samples and the bending loads.

Test steps (remember to keep the data for each sample identified *to that individual sample* for analysis):

1. Measure the length, height, thickness, and weight of each sample; and mark it with an individual code so you can identify it[6]. Measure the weight of your applied weights and the supporting wire (or other support for the weight.) I measured the weights of the samples to 0.01 gram and the weights of the applied weights to within 0.1 gram. I measured the length of the samples (and the L dimension on the test fixture) to within 0.01 inch. I measured the thickness and height of the samples to within 0.001 inch using a caliper.
2. Place each sample into the fixture and clamp it tightly
3. Record the unloaded (tare) position (to 0.01 inch)
4. Load the sample
5. Record the loaded position (to 0.01 inch)
6. Perform the data analysis as shown in Appendix B to determine the stiffness (Young's Modulus, E)

For this proposed method, the sample must be tightly clamped (fully fixed support) for the calculation of Young's Modulus (***E***) to be accurate! If it's not tightly clamped, then you have a support system that does not conform to the formulas presented in Appendix B. If not tightly clamped the test becomes essentially a three-point bending case, which yields very different deflections – and therefore the formula for ***E*** is not correct and you will not get useable data.

I chose to use small samples for a number of reasons[7]. Smaller samples mean that they will have less variation, they will be more uniform that a larger sample (which increases the accuracy of the results because the formulas assume uniform properties). Small samples are cheaper and easier to make; and they can be made from offcuts of tone wood sets. Small samples can be tested at home, using small loads; and, since the loads are small, the testing is safer (I did have a few samples fail during testing). The exact size of each sample can vary, since you will be measuring each sample individually (in order to get highly accurate results).

Figure 12 through Figure 14 show my test set-up. It's very simple: A solid platform to which the sample can be clamped in a "fully fixed" support configuration, and a scale from which to measure the tare and loaded positions of the sample. I made mine out of shop grade plywood. For the scale, I just taped an engineer's 6-inch steel scale to the edge of the rig. The distance to the load, L, is fixed by the rig (10 inches (254mm) in my case). The upper clamping block (loose part) has a half-dowel on it to improve the clamping. I used a stiff piece of wire to suspend the weight (bending load) and I sharpened its end (Figure 14) so it would not slip on deflected samples (some samples bend down a long way).

[6] Compute density as weight divided by: (length X width X thickness)). You may also wish to record grain density, grain direction, figure, etc., as I have done.

[7] My typical sample was 11.5 – 14 inches long (292mm – 356mm), and 0.12 – 0.20 inches X 0.25 – 0.40 inches in cross section (3 – 5 mm X 6 – 10 mm). The sizes varied considerably; but, since I measured every one precisely, this has no effect on the test results.

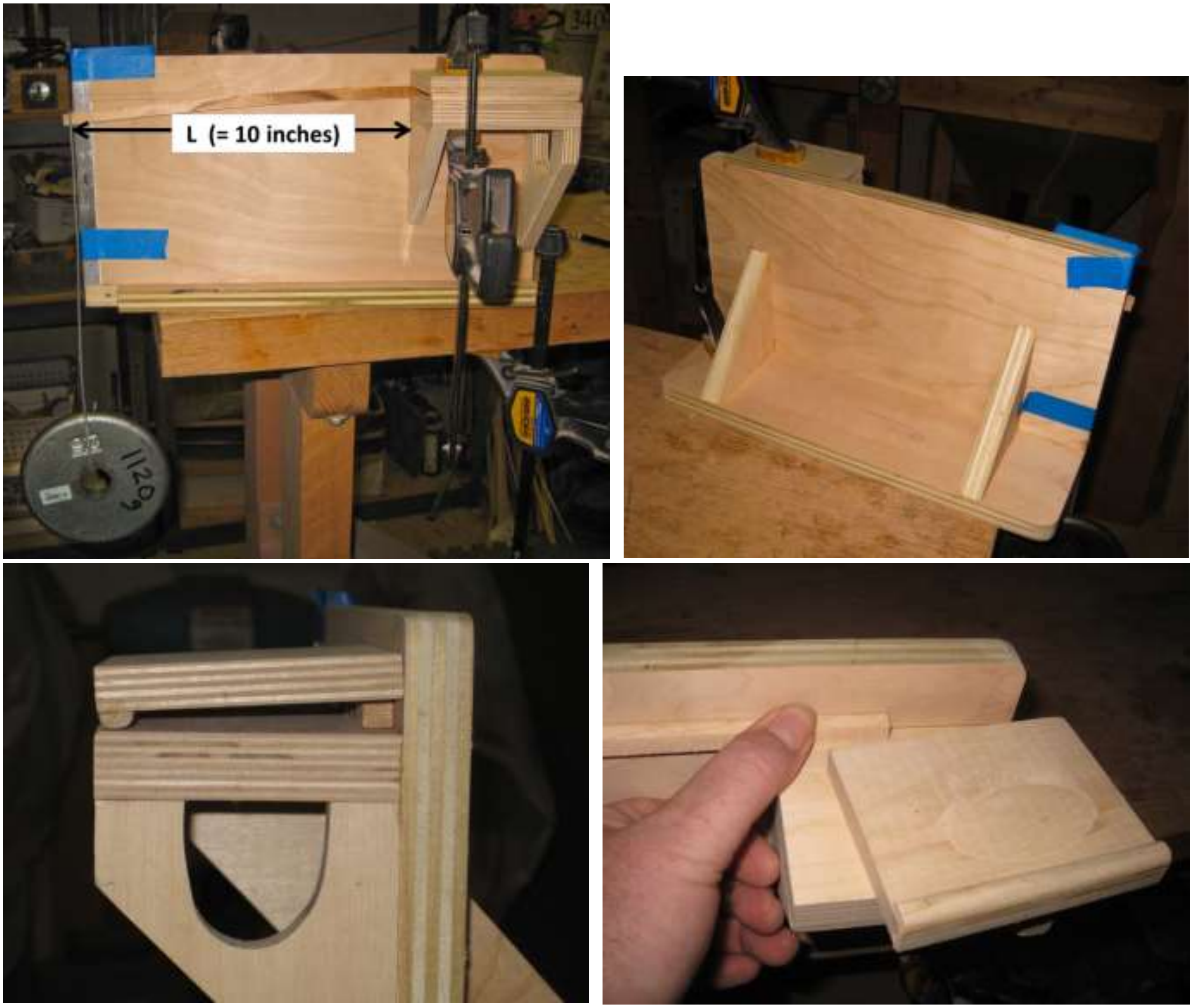


Figure 12: Bending Test Rig

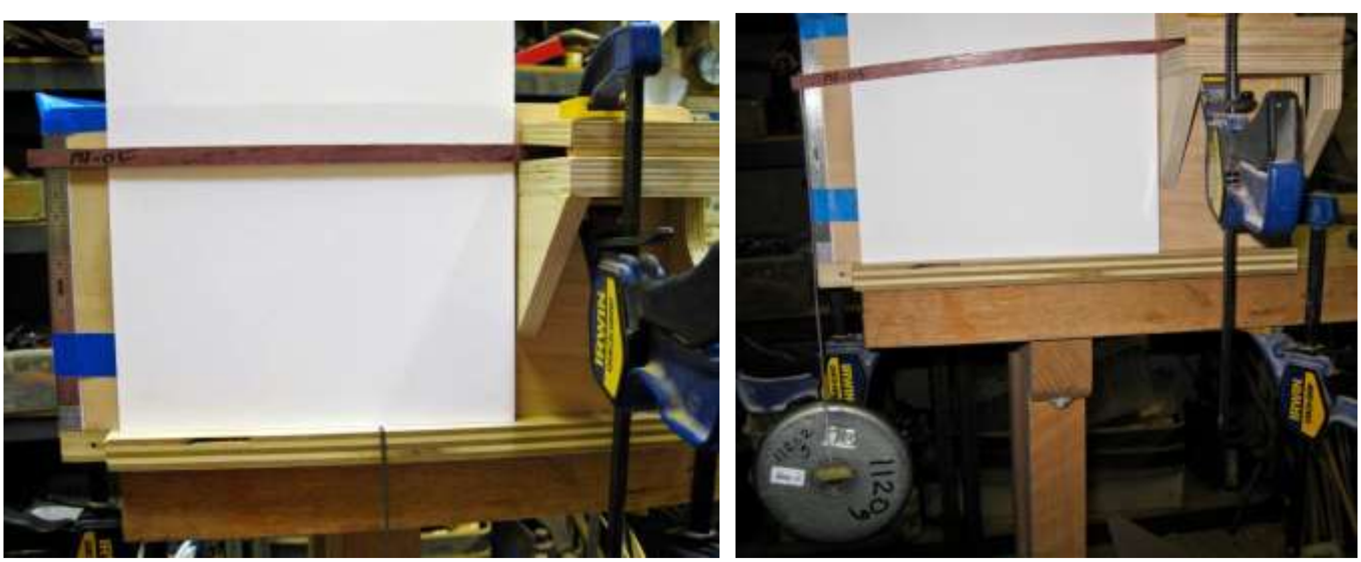


Figure 13: Bending Test Rig with Unloaded and Loaded Specimen

Figure 14: Tip of the Weight Support Wire

Further Reading

https://en.wikipedia.org/wiki/Young's_modulus (wiki for Young's Modulus)
https://en.wikipedia.org/wiki/Density (wiki for density)
https://en.wikipedia.org/wiki/Box_plot (wiki for box plot)
https://en.wikipedia.org/wiki/Outlier (wiki for outlier)
https://en.wikipedia.org/wiki/Sample_size_determination (wiki on sample size)
https://en.wikipedia.org/wiki/Strength_of_materials (wiki on strength of materials)

Statistics for Dummies, Rumsey
Structures, Or Why Things Don't Fall Down, Gordon

The NFS *Wood Handbook*: Available for free download:
http://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr190.pdf

Appendix A: Previous Testing

Alan Carruth and I reported Alan's test data for bending stiffness and density for the wood he has tested over the years in American Lutherie #125 [1].

In addition, some time ago, well-known luthier Ervin Somogyi did some testing of brace wood stock in order to understand, for himself, its stiffness relative to species, grain orientation, density, etc. His testing [2] was informal and provided only relative data: Differences between the several factors he studied within the same dataset. This is because, although he took care to make the specimens as identical as he could, he did not measure the density of the specimens or compute their Young's Modulus. Instead, he grouped specimens into categories of "lightest wood, medium wood, and densest wood".

This makes comparison with others' data extremely difficult. Without exact dimensions, deflection forces, deflection values, dimensions to the deflection force, and the weight or mass of the specimen, there's no way to compare them. Hence I am proposing the standard method, above, for making these measurements.

Mr. Somogyi wanted to compare grain orientation and wood density and how they affected wood stiffness (***E***). He noted, "I'm not reporting actual densities of these samples in terms of comparative numbers: I want to present this experiment as being part of the same hands-on way in which I operate normally, and I consider informal labeling such as 'heavy,' 'average,' or 'light' to be meaningful unless there are other compelling or overriding factors in play."

He's clearly comfortable with vague language and conclusions (and, given the variable nature of wood as an engineering material, that may be fine). To draw more clear conclusions, to more confidently state our findings, a full set of data is needed. I encourage people to measure their wood and record all the relevant information and also share the data with the general lutherie community.

He also used quite small sample sizes: 4 or 5 specimens for each variant tested. Having fewer than the minimum level of 10-15 samples makes drawing conclusions significantly more difficult (the experiment has less power, in the statistical sense of the word power).

Mr. Somogyi's conclusions were:

- Grain orientation doesn't matter for stiffness
- Denser wood is stiffer than less dense wood

He suggested (as do I) that others carry on with this work and repeat similar tests.

In addition, in American Lutherie #124, Michael DaSilva describes a similar method [3] of testing for stiffness using bending and weighing and the dimensions of the specimen to determine the wood's stiffness and density. Mr. DaSilva, similar to Mr. Somogyi, seems to use a standard-sized test sample.[8]

[1] Wood Stiffness, *American Lutherie*, #125, pp. 20-23, Blilie, Carruth
[2] *The Responsive Guitar*, Ervin Somogyi, (Hal Leonard Corporation; (March 1, 2011)) pp. 65-67; First appeared in *American Lutherie*, #60, page 19.
[3] Ukulele Building: Tradition and Trends, *American Lutherie*, #124, pp. 4-15, DaSilva, Gleason, Lichty, White

[8] Using a standard sample size saves measurement time: All you need to measure for each sample is: Weight, tare position, and loaded position.

Appendix B: Formulas

This appendix shows the calculations used to determine the stiffness (Young's modulus) for the bending test samples[9]. The formula is well established and has been in use for a couple of centuries (L. Euler, 1727) in the design and analysis of structures and materials. The formula is shown in Figure 15.

Since we are applying a point load at the tip of the sample and we are interested in the deflection at the tip, we can use the equation for **Δmax**. (at free end).

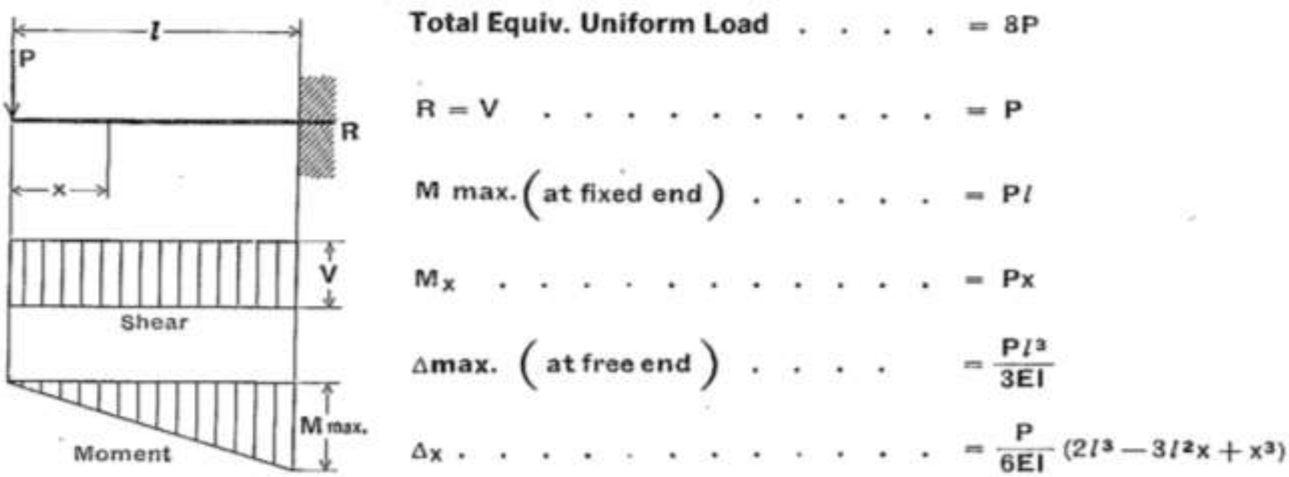


Figure 15: Formulas for Deflection, Moment, Shear in a Cantilever Beam Loaded at the Tip

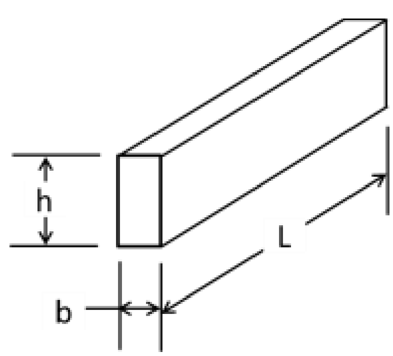
The weight and shape (some samples have a little curve to them) of the sample is accounted for by taking a tare measurement (vertical position of the sample tip at the loading point without the load applied) before applying the load and measuring the deflection under load.

Equation 1: **Δmax = (loaded measurement) – (tare measurement)**

I (bending modulus or second moment of area) is calculated from the dimensions of the sample. In this case, all samples are rectangular and the following formula is used:

Equation 2: $$\boldsymbol{I = \frac{1}{12} b h^3}$$

Where $\boldsymbol{b}$ is the width of the sample cross section and $\boldsymbol{h}$ is the height of the sample cross section.



[9] Wood typically fails in brittle fracture with essentially no necking due to plastic deformation. This means that we can safely assume that if a sample does not fail, then it remains in the elastic stress zone and Young's Modulus is applicable.

Therefore, to calculate **E**, use the following formula (rearranged from the equation for **Δmax** shown above):

Equation 3: $$\mathbf{E} = \frac{\mathbf{PL^3}}{\mathbf{3}\ \boldsymbol{I}\ \mathbf{\Delta max}}$$

E is what we want to find. **P** is the applied load on the sample (the weight and its support). **L** is the distance from the support of the sample to the applied load. **Δmax** and ***I*** are measured (**Δmax**) and calculated (***I***) as shown above.

To find the density of the samples, you need the length (**L**), height (**h**), width (**b**) and **weight** for each sample. Compute the density using the following formulas:

Equation 4: $$\boldsymbol{Volume = L \times b \times h}$$

Equation 5: $$\boldsymbol{Density = \frac{Weight}{Volume}}$$