Wood Stiffness – An Analysis of a Substantial Sample of Woods of Interest to Guitar Makers

I think all acoustic guitar makers will agree that the weight and stiffness of the wood that they use is important to the sound produced by their instruments. I think nearly all guitar makers use some method to assess the stiffness and weight of the wood they use, especially for guitar tops.

My own practice (Jim) is to constantly tap, scratch, and flex wood in all its forms, from rough sawn billets through the completed guitar. Most importantly, I constantly tap and flex a guitar top as it progresses from a matched set through to a complete top ready to assemble into the guitar body. I have accumulated a substantial mental library of flexing and listening that helps me produce guitars the sound good to me. This method, however, is highly subjective and very difficult to transfer to another person.

Alan's approach is much more scientific. In his words:

> I use top or back halves (mostly) from guitar sets. These are [acoustically] driven using a loudspeaker, and a magnet and coil to sense small piece of magnetic material stuck to one end of the plate for the amplitude measurement. I find the lengthwise and crosswise fundamental mode frequencies with the 3 dB down points, and plug those numbers, along with size and weight, into a little BASIC program I wrote to calculate the E values, Qs, and density.

Alan's method will provide accurate (within its precision) and, especially, repeatable data on the wood that he tests. He uses the frequency at which the plate resonates to find its internal resonant frequency, which in turn, together with the weight and dimensional data, allows him to accurately calculate the stiffness (E, Young's Modulus) of the wood.

What are stiffness and density, and how are they measured?

Stiffness and density or two of the most important factors in determining the vibration (acoustic) response (internal damping is also important).

Stiffness is a measure of how much a material compresses (shrinks) under compressive loading or extends (stretches) under tension. This is analogous to a spring. <u>Anytime</u> something is under loading, the material compresses or stretches under that load[1]. Most of the time, we don't notice this because the size changes are very small compared to our bodies.

For the materials of interest to us (wood, metal), stiffness is most often expressed as the elastic modulus of the material (also known as Young's Modulus), symbol: E, with units of stress (typically pounds per square inch (psi) or Pascals (Pa) (1 Pascal = Newton/m^2 = N/ m^2).[2]

The resonant frequency of an object is dependent on its size & shape, mass, and inherent material stiffness. When Alan measures the size, weight, shape, and resonant frequency of the wood plates he's testing, he can then solve for the inherent material stiffness or E.

Another way to measure E in wood samples is to apply a weight to them and measure how far they deflect under this load. Together with the size & shape of the wood sample, the applied weight, and the configuration of the supports for the sample, one can calculate the Young's Modulus by using the correct beam bending formula. (I intend to develop the design for a simple, easily built tool for this method, which I will share in a

[1] The way a material supports a load is by compressing or stretching. Nothing is perfectly rigid.
[2] I won't go into the engineering reason for this. Pascals typically have a Mega or Giga prefix (MPa, GPa)

future article; and I hope to begin adding to the data set of measured stiffness data of various wood types. Stay tuned for a future article.)

Density is simpler: It is mass[3] for a given volume of material. Measure the weight and the dimensions of the sample. Divide the weight by the volume. Units are mass (or weight) per volume: Pounds per cubic foot (lb/ft^3) or kg/m^3

The data set

Alan has been gathering these data for quite some time; and, fortunately for us, he was written them down. And, even better, he's willing to share these data with the community (thanks!). The data presented below are from the samples summarized in Table 1. (Species with fewer samples are not detailed in Table 1.)

The more samples you measure, the clearer picture of the population you are sampling (in this case stiffness of a species of wood): The more samples you test, the more of the variation within the population you are "capturing". That's why these data are interesting: There are a lot of them.

Alan notes that the great majority of these data are from woods that were used to build guitars (luthier-quality wood samples). Either Alan or one of his students performed these measurements. Total samples measured: 72 softwood samples, 67 hardwood samples[4]. Note that these are measured individual values, not averages or estimates for a species.

Table 1: Wood Species Sample Sizes

Species	N
Sitka Spruce (*Picea sitchensis*)	10
Engelmann Spruce (*Picea engelmannii*)	12
European Spruce (*Picea abies*)	17
Western Red Cedar (*Thuja plicata*)	8
Redwood (*Sequoia sempervirens*)	7
Red Spruce (*Picea rubens*, aka "Adirondack spruce")	6
Brazilian Rosewood (*Dalbergia nigra*)	7
Indian Rosewood (*Dalbergia latifolia*)	16
Mahogany (*various*)	7
Walnut (*various*)	7

I want to present these data in a certain order and provide comments and analysis.

First, look at the distributions of stiffness and density[5] for softwoods and hardwoods (throughout: these are species of interest to guitar makers).[6]

For all the graphs: Density is in kg/m^3 and stiffness is in mega-Pascals (MPa).

[3] Colloquially considered to be the same as weight; but formally mass only.
[4] 1 hardwood sample was removed: It was an extremely hard outlier oak sample.
[5] Density is what most people would call weight – weight for a given amount of volume.
[6] These data are presented in a common statistical display: A box plot. A box plot is a visual way to summarize the distribution of the data. The central box represents the middle 50% of the data, with the average of the set of data shown by the central line. The two "whiskers" on either end of the box show the upper and lower 25% of the population. The asterisks show individual values that are "outliers" in the populations. Outlier has a specific technical meaning in this case; please see the Further Reading section.

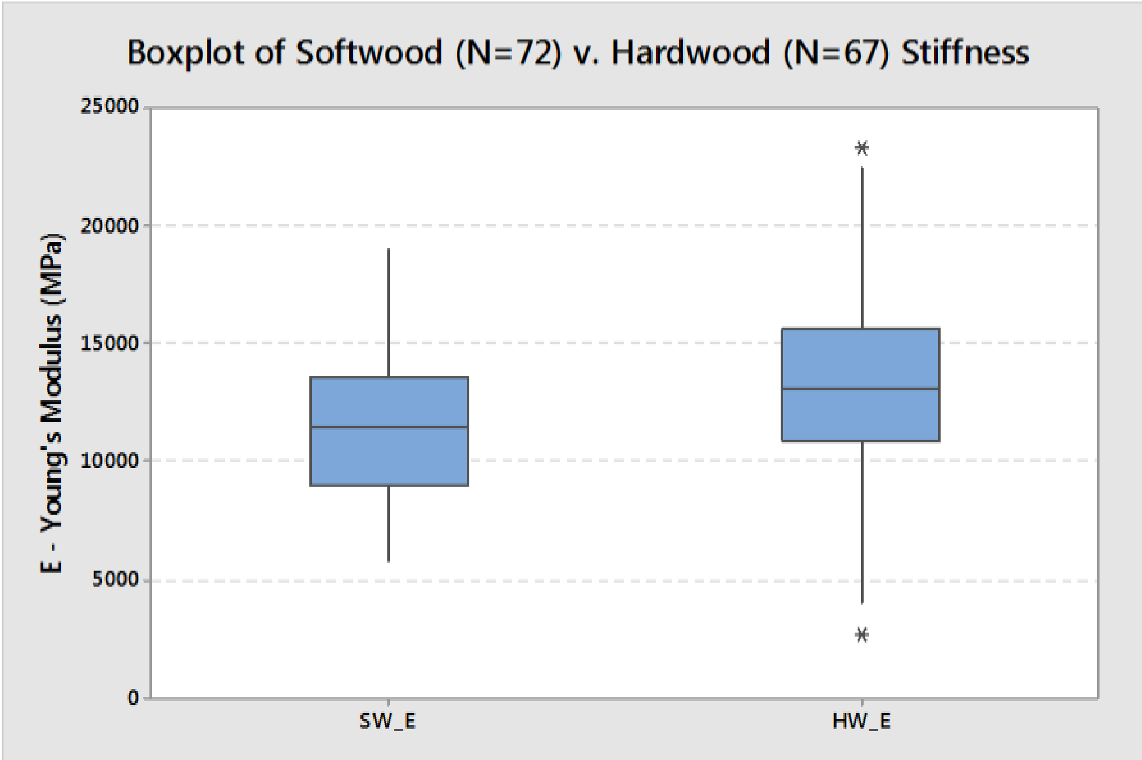

Figure 1: Stiffness, Hardwoods vs. Softwoods

The thing to note in Figure 1, showing stiffness, is that there is nearly 100% overlap between the stiffness of the softwoods and hardwoods. In general, you should expect a random piece of hardwood to be about as stiff as a random piece of softwood. I was surprised by these real data (I expected hardwoods to be notably stiffer than softwoods).

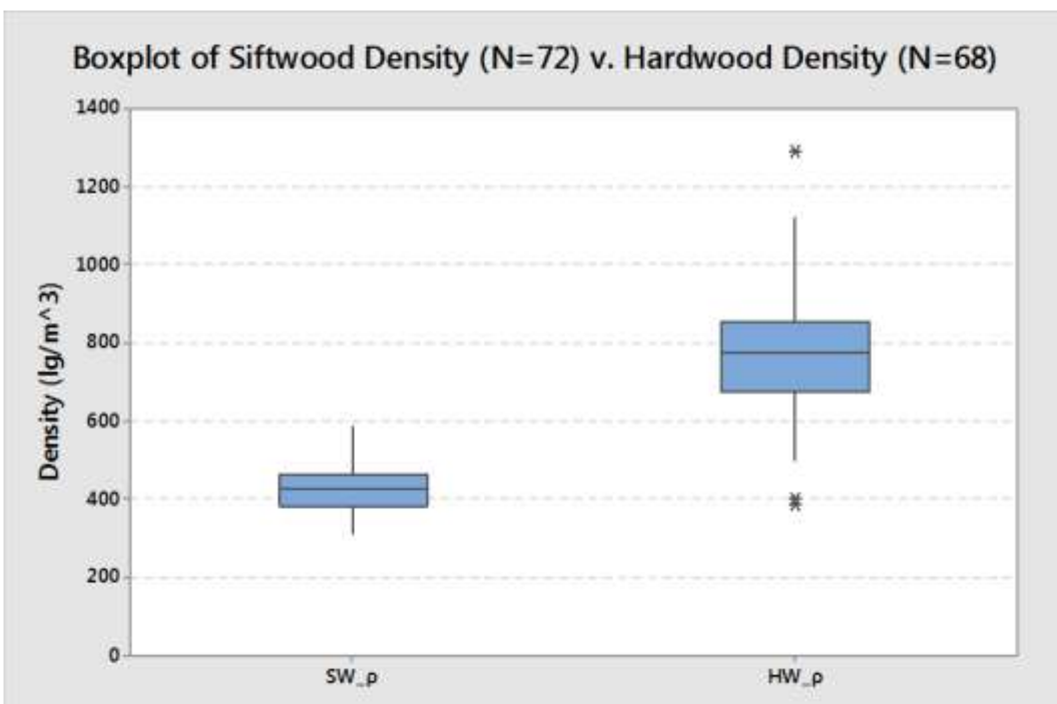

Figure 2: Density, Hardwoods vs. Softwoods

Figure 2 shows the density of the samples measured for hardwoods and softwoods. The thing to note from Figure 2 is that hardwoods are generally much denser (heavier) than softwoods. This conforms to our general impressions about hardwoods. However, there is also quite a bit of overlap between these distributions.

Alan notes that these data in the graphs presented here are a subset of all the data he has gathered. The full range of stiffness and density for selected softwood species are shown in Table 2.

Table 2: Full Range Data for Selected Softwoods

Species	Density (kg/m3)		E (Mpa)	
	Min.	Max.	Min.	Max.
European spruce	340	540	8800	19,000
Sitka spruce	380	530	8900	17,000
Engelmann spruce	354	500	8200	16,000
Red spruce	360	490	9500	13,000
Western Red Cedar	314	400	6000	11,000

As Alan notes, "There's a *lot* of overlap. Not all of that was from samples that you'd use for a top, but much of it could have ended up as brace wood. Again, these are the extremes of the distribution."

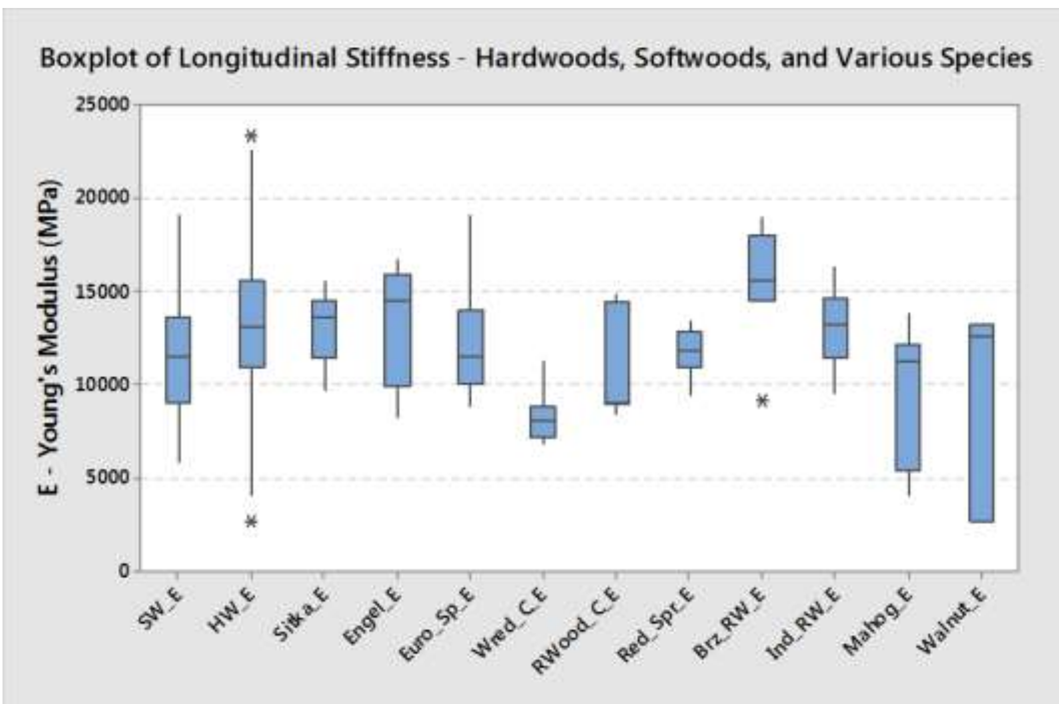

Figure 3: Stiffness of All Softwoods, All Hardwoods, and Various Species

Figure 3 shows the stiffness of various species compared to the all the hardwood samples and all the softwood samples. It shows that there's little difference in the stiffness of the various softwood (top wood) species, except for Western Red Cedar, which is softer than the others. For the hardwoods: Brazilian rosewood is notably stiffer and mahogany and walnut are notably less stiff than the softwoods. Indian rosewood is about the same stiffness as the softwoods.

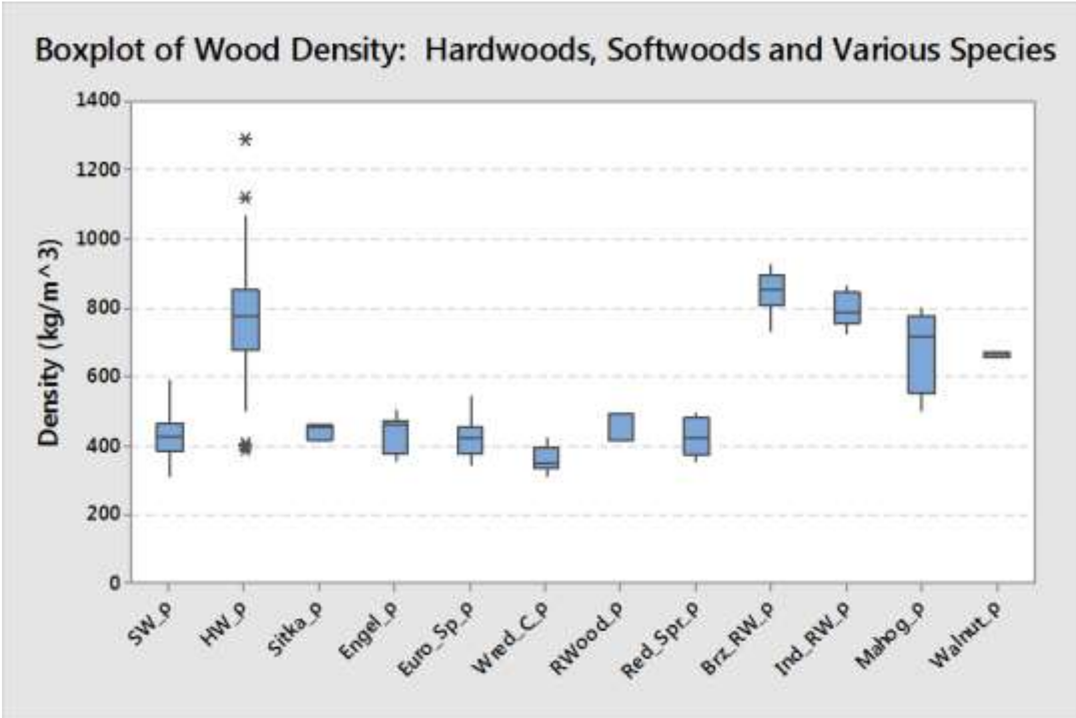

Figure 4: Density of All Softwoods, All Hardwoods, and Various Species

Figure 4 shows the density of various species compared to the all the hardwood samples and all the softwood samples. It shows that all the softwood species are similar in density and that the hardwood species are much denser, with Brazilian the densest, mahogany and walnut the least dense (and similar to each other), and Indian rosewood in the middle.

Next, let's look at the relationship between stiffness and density. For this, we will plot stiffness (Young's Modulus) versus density. First, look at Figure 5.

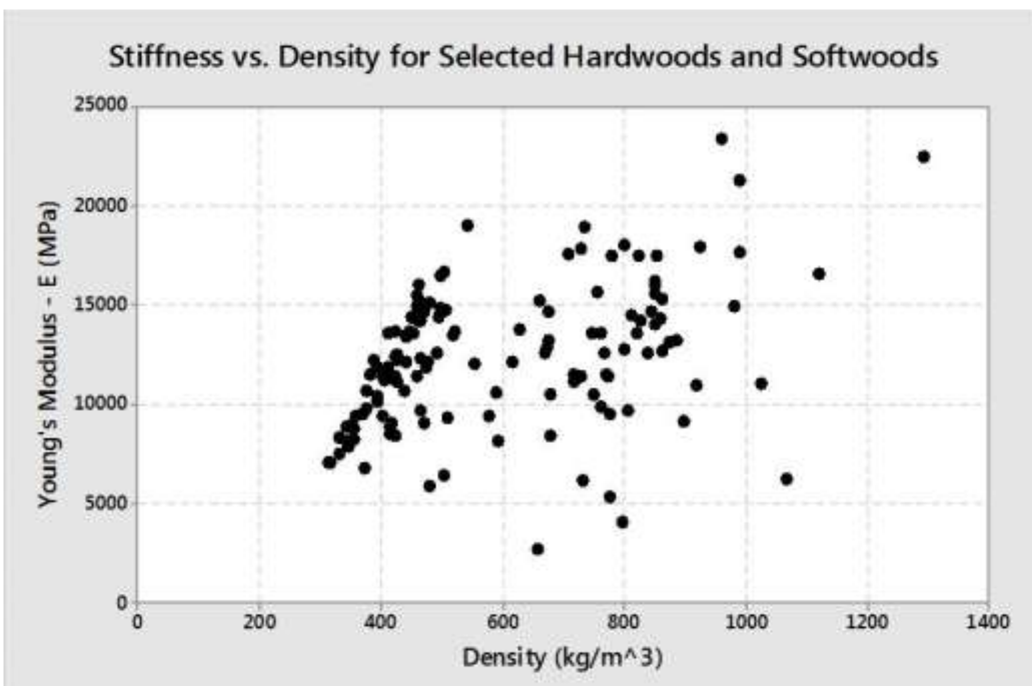

Figure 5: Stiffness vs. Density, All Samples

In Figure 5, one can see a weak direct relationship between density and stiffness (as density gets larger, so does stiffness). However, there a lot of scatter and it's clear that the wood measured varied a lot. There is an interesting clump of data on the left end of the plot.

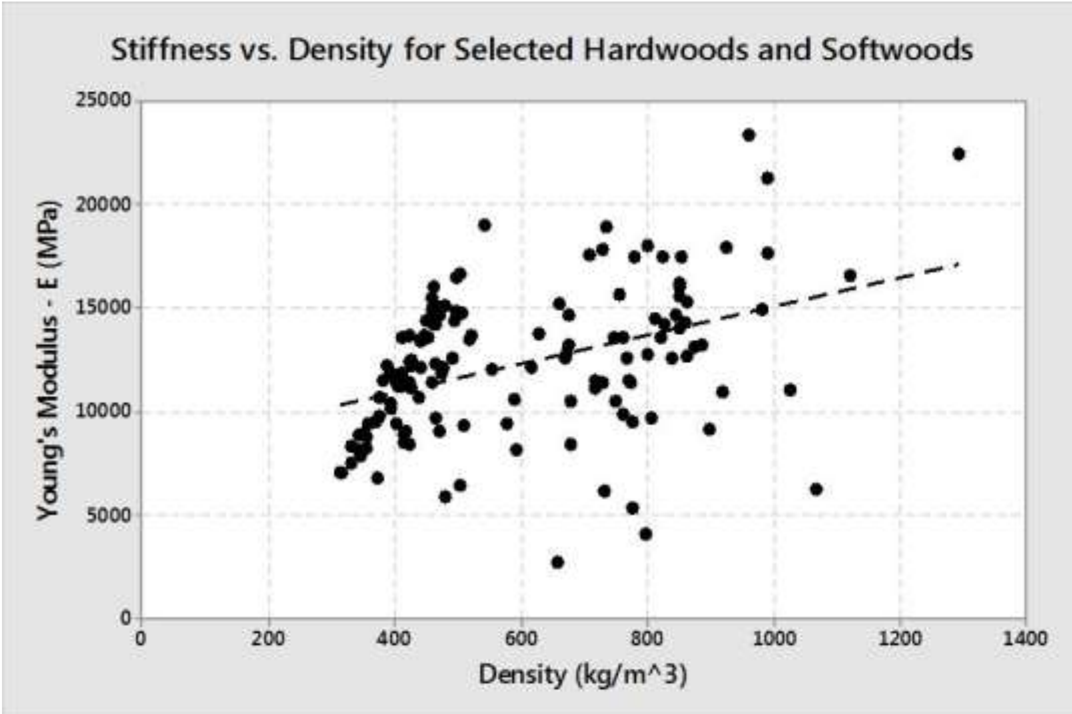

Figure 6: Stiffness vs. Density, All Samples

In Figure 6, a linear regression line has been added to the data in Figure 5. This line shows (in a statistically well-defined way) the general trend for increasing stiffness with increasing density.

If we differentiate between the softwoods and hardwoods, a more interesting pattern emerges.

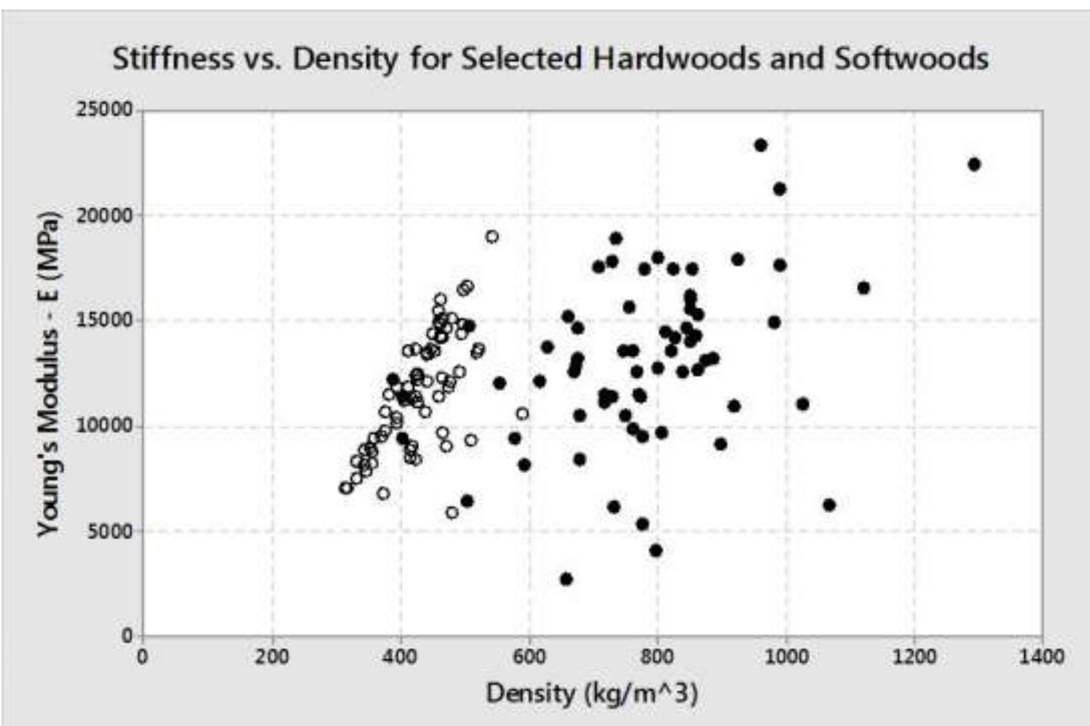

Figure 7: Stiffness vs. Density, Softwoods vs. Hardwoods

In Figure 7, we can see that the softwoods are all grouped in the left end of the plot (they are less dense, lighter) and they gain stiffness faster than the hardwoods do (as you increase density, the softwoods get stiffer faster). Note that the range of stiffness within the softwood is very similar to the range of stiffness within the hardwoods. Also note that the hardwoods have much greater scatter than the softwoods do – in both stiffness and density.

Adding linear regression lines to the softwood and hardwood data, in Figure 8, shows these relative behaviors mathematically: The line for the softwoods is steeper than the hardwoods. (Please also refer to the caveats section.)

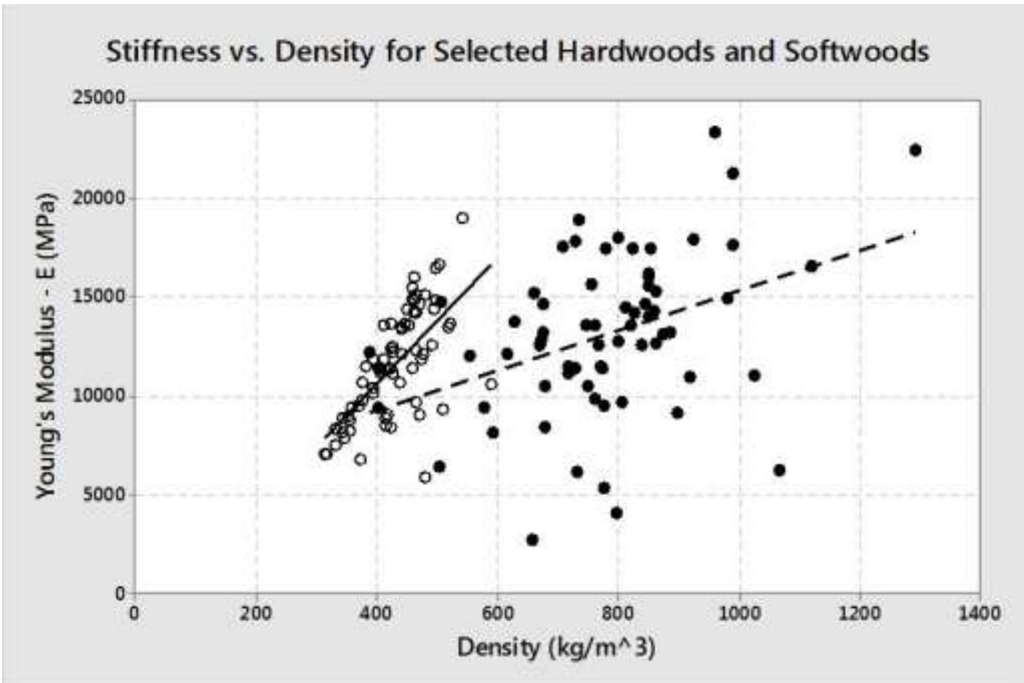

Figure 8: Stiffness vs. Density, Softwoods vs. Hardwoods

Lastly, let's look at stiffness and density for the species that are probably of greatest interest to guitar makers: Various softwood species. I think most of us devote the greatest care to selecting our top wood sets (compared to back and sides wood, neck billets, etc.). Therefore, I find these data of the greatest interest.

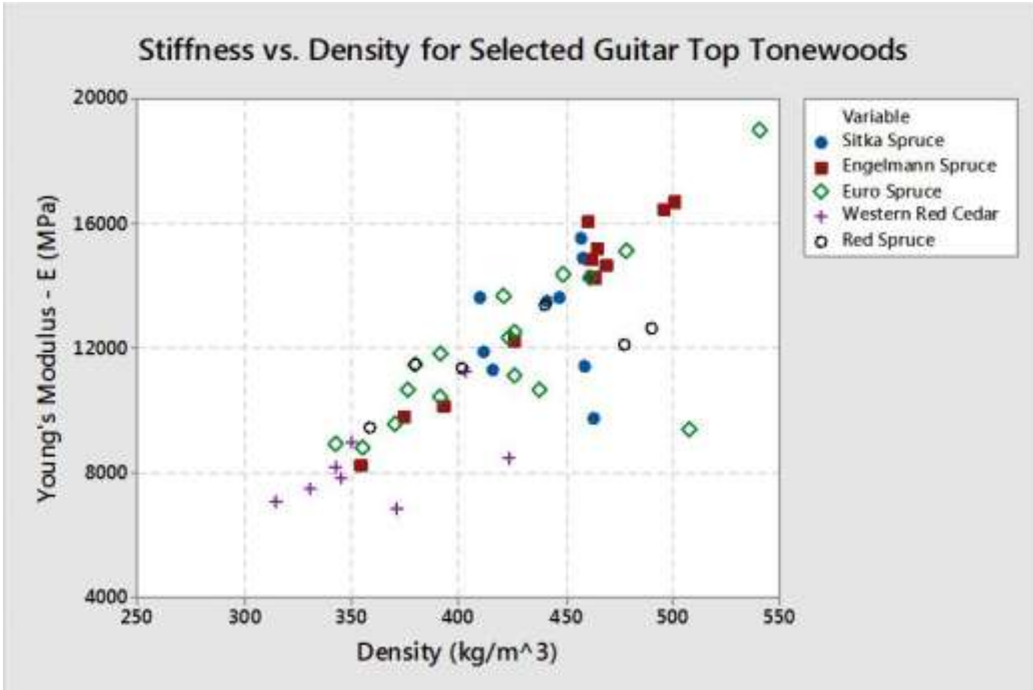

Figure 9 Stiffness vs. Density: Selected Softwood Species

Things to note about the data shown in Figure 9: The data show a tight, linear distribution. They show less scatter than most of the other data. And, most importantly, except for Western Red Cedar (which are all pretty low on the plot), there's not much difference in the properties of the various species of softwoods typically used for guitar tops. (Total samples measured for this graph: 60 samples.)

Making use of the data

So what does all this mean?

My main conclusions are:

1. Wood selection is key to ensuring good sounding instruments. I think we all know this. These data show that variation within a species is as great or greater than variation between species. Looking at these real data confirm that selection is more important that species.
2. Stiffness increases as density increases.
3. As I noted in my article, The Guitar as a Structure, in American Lutherie #100, vibration response 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. 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 repeatably create the sound you like.
4. More data (larger samples sizes) means more accurate data. The data characterize the overall population better. I encourage people to measure their wood and to share those data with the community.

A few caveats

First and most importantly, the data presented here do not cover the third important determinant of vibration response: The internal damping characteristics of the material. These are important for the strength, duration, and overtones of a vibration response. However, there's no convenient way to measure this characteristic of wood. The best we can probably do, from a material properties standpoint, is to measure density and stiffness.

Obviously design is important to the sound of a guitar. That's a big part of why we 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 given design.

I suspect that the softwood samples measured (wood used for guitar tops) were more uniform and of higher quality than the hardwoods. This is because we know that the top is the most important determinant of guitar acoustic response; and we consequently select top woods more carefully than back and sides wood (which are often chosen largely for their visual beauty). I speculate that this is a significant factor as to why the softwoods in this dataset showed a more distinct pattern, less scatter, and great stiffness relative to their weight. (As opposed to randomly chosen samples from a lumberyard, which I would expect to have lower stiffnesses, more scatter, and less distinct difference between hardwoods and softwoods.)

All test systems have errors inherent to the system. Errors accumulate at each step: Each measurement includes some level of error and calculations can also accumulate error[7]. Therefore, no data are exactly accurate. However, 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 inherent in these numbers: Stiffness (Young's Modulus, E), is calculated using measured data such as weight, dimensions, deflections, and resonant frequency. The calculations (well-established formulas for simple structures) used to determine the Young's Modulus 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.

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

---

[7] Due to rounding; and when combining very large and very small numbers.