Sustainability and Life Cycle Management in Guitar Production

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Abstract

The manufacture of stringed instruments has strong elements of traditional practice, particularly in the choice of materials from which the instruments are made. While man-made materials have been used in successful instruments, they are overwhelmingly made of wood. The preferred species include Sitka Spruce, Mahogany, Rosewood and Maple. Furthermore, the grade of materials used for instruments is extremely high, only one step below that used for the load-carrying structures of aircraft. The ideal piece of wood is straight-grained and without imperfections such as knots, checks or discoloration. The growth rings should be close together, so slow-growing trees are preferred. The result is that trees yielding instrument-quality wood have been heavily logged and are becoming very scarce. This is reflected in the rising prices of instrument grade wood. At this writing, a master-grade top blank for a single acoustic guitar can cost up to $300. The retail value of guitars sold in the US is approaching $1 billion per year, so the demand for materials is not going to ease soon.

Clearly, the industry must change its practices if it is to sustain production. Several fundamental changes are required. One is the strong prejudice against laminated materials; high grade plywood exhibits structural properties and uniformity that would make it ideal for instrument manufacture, but its use is limited to student grade instruments. The Convention on International Trade and Endangered Species (CITES) outlines the terms under which traditional species can be legally and sustainably harvested, but it limits production volumes and the temptation to skirt the regulations is strong. Thus, another required change is to switch to fast-growing species. Finally, manufacturing processes must be modified and life cycle management procedures should be implemented to allow for the effective and efficient use of smaller, younger trees.

Introduction

Makers of stringed musical instruments (luthiers) have an increasing problem in securing high quality materials. The traditional top materials, Spruce and Cedar, come from trees more than 200 years old. The traditional side and back material, Rosewood, also comes from old trees and is now protected as an endangered species. The National Association of Music Manufacturers

(NAMM) reports that approximately 813,000 acoustic guitars were sold last year in the United States alone [1] and that the trend is towards increased sales as shown in Figure 1.

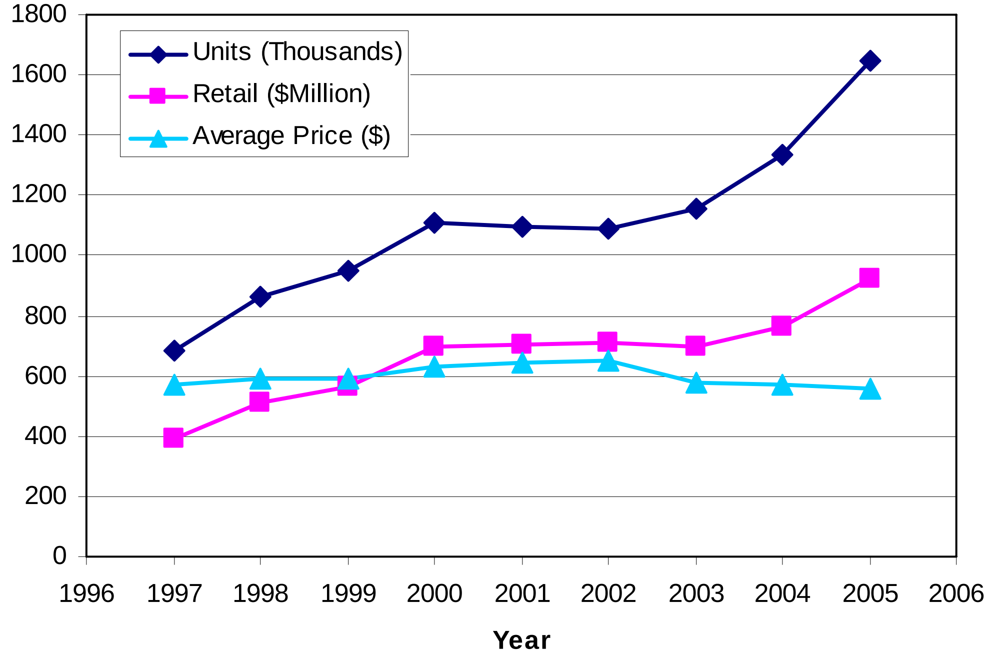

Figure 1: Guitar Production in the United States

It is clear that the unit cost is not increasing. Indeed the increasing market presence of offshore manufacturers is likely to prevent increases in unit cost and may even further drive it down. In this business environment, it would seem critical to identify sustainable materials for high quality instruments. The current practice of using Spruce for soundboards and Mahogany or Rosewood for sides and backs is simply not sustainable. The CITES treaty is a necessary step to preserving the biodiversity of the World's forests. However, it has the practical effect of limiting access to the species of wood traditionally used for making stringed instruments. Specifically, Rosewood and Mahogany are protected under the terms of the treaty and their export from the country of origin is strictly limited.

Figure 2 shows one of the wood storage areas at Taylor Guitars, a major manufacturer of high quality guitars. The company currently makes about 300 guitars per day; availability of materials is not yet a problem, although they do buy backs and sides woods of many different species as they become available. Locating materials is an ongoing process and likely to become a more difficult one.

Figure 2: Wood Storage in a Modern Guitar Factory

Figure 3 shows laser cut Spruce guitar tops at the Taylor Guitars factory. This is only a day or two of stock.

Figure 3: Spruce Tops At A Modern Guitar Factory

Traditional Materials

The range of materials used for acoustic guitars is much broader than that for violins, but is still fairly limited. The tradition established for classical guitars in the middle 1800's is a spruce soundboard with rosewood being used for the back and sides. In addition, the grade of preferred woods is extremely high.

The ideal wood for instruments is quarter-sawn with closely-spaced growth rings. Quarter-sawn boards are cut from the log so the grain is perpendicular to the large side as shown in Figure 4.

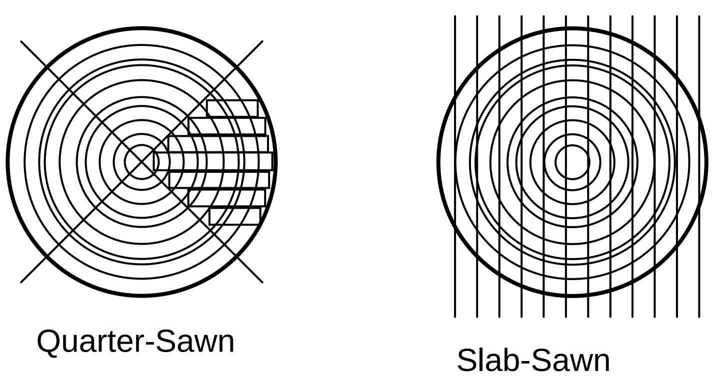

Figure 4: Quarter-Sawn and Slab Sawn Lumber

The vast majority of commercial lumber is slab sawn because it minimizes waste. However, the resulting boards have curved grain lines. As the wood ages, the grain lines tend to straighten and the board tends to cup. This effect is familiar to anyone who has purchased a wide board at a lumber yard. In addition, the mechanical properties of the wood vary as the angle of the grain changes across a plank. Quarter sawn lumber has vertical or nearly vertical grain lines and these grain lines are nearly straight. The resulting boards, when properly dried, are very stable and the mechanical properties are much more uniform that for slab sawn lumber.

In addition to being quarter sawn, high quality instrument grade wood has closely spaced grain lines. This means that the tree must have grown slowly. A favorite species is Sitka Spruce, usually found in the Pacific Northwest. Long winters and cold temperatures mean that the trees grow slowly and the grain lines are close together. Such a tree capable of yielding a piece of wood large enough to make a guitar soundboard is necessarily very old – at least 200 years.

The availability of old trees is problematic for two reasons. The first is that the natural cycle of large areas of forest includes periodic fires that destroy many of the old trees. Thus, many forests simply do not contain trees old enough. The second is that the old growth forests in the United States have been heavily logged since the 1700's [2] and much of the remaining old growth forest land is protected from further cutting. Trees capable of yielding high quality solid wood tops are being cut much faster than they can be replaced.

Generally, it is assumed that the choice of a soundboard material is more important that the choice of materials for the back and sides. A perhaps apocryphal story maintains that Antonio de Torres (1817 - 1892), generally accepted as the father of the modern guitar [3], once made a guitar with a spruce top and a paper maché back and sides to make the point that the soundboard is the most important component in sound production. Acceptance of this idea is reflected in the choices made by producers of high quality instruments. Soundboards are made almost exclusively from Engelmann Spruce, Sitka Spruce, and Western Red Cedar or, less frequently, Redwood. Backs and sides, traditionally made from Rosewood, can be found in a range of tropical hardwoods far too broad to be listed here. Additionally, domestic hardwoods such as Maple and sometimes Cherry and Beech are also used.

There are essentially four alternatives to traditional woods: Alternative old growth species, alternative fast-growing species, laminated wood and man-made materials. Guitar manufacturers are pursuing each of these options. Low cost instruments are often made of plywood while high end instruments are tending toward alternative old growth species. A limited number of manufacturers are using man-made materials, though none currently have a significant market share.

Mechanical Requirements for Guitar Materials

We believe that the focus on Spruce and Rosewood as building materials has as much to do with tradition and customer expectations as it does with acoustics. The conventional wisdom that high quality instruments can only be made from the finest solid wood should not be accepted without some examination. Jose Oribe, a maker of very fine classical guitars states clearly that only the best traditional materials are suitable for high quality instruments [4]. Indeed he maintains that using anything else will not result in a 'legitimate' instrument. His guitars currently sell for more that $10,000 each, so one might be understandably reticent about disagreeing.

However, Bob Bennedetto, a maker of the finest quality archtop guitars maintains that a sufficiently skilled luthier can make a good instrument from just about any piece of wood [5]. To illustrate his point, he made an instrument using a piece of wood from a lumber yard for the top (complete with knots) and an inferior piece of slab sawn maple for the back. He reports that the resulting instrument sounded as good as any of his others. Since his instruments regularly sell for more that $25,000, the market clearly respects his skills. Furthermore, a long list of exceptional performers currently play his instruments, so we can assume that, like Mr. Oribe, he is an expert in this area.

Finally, Bob Taylor of Taylor Guitars (another very successful luthier) made a guitar from wood salvaged from a shipping pallet (Figure 5). This instrument has achieved nearly legendary status among the guitar cognoscenti. Its attraction is such that a limited edition production version was issued and quickly sold out.

Figure 5: The Taylor 'Shipping Pallet' Guitar

Since eminent luthiers have successfully used inferior materials to make good instruments, the mechanical requirements for guitar materials must be viewed as being somewhat flexible. The commonly heard view, and one to which we ascribe, is that very skilled luthiers can make a good instrument out of just about any kind of wood. The rest of us should probably use the best materials we can reasonably afford.

Different components of the instrument have different material requirements. Sides and necks can probably be made from the widest range of materials since their dynamic response characteristics least affect the tone of the complete instrument. It has also been shown [6] that the bending process can dramatically affect the mechanical and acoustic properties of wood, so there may not be much point in selecting side materials for their mechanical properties in the unbent state.

The choice of materials for the soundboard is probably the most critical in determining the tonal quality of the complete instrument. The choice of material for the back is also important, but to a lesser degree [7]. The ideal wood for a soundboard is stiff and light or, in other words, the ratio of E/ρ is high. Note that the speed of sound, c, in the wood (the speed of a non-dispersive wave) is

$$c = \sqrt{\frac{E}{\rho}} \quad (1)$$

Where E is the elastic modulus and ρ is the material density. Note that there is a fundamental difference between longitudinal and bending waves in an elastic material. Longitudinal waves are essentially pressure waves propagating in the plane of the thin top or back plate. Their speed is not a function of frequency and they are termed non-dispersive [8]. Bending waves, on the other hand, are out of plane displacements and their propagation speed is a function of frequency. These are termed dispersive waves.

An additional parameter of interest when selecting a top material is the acoustic constant, A, given by

$$A = \frac{c}{\rho} = \sqrt{\frac{E}{\rho^3}} \quad (2)$$

Much has appeared in the literature about the desired relationship between A, E and ρ for high quality musical instrument wood; a particularly interesting analysis by Rajčan [9], presents the results in a three-axis plot whose axes are A, E and ρ. The box enclosing the points measured for a pool of high quality spruce samples is a small volume inside a larger box enclosing the points measured from a pool of samples made from Spruce. The center of the box lies at $\rho = 427$ kg/m^3, A=13.2 m^4/kg·s, E_L=13.6 GPa.

It is also important to consider the non-isotropic nature of wood. The strength and stiffness of most woods is much higher the grain direction (longitudinal) that across the grain. The microstructure of wood is very similar to that of a synthetic unidirectional composite material such as graphite or fiberglass. This makes it well suited to instrument tops since a top must be strong and stiff in the string direction (to resist loads created by string tension) while being relatively flexible in other directions (to move and thus radiate as a result of string vibration).

The traditional wood, Sitka Spruce has an elastic modulus along the grain of approximately 11.7 GPa (1.72 Mpsi) and a specific gravity of approximately 0.40 ($\rho = 400$ kg/m^3). The ratio of longitudinal to cross grain (transverse) modulus of elasticity is $E_L/E_T = 23.3$. Western Red Cedar has an elastic modulus along the grain $E_L = 8.41$ GPa (1.22 Mpsi) and a specific gravity of approximately 0.32 ($\rho = 320$ kg/m^3).

In addition to the mechanical properties, instrument wood should have desirable acoustic properties. Being a porous material, wood absorbs and reflects sound waves as a function of their frequency. One of us (French, see Figure 6) owns a guitar with a single piece plastic component forming both the back and sides. The tone is surprisingly good for an instrument with a small body volume as this instrument has. This may have to do with the fact that the back and sides are lined with thin wood strips of some unidentified soft species.

Figure 6: Acoustic Guitar with Plastic Back/Sides and Wood Lining

Note that the acoustic properties of the wood are most important on the inside of the sound box. It is very rare to apply any type of finish to the inside; Benedetto is the only builder of which we are aware who does so and he applies only a thin sealing coat of shellac. The acoustic effects of a hard, smooth finish are well-documented in the literature [10-13] and a lively conversation on this topic among the luthiery community shows no sign of fading. Kopač and Šali [14] have even shown that the process by which wood is machined can have a discernable effect on the sound quality.

Alternative Materials

Clearly, the current practice of using solid wood whose supply is very limited cannot continue, at least not on the scale required to meet the vast majority of the market demand. There are roughly four possibilities for alternative materials:

- Alternative Old-Growth Species
- Alternative Fast-Growing Species
- Laminated Wood
- Synthetic Materials

Alternative old-growth species have been used for decades. Redwood has become popular for classical guitar tops and a wide range of tropical hardwoods has been used for backs. Classical and Flamenco guitars have been made with Spanish Cedar and Cypress since at least the early 1900's. However, the very nature of old-growth wood the commercial demand for large numbers of instruments means that this approach is not sustainable.

We speculate that a limited amount of old-growth wood will always be available, though at very high prices. Even now, master grade top blanks can easily cost more than $100 each and master grade backs can cost more than $200. Especially fine top and back blanks are often sold individually and their use can easily add $500 in materials costs alone. We believe that the market for these materials will be limited to very expensive custom made instruments or those produced in limited quantities. The average cost for an acoustic guitar in the United States is currently $500-$600 – just the material costs for an instrument made of solid, old-growth wood can exceed this.

An obvious alternative is to use the large stocks of fast growing soft wood species being farmed on a sustainable basis for use as dimensioned lumber and wood pulp. We know of no manufacturer making use of fast-growing softwoods for guitars. However, one of us (French) has had success in making soundboards and necks from spruce cut from lumber yard 2x12 planks and from Cedar cut from commercially available fence posts. By carefully selecting commercial lumber and joining suitable sections, a reasonably high quality, quarter-sawn tap blank can be manufactured. Figure 7 shows a pine board purchased from the bargain bin at the local home center for $0.69. It has sections that are close-grained and quarter sawn.

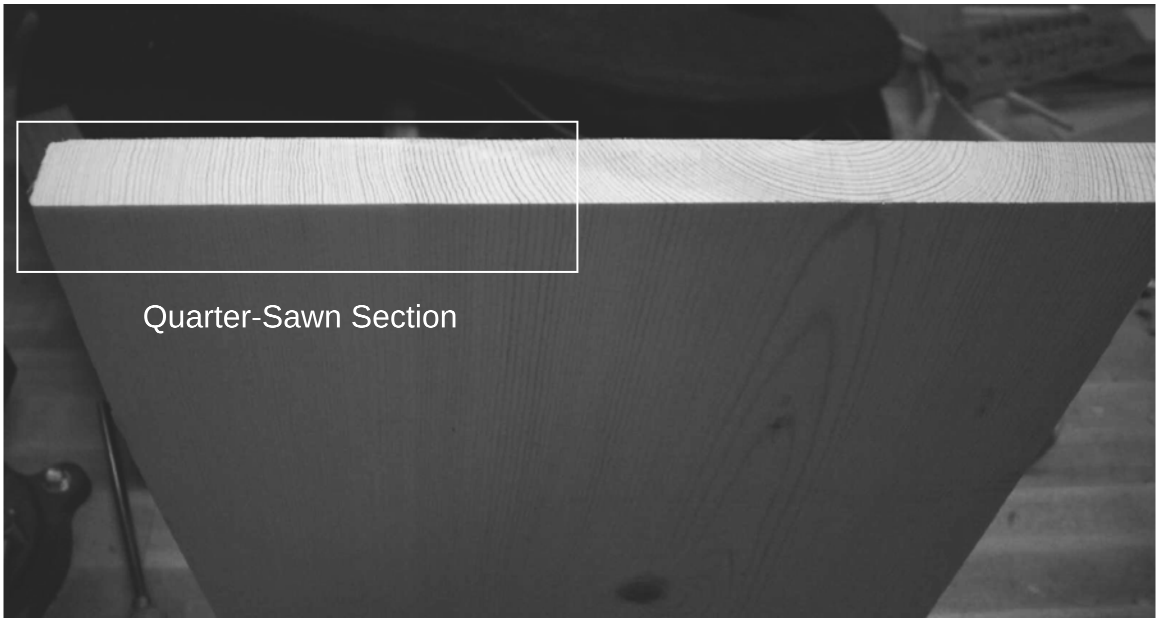

Figure 7: Commercial Plank Containing Section of Instrument Grade Wood

The desire to have closely-spaced grain lines necessarily means using younger and smaller trees. However, going from a two-piece top, as is the current practice, to a four-piece top drastically reduces the required size of the tree. The practice gluing several pieces of wood together to create a top blank wide enough for use as a top plate is not uncommon. Benedetto uses this method regularly on his instruments and Antonio Stradivari did this on some of his most celebrated violins [15]. This would seem an acceptable precedent for even the most critical customer.

The mechanical properties of Eastern White Pine are close to those suggested for guitar tops of Spruce and Western Red Cedar [16]. E_L = 9.38Gpa (1.36Mpsi), specific gravity is 0.35 (350 kg/m^3) and A = 14.8 m^4/kg·s. Additionally, slight changes in the top bracing pattern should be able to account for remaining differences in the completed instrument due to the mechanical properties of the wood. Figure 8 shows a small, 8-string instrument made by one of us (French) using clear Sugar Pine salvaged from a shipping pallet. In spite of the non-traditional design and materials, the completed instrument has a pleasing tone and is now owned by an accomplished musician.

Figure 8: A Small, Non-Standard Instrument Made With Salvaged Soft Wood

The next possibility for alternative materials is laminated wood (plywood). Plywood is already being used for low and medium-priced instruments. Often, its use is hidden by applying a thin veneer of spruce or maple to the visible surface. The most obvious mechanical difference is that plywood is orthotropic since the different plies are almost always orthogonal to each other. A less obvious characteristic, though, is that high quality plywood is extremely uniform and free of structural defects.

Marine grade plywood is approved for use in boat hulls and aircraft grade plywood is approved for use in the load-carrying structure of man-carrying aircraft. Both have been in widespread use since the early 1900's and would seem ideal materials for musical instruments. One of use (French) regularly uses high grade Birch and Mahogany plywood in stringed instruments and the results have been quite encouraging. Figure 9 shows top blanks cut from aircraft grade Birch and aircraft grade Mahogany.

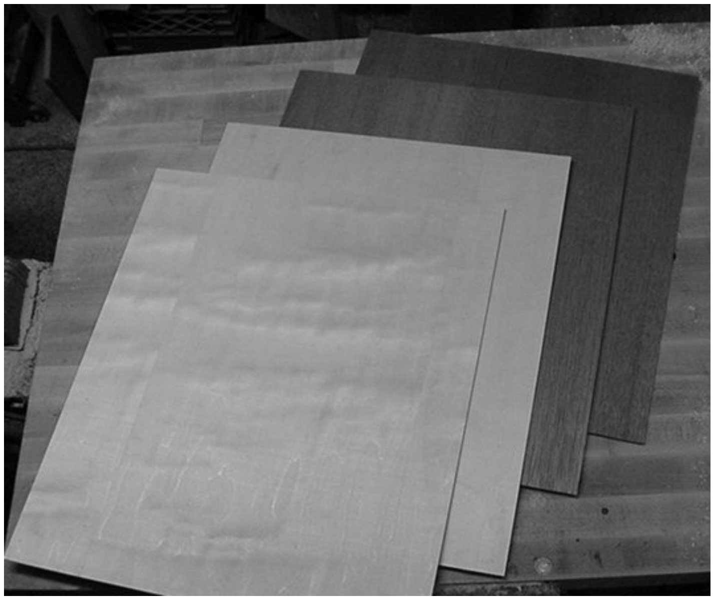

Figure 9: Top Blanks of Aircraft-Grade Plywood

Plywood offers benefits that can not be ignored. It is sold in standard sized sheets, so it is convenient for large-scale production in which jigs and programs for CNC equipment represent a significant cost to be amortized. Its remarkably uniform material properties naturally reduce build variation in the completed instruments. Anyone familiar with large-scale production knows that build variation is inversely related to build quality. Plywood also offers design freedom not possible with solid wood. Figure 10 shows side blanks used by Taylor Guitars for some of their instruments. The pre-formed, laminated sides are provided by a supplier in long sections. The manufacturer has only to slice off pieces of the correct width in order to have precise, uniform instrument sides.

Figure 10: Preformed Laminated Guitar Side Blanks

The final option for alternative materials is man-made synthetics, usually fiber reinforced composites. Several companies have made guitars with significant amounts of reinforces plastics. Perhaps the best known is Ovation (www.ovationguitars.com), a company that has been making guitars with composite tops and bodies since the 1960s. A more recent development is Rainsong Guitars (www.rainsong.com), which makes instruments with all graphite construction. Figure 11 shows part of a graphite top blank for an Ovation guitar. An off-axis wood veneer is sandwiched between sheets of unidirectional graphite. One of us (French) has had the opportunity to play a Rainsong instrument and found the tone to quite good.

A limited amount of work on synthetic tops and backs has appeared in the literature. Work had addressed both completely synthetic tops [17, 18] and of hybrid materials made of natural wood that has been processed and impregnated with a plastic-like material [19-22]. We know of no reason that synthetic or largely synthetic materials cannot be used to make high quality guitars. We suspect that the principal is acceptance by customers conditioned to expect instruments made of master grade wood.

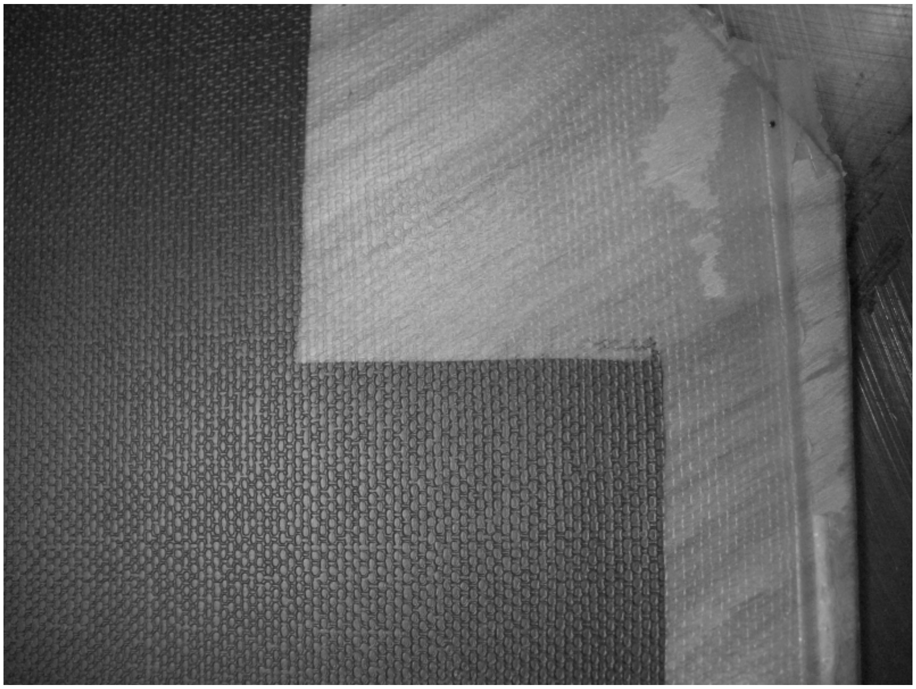

Figure 11: Close-up of Composite Top Blank

Lifecycle Management in the Guitar Manufacturing Industry

Lifecycle management techniques, devised in order to manage the product from "cradle-to-grave", should be implemented in the guitar manufacturing industry whether or not the type of wood used is significantly altered in the short-term. These techniques provide for more effective and efficient production in almost every industry from the product design stage to the material eventual recycling/reuse. The process involves an ideology that is focused on making the engineering process more streamlined, with less need to repetitively modify the prints and specifications for a particular product (e.g., guitars). An effective lifecycle management program can be significant complementary component of any successful sustainable manufacturing effort.

Summary

The guitar manufacturing industry is dependent on a supply of fine tonewoods that simply cannot be maintained. It is critical that manufacturers identify high quality alternatives and that the resulting instruments can be shown to have superior tonal qualities. We have examined the mechanical requirements for tonewoods and explored four possibilities for alternative materials. We know of no reason why alternative, sustainable materials, coupled with a successful manufacturing lifecycle management program, could not be used effectively to make instruments of very high quality.

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