The Rise and Fall of Iconic Guitar Tonewoods and Evaluation of Alternative Species

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Declaration

I do hereby declare that this thesis was composed by myself and that the work described within is my own, except where stated otherwise.

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Abstract

The future use of traditional tonewoods in the art of lutherie is at a critical juncture. The over-utilization of tropical hardwoods is forcing guitar makers to consider suitable substitutions for the wood species that have become iconic for concert quality instruments. The historical evolution of material selection was examined to determine how and why certain woods became de facto in the art of lutherie. Objective testing methods were designed to quantify the properties essential to material selection and provide a benchmark to compare potential substitutes. Different wood species were subsequently tested to determine their suitability for substitution. A blind test was carried out to demonstrate the indistinguishability of guitars made from different woods having similar physical and vibrational characteristics. The results indicate that a specific wood sample's physical and vibrational characteristics are more important than the wood’s identity.

This thesis explores the historical development of the guitar in terms of the evolution of the iconic woods preferred for use in concert quality instruments. With the potential loss of access to these woods due to overutilization and subsequent international trade restrictions, the research goes on to define their physical and vibrational qualities to establish benchmarks by which alternative species can be measured. The objective testing methods devised in the research are based on the traditional subjective methods used for centuries by luthiers to ascertain wood quality. In addition, the testing methods were designed so that they could be easily replicated by other luthiers. Finally, four guitars were made by the author in an identical fashion except for their back and sides. Two of the guitars were made from a threatened resource, Indian rosewood, while the other two instruments were made from a currently sustainable resource, African padauk. The woods selected were matched as closely as possible in terms of their physical and vibrational properties. The test determined that instruments made from wood with nearly identical physical and vibrational properties are indistinguishable in a blind performance test by experienced guitarists.

Acknowledgments

I would first like to thank the **University of Edinburgh** for providing me the opportunity and support to pursue the research contained herein. Their postgraduate by research program allowed me to concentrate specifically on the answers to questions that have arisen in my 20 years as a luthier. I suspect **Dr. Darryl Martin** had a substantial role in advocating for my acceptance. His background in musical instrument manufacture and particular interest in guitars made him an ideal supervisor at the outset of my study. In addition, Dr. Martin had the foresight to recognize the increasingly scientific direction my research was headed and suggested the addition of **Dr. Murray Campbell** as a second supervisor. I will be forever grateful for Dr. Campbell "setting me straight" in my scientific perspective and the contribution he made in guiding my research. I am quite certain, though, that the content contained herein would not have achieved a level of "academic rigor" without the guidance, input, and insistence by my primary supervisor, **Dr. Mike Newton**. I would further like to express my gratitude to Dr. Newton for the patience he demonstrated bringing me along as I progressed in my use of physics for wood testing and analysis.

I would also like to acknowledge the gracious contributions from those outside the University of Edinburgh. In addition to much enlightenment regarding string instrument physics, **Professor Woodhouse** suggested the framework for the blind test in Chapter 12. Friend and colleague **Daniel**

Wheeldon introduced me to the greater instrument research community from which much can be gleaned, and eventually contributed. In fact, much is owed to the greater luthier community that has always shared its own ideas, techniques, and resources without reserve to further benefit the industry as a whole. For me, no single individual has been more central to my success than master luthier **James Olson**. He did not teach me everything I know about making guitars, only the stuff I do well. I have long endeavored to contribute something back to the luthiery community, as it has given me much.

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Section I

Section I explores the historical development of the guitar from its inception and provides an overview of the vibroacoustic concepts that are pertinent to the successful function of the guitar as a musical instrument. While combining these very disparate topics in the same section might seem a bit incongruous, each topic builds a foundation of insight that eventually transcends to the analysis and experiments contained in Section II.

Chapter 1

Introduction and Intent

1.1 Background

The guitar, as we know it today, traces its inception back to the fifteenth century vihuela [Romanillos and Winspear 2002]. It was in this first archetype that this novel instrument took on the unmistakable hour-glass shape that differentiated it from other plucked chordophones. Over the span of more than five centuries, the instrument has evolved in size, design, architecture, number of strings, and conventions in material selection. Preserved relics provide a record of the physical metamorphosis, but little remains of the thought process behind these changes, especially during the guitar's early years. In the preface to *The Guitar from the Renaissance to the Present Day*, Harvey Turnbull [1974] laments, "If the general histories were uninformative, a little research revealed that many of the specialist books were positively misleading in their promulgation of legends and misrepresentations of historical fact." Turnbull succeeds in his research to account for many of the guitar design changes, often citing cultural musical predilections to motivate instrument modification, particularly in terms of adopted stringing conventions. However, while Turnbull provides descriptions of materials used for historical guitar components, the decision process behind their selection remains unanswered. In *Guitars: Music, History, Construction and Players from the Renaissance to Rock*, Evans and Evans [1977] offer a similar account of the guitar's history but delve no deeper into material selection other than to suggest a guitar had high initial value due to the price of the woods used in construction. What is lacking from historical accounts is the analysis behind material selection as the instrument evolved.

Early luthiers were forced to rely on the timber species indigenous to their proximity before the proliferation of non-domestic trade. However, as availability to the woods of the world commenced with the opening of trade routes at the dawn of the sixteenth century to Africa, Asia, and the New World, it is intriguing to ask how and why did tropical hardwoods come to dominate every aspect of the guitar, other than the soundboard? Around the time that Antonio de Torres (1818-1892) amalgamated what is currently known as the "modern" guitar in the mid-nineteenth century, concert-level instruments were most likely to be made with ebony fretboards, Spanish cedar or mahogany necks, ebony or rosewood bridges, and rosewood back and sides. To this day, these same materials are often viewed as a differentiating clue as to the quality level of a specific instrument. As such, rosewood, ebony, Spanish cedar and mahogany are held in iconic status by luthiers and guitar consumers alike. Modern-day guitar aficionados insist that the ultimate performance of an instrument depends on the inclusion of these woods in its construction. However, centuries of overutilization and poor timber management practices have diminished these natural resources to the point of putting their future viability in question. The guitar community is faced with the possibility of losing those species that, within established convention, are seen as helping to create exceptional instruments.

This threat to the guitar's quality reputation comes not only at a time of great popularity for guitars in general, but also during a renaissance in craftsmanship that has elevated guitars from leading luthier's instruments to a status approaching that of the traditionally revered bowed instrument luthiers.

This premise is evidenced by the sheer number of independent guitar luthiers currently supported by this micro-economy and the prices commanded for instruments by renowned luthiers. A loss in confidence by the consumer regarding quality could spell the end of what master luthier Rick Turner [2000] termed “The New Golden Age” of handcrafted guitars. The long-term success of guitar luthiery may depend on interrogating, and potentially debunking, the prejudices towards established wood species that have developed through centuries of adherence to tradition.

The modern-day assumption is that the master luthiers of the nineteenth century effectively determined which woods exhibited the highest suitability to purpose in guitar construction. The comprehensive objective of this research is to investigate the merit of this assumption. From this, the following questions emerge:

(1) Why did certain woods become *de facto* in various guitar making applications?

(2) To what extent are the most well-renowned “established” woods critical to the success of the guitar in performing at the highest level?

(3) Can other more sustainable woods perform in a comparable, or even superior, fashion to the established woods?

Exploring these research questions may not only be of benefit to the future of guitar luthiery but may also help to reduce some of the consumption pressure on threatened tree species.

It may seem incongruous to research the guitar's history and construction without devoting the bulk of attention towards what is arguably the most important component, namely the soundboard. Admittedly, the soundboard is indeed the most essential aspect of the guitar in terms of sound radiation. As such, the bulk of academic chordophone research to date has focused primarily on instrument soundboards. This research takes a decidedly different tack. The impetus for this research is the growing uncertainty regarding the future of the tonewoods commonly used in guitar construction, particularly for the components other than the soundboard. The overutilization of the conventional tropical hardwoods used for the guitar's neck, fretboard, bridge, and back & sides necessitates assessing the mechanical and vibroacoustic properties of non-threatened wood species to find suitable alternatives.

Limiting the specific attention paid to the soundboard should not be construed as an attempt to disparage its importance. The limited attention is more the result of focusing on those wood species with threatened futures. Since time immemorial, various spruce species (*Picea spp.*) have been the overwhelming preferred choice for soundboard use. More recently, Western Red cedar has also become popular, albeit to a lesser extent, for guitar soundboard use. Fortunately, at least at the time of this writing, the future availability of spruce and cedar is relatively secure. Even so, through the process of developing selection criteria for the guitar's structural components for this research, a process to improve material selection for the soundboard was developed and is thoroughly described in Chapter 10.

As mentioned previously, prejudices towards the specific wood species used for guitar components have developed through centuries of adherence to tradition. Compounding this prejudice is the inclination of human nature to believe that if something is rare and expensive, it must be superior. This tendency was reinforced throughout the twentieth century by guitar manufactures tendency to include expensive woods on their top-of-the-line models. The natural reaction by a consumer would be to question the quality of a maker's high-end model if those prized woods were suddenly substituted with an unfamiliar wood species. This condition embodies the most significant obstacle for the successful introduction of sustainable wood species into guitar luthiery, especially on concert level instruments. Adherents of tradition would likely receive mere subjective testimony of equality with great skepticism. A greater chance of success would necessitate a large body of objective research to provide unequivocal proof of equitability. The research in this thesis aims to join a growing body of work investigating how different wood species affect the guitar as a sound-producing musical instrument.

1.2 Scope of Thesis

The research contained herein is divided into two sections. Section I, Chapters 1-6, provides an overview of the vibroacoustics of the guitar and the historical development of the instrument from its inception to the current era. Chapter 2 contains a background overview of guitar vibroacoustics to illustrate the guitar's components in detail and provide a basic understanding of some key vibroacoustic concepts that pervade the subsequent chapters. Chapter 3 examines the guitar’s 600-year evolution primarily in terms of the historical events that enabled the instrument to proliferate and prosper. The entire history is broken down by musical eras to help delineate the dominant forms the instrument exhibited throughout history. The primary factors explored to establish inferences were political and socio-economic conditions, era-centric cultural-artistic predilections, technological advancements, and the development of music styles specific for the guitar. Chapter 4 introduces the tropical hardwoods that would come to dominate the structural components of the guitar. This section considers the impetus and important markets that initiated their introduction to Europe from their trans-oceanic origins of Africa, Asia, and the New World. Chapter 5 details the traditional application of different hardwoods in lutherie. This analysis also establishes a status hierarchy between species based on their cultural reverence within the furniture market. Chapter 6 introduces the subjective and objective criteria by which tonewoods have traditionally been judged for application to the guitar's specific components. While this research strives to remain strictly objective in its analysis, this section accounts for the subjective visual appeal and status epitomizing specific wood species, lending them particular esteem. More to this research's nature, Chapter 6 breaks down the guitar into specific components to analyze the essential properties that selected woods need to satisfy.

Section II, Chapters 7-12, compiles a set of experiments, examinations, and analysis to compare various alternative wood species' suitability for specific guitar components. The bridge, fretboard, neck, and backplate were considered separately for their function and requirement to perform optimally. Using the mechanical properties of woods traditionally used for these components as benchmarks, alternative species were objectively compared to determine their suitability to purpose. Finally, Chapter 13 summarizes the research of this thesis in terms of the historical evolution of material selection and the objective testing of materials for use in the guitar.

1.3 Objectives

Material selection for the components of the guitar has largely been constrained by an adherence to tradition. Conventional wisdom in the luthier community assumes that the wood species paradigm established in the middle of the nineteenth century is the full realization of the material selection evolution to achieve the guitar's optimal performance as a musical instrument. The threatened future of the traditional tropical hardwoods used in luthiery precipitates an urgent need to assess their presumed superiority and determine whether non-threatened species can perform as equal, or even superior, alternatives. This research endeavors to objectively analyze various wood species to determine the optimal wood candidates for specific roles in the guitar’s construction. For each of the studied guitar components, the mechanical properties critical to their function are identified and defined. Analytical methods are established to compare candidate species on measurable metrics. The testing methods were explicitly designed to enable easy replication by other researchers or those in the luthier industry. Finally, the tests' results provide quantifiable analysis for traditional and alternative wood species' role-specific functionality.

Chapter 2

The Acoustics of the Guitar: Components, Systems, Metrics, and Terms

2.1 Background

Even though this thesis focuses primarily on guitar woods, much of the criteria for specific material selection were developed based on the fundamental principles of vibroacoustics pertaining to sound propagation by the guitar. This section provides a general overview of the science behind the mechanisms responsible for guitar sound production and identifies their implications in terms of material selection. These preliminary concepts are referred to throughout the entire thesis and are particularly relevant in the testing and analysis chapters contained in Section II.

While the guitar's outward appearance is commonly recognizable, as shown in Figure 2.1, there are nuances in its construction that are often taken for granted or hidden from view.

Chapter 2 - The Acoustics of the Guitar: Components, Systems, Metrics, and Terms

Figure 2.1. Steel-string guitar by Applegate Guitars. Photo by author.

By deconstructing the familiar image in Figure 2.1, the guitar is an assembly of components, each critical to the instrument's success in terms of producing sound, providing a structural resistance to tensioned guitar strings, or a combination of the two. Figure 2.2 illustrates the separate components in various states of production that are ultimately used to construct a typical steel-string guitar.

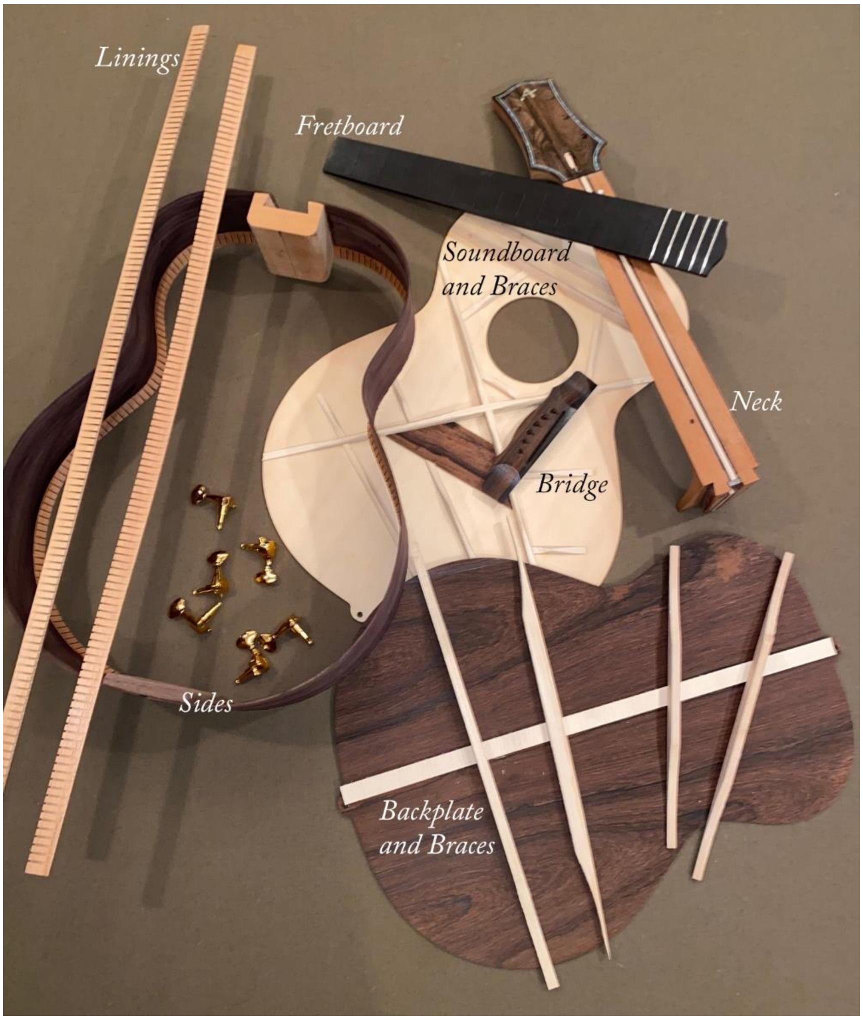


Figure 2.2. Deconstructed view of the components that make up a typical steel-string guitar. Photo by author.

Of particular interest in Figure 2.2 is the ability to view the finished bracing of the spruce soundboard and implicit bracing of the rosewood backplate that is otherwise obscured when viewing Figure 2.1. When referring to a finished instrument's soundboard, it is actually in terms of the coupled system created by the soundboard plate, the braces, and the bridge. Each of these separate components will have an effect on the soundboard's overall ability to vibrate and radiate sound. This assertion also applies to the backplate and its braces, the sides, and the neck-system (which is ultimately composed of the neck, fretboard, and, in the case of a steel-string guitar, the steel truss-rod). Absent from Figure 2.2 is the one indispensable component that is fundamental to the guitar's ability to function as a musical instrument, the guitar string. Moreover, since the guitar string initiates the entire vibroacoustic process of the guitar, it is only fitting that the implications of string energy be dealt with first.

2.2 String Energy

The guitarist's ultimate intent is to generate sound at specific frequencies to produce a pleasing aural experience defined as music. The initiation of this process begins with a plucked string. The note one hears is determined by the mass, stiffness and tension of the string being plucked. However, the actual vibration of a plucked string is made up of many harmonic components, even though a listener unconsciously compiles all the components and recognizes them as a singular note [Fletcher and Rossing 1998]. For instance, consider the guitar's "A" string, which is typically tuned to 110 Hz. When this string is set into vibrational motion, not only will it vibrate at a frequency of 110 Hz, but it will also vibrate at frequencies that are multiples of 110 Hz. Figure 2.3 illustrates the frequency components of the "A" string, through analysis of the frequency spectrum of a recorded string pluck.

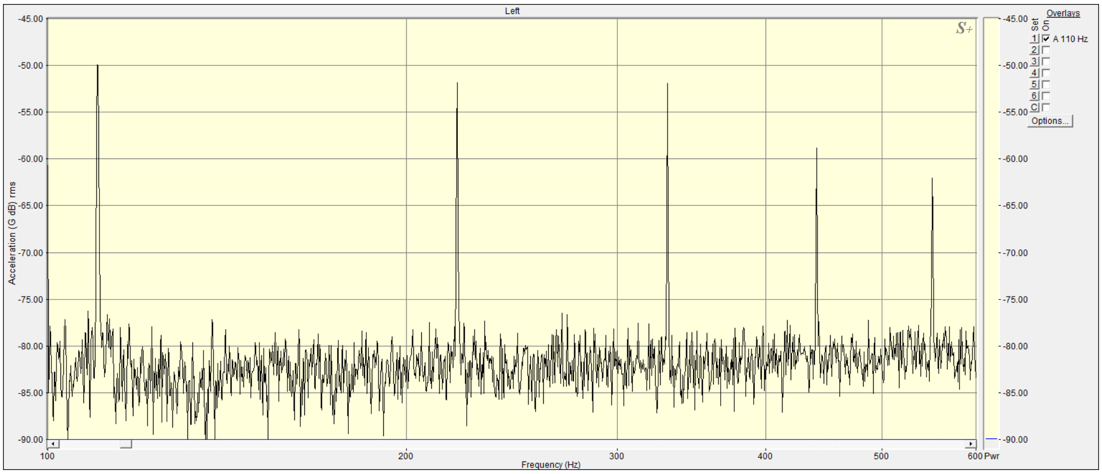


Figure 2.3: A plot of the vibrational modes produced by a plucked "A" string (110 Hz).

Of particular importance is the understanding that the many frequencies simultaneously excited when a guitar string is plucked collectively represent the energy available for the guitar to emphasize (e.g. through efficient sound radiation) or de-emphasize (e.g. through internal energy dissipation), based on the specific instrument's vibroacoustic characteristics. All string variables being equal, it is the frequency response of a specific guitar that will, in the end, determine its idiosyncratic volume and tone attributes [Gore and Gilet 2011]. However, the frequency response depicted in Figure 2.3 was recorded using a rig specially designed to omit any of the additional body resonances of a typical acoustic guitar so that only string modes would be captured. See Figure 2.4.

Figure 2.4: A photo of a solid bar-stock aluminum string rig. Because the bar-stock is so stiff, its mechanical resonances are sufficiently high in frequency to effect relatively little influence upon the vibration of the string in the frequency range of interest to human listeners, and subsequent sound radiation characteristics. Hence, the string is essentially "isolated", allowing for analysis of it in a largely de-coupled state. Photo by author.

The dissipation of string energy is another consideration central to a guitar’s identity. There are three factors that determine string energy decay: (1) string vibration damping due to “viscous air-drag”, (2) string vibration damping due to internal friction factors at a molecular level, and (3) energy loss to end supports [Errede 2017]. The primary consideration for this research is energy loss to end supports as this physical mechanism is, in fact, responsible for the eventual sound production by the guitar. However, for a further examination of string damping due to viscous air-drag and internal mechanisms, Fletcher and Rossing [1998] provide an in-depth elucidation.

The eventual flow of string energy through the entire guitar is outlined in Figure 2.5.

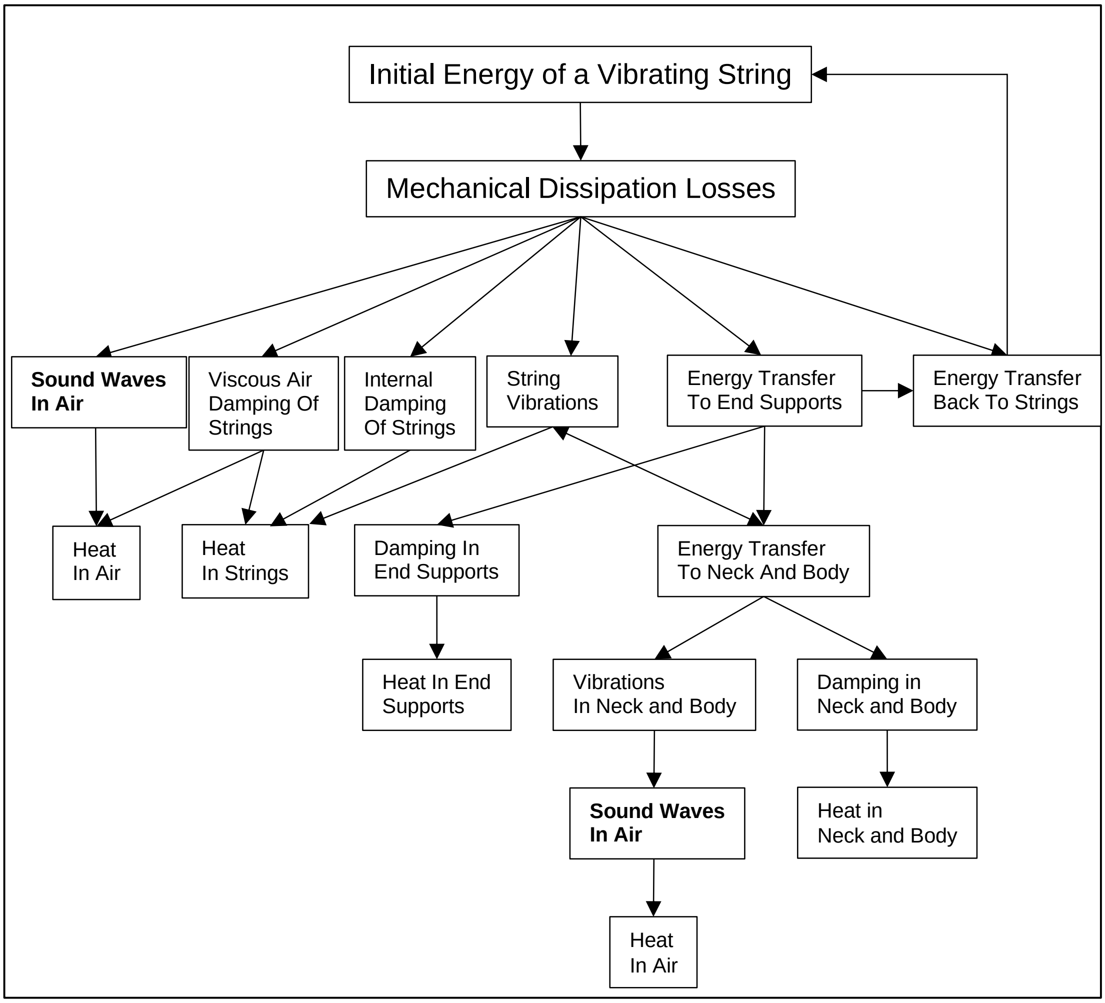


Figure 2.5: Flow chart demonstrating the transfer of vibrational energy from a plucked string to the significant components. Modified from Errede [2017].

The most obvious detriment to directing vibration to the ultimate goal of producing sound waves in the air are the various damping mechanisms. These mechanisms, in effect, waste vibration that could have otherwise been directed to sound-producing components. Unfortunately, the damping mechanisms associated with the guitar string are inherent to their behavior in a real-world scenario and cannot be avoided. The damping mechanisms associated with the guitar, in contrast, can be exacerbated or mitigated through material selection and structural design.

2.3 Guitar Systems

As indicated in Figure 2.5, the guitar string is coupled to the instrument via two end supports, the neck and soundboard structures. The neck structure is composed of the actual neck, the attached fretboard, and metal frets that have been seated into narrow slots. The soundboard consists of a thin soundboard plate, internal braces, and bridge. While the bridge acts as the attachment point for the strings, it also acts as a primary structural brace for the soundboard and significantly influences the soundboard structure's eventual vibrational properties. From these two structures or systems, string vibration is distributed throughout the rest of the instrument [Somogyi 2009a]. A detailed representation of this vibration flow is illustrated in Figure 2.6.

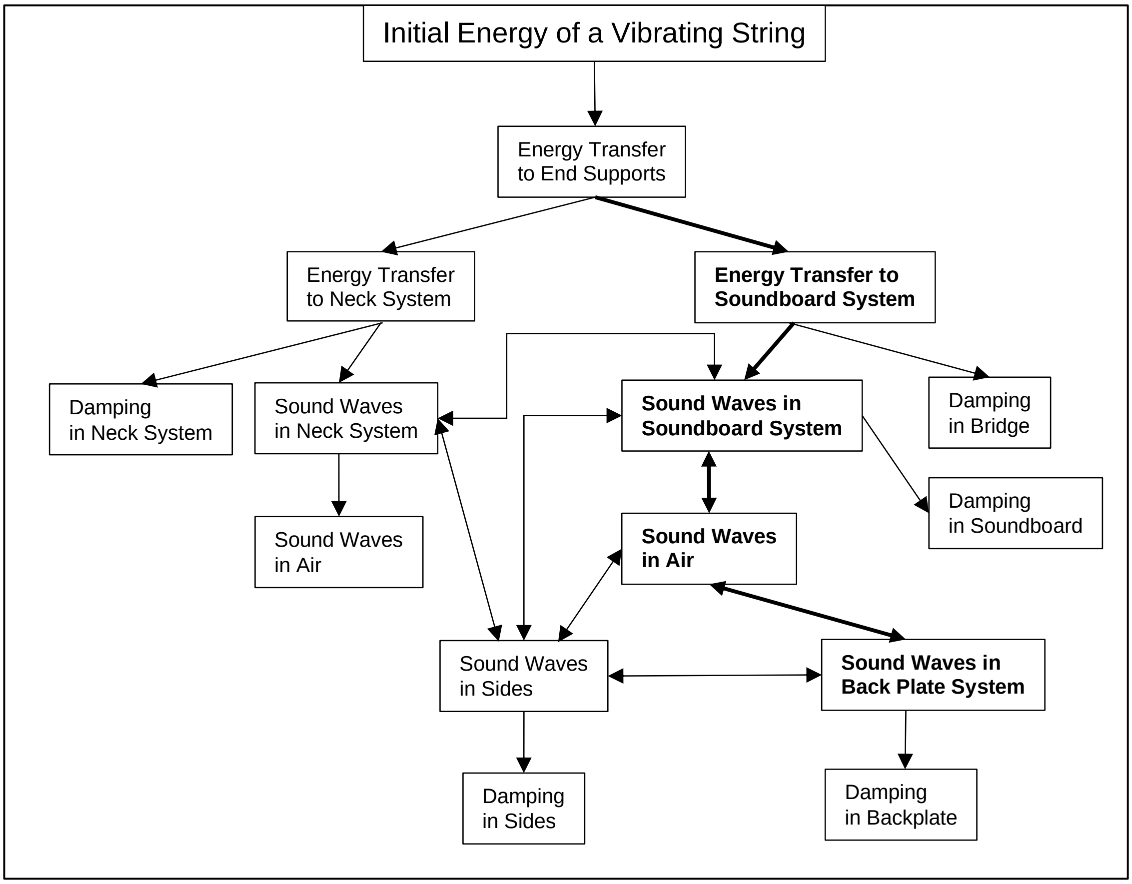


Figure 2.6: Detailed flow chart of string vibration transfer through a guitar's components.

Figure 2.6 was drawn so that optimal vibration transfers and results are indicated in bold. It is commonly accepted that the soundboard system is the most efficient producer of sound waves, which is why vibration transfers to the neck system and guitar sides are not included in bold. One of the luthier's intentions is to mitigate the vibration transfer to the neck system and sides by the addition of mass and stiffening elements to reduce vibration admittance [Somogyi 2009a; Gore and Gilet 2011]. The result is the direction of string vibration to the three resonating systems of primary importance to the luthier, the soundboard system, the air cavity inside the guitar body, and the backplate system.

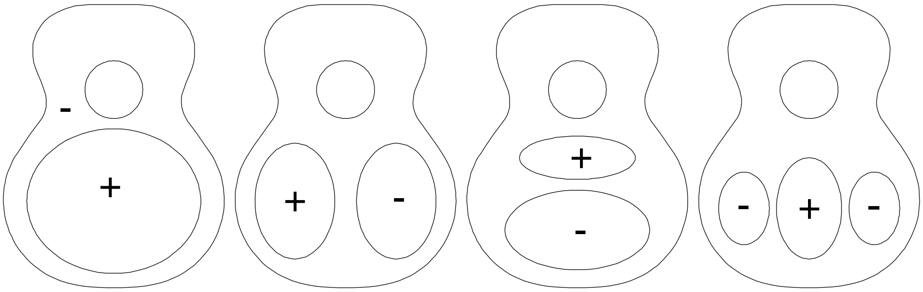
2.4 Coupled Resonators

Efficient production of sound from a guitar comes from effective operation of the soundboard, internal air cavity, and backplate resonating systems which collectively rely on mechanical and pneumatic coupling mechanisms in order to properly contribute to the guitar's sound, volume, and tone. In a most simplistic description, the soundboard's vibrations excite air vibrations in the guitar's internal cavity, which in turn excites vibrational resonance in the guitar’s backplate; sound is subsequently radiated from the soundboard, soundhole, and backplate. The combination of these resonating systems contributes to the sound produced by the guitar. More specifically, these systems' frequency response will determine the overall tonal characteristics of a specific instrument [Campbell and Greated 1987]. Moreover, each system requires individual attention, alongside consideration of the overall coupled system.

2.4.1 Soundboard System

In addition to being the guitar's primary sound producer, the soundboard also acts as the gateway for string energy transfer. Simply, a high-mass/high-stiffness (i.e., high impedance) soundboard will resist string energy transfer while a low-mass/low-stiffness (i.e., low impedance) soundboard will accept string energy at a higher rate. To further illustrate the concept of **impedance**, consider it with its antonym **admittance**. String energy that is admitted to the soundboard is subsequently used to set it into motion to create sound waves in the air, whereas string energy that is impeded gets reflected back to strings. The implications of these two scenarios illustrate the balance of volume versus sustain that is managed in the building process by the luthier. Efficient radiation of sound comes with a resulting decrease in sustain as string energy is transferred to excite the soundboard, and then into airborne acoustic waves. An excellent example of a low impedance stringed instrument is the banjo, which produces a loud but short sustaining note when a string is plucked. On the other end of the spectrum is the solid-body electric guitar that produces minimal airborne acoustic sound due to its rigid bridge and body mass, but which typically exhibits a much longer sustain.

Also significant is the effect the soundboard system will have on the guitar's tonal characteristics when played. The soundboard's combined vibrational behavior can be broken down into distinct spatial patterns of large/small transverse motion that are termed normal modes of vibration. These patterns can be witnessed visually when a particular mode is excited at its given frequency. Figure 2.7 illustrates the first four normal modes of vibration obtained by Gore and Gilet [2011] for an X-braced steel-string guitar.



Top Monopole	Cross Dipole	Long Dipole	Cross Tripole
181 Hz	304 Hz	404 Hz	448 Hz

Figure 2.7: An illustration of the vibrational patterns, phase relationships, and fundamental frequencies of the first four modes of vibration for a guitar soundboard. Data for frequencies provided by Gore and Gilet [2011].

The vibrational patterns illustrated in Figure 2.7 establish themselves when the top plate is driven by the frequency indicated for each mode. The phase relationship describes the directional movement of vibrating regions relative to each other (i.e., when the "+" region is moving up, the "-" region is moving down and vice versa). While the existence of these modes is invariable in typically constructed guitars, the specific characteristic mode size, shape, amplitude, and natural frequency will determine how the guitar responds to string energy input, subsequently affecting the tones the instrument produces. Gore and Gilet [2011] contend, "Because guitars have a generic tendency to vibrate in certain ways, it requires a significant change in the bracing structure to precipitate a change in the shape or amplitude of a mode. Changing a mode's frequency is a little easier." Luthiers often manipulate the stiffness of the top by removing material from the major braces, which can permit a targeted adjustment in the preferred frequency response for the top plate's monopole mode, or fundamental frequency.

2.4.2 Air Cavity Resonance

Another significant frequency response in determining the guitar's perceived sound is that of the air cavity enclosed by the guitar’s soundboard, sides, and backplate. This frequency response is often referred to as the guitar’s Helmholtz resonance. During a guitar performance, the air cavity is excited through a pneumatic coupling with the soundboard system. When the soundboard is driven, a resonant response is introduced in the air cavity through air pressure compression and rarefication. The frequency filtering effected through this process adds additional color to the tone of the guitar and is independent of the frequency driving the soundboard itself. Figure 2.8 illustrates the frequency response of a typical steel-string guitar when the “A” (110 Hz) string is plucked. The most prominent resonance other than the string modes is the Helmholtz resonance, or air cavity resonance, at 101.8 Hz.

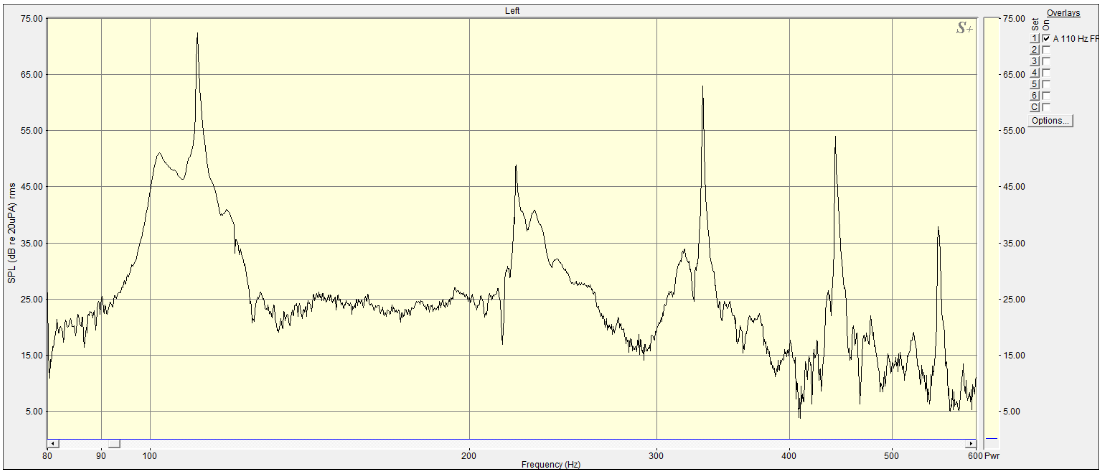


Figure 2.8: A plot of the frequency response when the “A” string is plucked. The Helmholtz frequency is the peak at 101.8 Hz.

The Helmholtz frequency of the air cavity is determined through the combination of the body dimensions, the soundhole diameter, and the soundhole location. Because these dimensions are fixed in the guitar construction process, the Helmholtz frequency response cannot be altered after the guitar is completed. This characteristic contrasts with the soundboard and backplate fundamental frequencies that can effectively be lowered through material removal from the braces.

2.4.3 The Backplate System

The coupling of the backplate to the air cavity and soundboard systems depends significantly on the luthier's intention to produce a live-back instrument. According to Somogyi [2011], the ability of the back to couple is affected by the mass and stiffness of the back-plate and its attached braces. A backplate system needs to be light and flexible in order to respond to the vibrations being offered mechanically by the guitar sides and pneumatically by the air cavity resonance. A massive, stiff backplate system would be, for all intents and purposes, unmovable. The implications of an actively resonating back would be a reduction in volume, but with the benefit of adding additional tone coloration due to the sympathetic resonance of the backplate system.

Assuming a live-back construction, the tonal contribution of the backplate system will be determined similarly to the soundboard system, a function of the backplate modes of vibration. However, Rossing and Caldersmith [2010] maintain that backplate system coupling diminishes above 400 Hz leading to the conclusion that tonal contributions by the backplate system exist primarily to benefit the low-frequency response of the guitar.

2.5 Guitar Sides and Neck System

The guitar's sides and neck are generally neglected when considering vibroacoustic wave propagation. It is generally regarded within the luthier community that these two components do very little to add to the guitar's tone and volume. However, there are implications to each of these components worth considering within the context of string energy, particularly string energy conservation. While these two components are vastly different in their role as a guitar component, their treatment in terms of string energy conservation is similar enough to be considered in the same section with only minor differentiation.

As shown previously in Figures 2.5 and 2.6, string energy admittance transfers directly into the neck system due to its role as an intended fixed end for string vibration. Because the neck is a poor transmitter of string energy into sound waves, the luthier's ultimate goal is to mitigate string energy loss at this location. In doing so, more string energy is available to drive the primary guitar sound producer, the soundboard system. While it would be practically impossible to completely eliminate these losses, they can be mitigated through design considerations during the building process. This process is the antithesis of the treatment of the soundboard and backplate systems suggested in sections 2.4.1 and 2.4.3. Whereas string energy admittance and coupling for the soundboard and backplate were enhanced by lowering mass and stiffness, the impedance of string energy losses to the neck can be achieved by the inverse, increasing mass and stiffness [Somogyi 2009a]. This process effectively increases the inertia of the neck system so that rather than be easily set into vibration, the neck will better approach the state of an ideal fixed end. The luthier has some control over the neck system's mass and stiffness via neck design dimensions, selecting material of appropriate mass and stiffness, and, primarily in the case of steel-string guitars, the addition of an adjustable steel truss-rod. However, overall neck mass is a two-edged sword as the instrument's ergonomic balance needs to be considered; a neck-heavy guitar can be uncomfortable to play in a seated position. An approach gaining popularity within the luthier community is to add carbon fiber rods inside the neck system to add stiffness while contributing only a small amount of added mass.

The guitar sides are approached in a similar fashion to the neck-system. The luthier's goal is to achieve the stiffest sides possible within the confines of not producing an instrument of such mass to become unwieldy. The traditional approach is to add wood braces to the sides' interior surfaces perpendicular to the planes of the soundboard and backplate. According to Doerr [2020], a modern approach that is gaining favor is to laminate an additional side set to the interior of the guitar box. This method not only stiffens the sides but also increase side mass, but not to the point of producing an instrument to be deemed “too heavy”.

2.6 Properties of Importance

Thus far, this chapter has alluded to the importance of material mass, stiffness, and damping. Because these three properties are fundamental in determining the guitar’s potential for sound production, it is important to further investigate (1) the methods to quantify these properties objectively and (2) their implications on additional acoustical properties of interest to acousticians. A review of previous research provided a consensus on additional metrics to provide further enlightenment as to the quality of a material in terms of vibrational behavior. Specifically, these acoustic metrics are Specific Modulus, Velocity of Sound, Radiation Ratio, and Acoustic Conversion Efficiency [Hansen 2006; Haines 1980; Gore 2011; Fouihle Houssay, and Brémaud 2012; Wegst 2006].

Of additional importance is the understanding that there can exist a wide range disparity in the measurement of these metrics. Wood sample testing by Gore [2011] and Brémaud et al. [2011] concluded that physical properties can differ by a factor of 2x within species and much greater between species. This implication reinforces the argument to not only consider macro material property comparisons between species but also micro level characterizations to properly define a specific wood sample. The statistical terms used in this research to analyze the disparity of measurement are (1) mean, (2) standard deviation, and (3) coefficient of variation. All of these terms are briefly overviewed below.

2.6.1 Component Mass and Density

As mentioned previously, the ability of a guitar component to vibrate will depend to a large extent on its ultimate mass as a finished part. Newton's Second Law of Motion defines the relationship between mass (m), acceleration (a), and force (f) as follows:

$$f = a * m \tag{2.1}$$

Simply put, in terms of a guitar, acceleration (a) is synonymous with the soundboard's vibrational response to string forcing (f). It would then follow that as mass increases, acceleration would have to decrease proportionally given a fixed amount of forcing. Altogether, the lower the soundboard's mass, the more responsive it will be to the force of a vibrating string. This relationship would also hold true for the other systems making up the physical structure of the guitar; the backplate and neck, most importantly. A low-mass component will succumb to vibrations while a high-mass component will reflect more vibrations back into the vibrating system, all other variables being equal. Therefore, a conscientious luthier would aim to produce an intended vibratory component at the lowest mass possible within the constraints of required structural integrity [Gore and Gillet 2011]. Conversely, adding mass to non-vibratory components, such as the neck, would conserve vibration-energy for use by the soundboard, and subsequently the air cavity and backplate.

Because a calculated mass is determined by the dimensions of a finished part, density is a superior means of comparing potential wood samples for consideration as potential guitar components. Simply, density is the measure of mass for a specific unit of volume, most often expressed as kg/m^3. For the purpose of this research, density (ρ) will often be used when analyzing the implications of mass for material comparisons.

2.6.2 Material Stiffness

Material stiffness is the other primary property to markedly determine the vibroacoustic characteristics of a given wood sample. Much like mass, a high-stiffness wood sample will resist vibration transfer while a low-stiffness wood sample will readily respond to vibration transfer and subsequent vibration. However, while there is no low limit on mass for a vibratory component, most guitar components exist in a state of stress due to the stress of tensioned strings [Gore 2011]. Therefore, there are structural implications to consider when considering reducing stiffness in order to maintain the structural integrity of the guitar.

Material stiffness has been given due consideration by luthiers for centuries, albeit using fairly subjective methods. The practice of hand-flexing prospective wood samples has traditionally been employed across most chordophone making disciplines to estimate stiffness. During instrument construction, luthiers would continue to thin the prospective vibratory plate until it seemed, to the individual maker, to be just right [Young 1975; Somogyi 2009a]. Unfortunately, the hand-flexing method takes years of experience to develop a sense of stiffness and would be of little help to a new builder or a line-worker at a factory [Benedetto 1994]. Additionally, there is no practical way to record this subjective method for analysis or comparison.

In order to provide a means to objectively quantify the stiffness properties of wood samples, this research will utilize a commonly accepted method to determine material stiffness. The specific quantification of stiffness employed in this thesis is that of modulus of elasticity (*MOE*), which is a term derived from elementary beam theory as provided by ASTM Standard D198-09 [ASTM 2012]. The *MOE* is also often referred to as the Flexural Modulus or Bending Modulus, which arguably better depicts the testing methods used herein. The applicability of this method is based on similar usage by Dumond and Baddour [2015], Yoshihara and Tsunematsu [2005], Haines [1980], and Leban, and Herbé [1996].

The *MOE* can be measured utilizing either **static testing** or **dynamic testing** methods and is typically expressed in units of **gigapascals** (GPa).

A three-point bending test is a static method that physically measures the amount of deflection resulting from a static load exerted midway between two end supports. Figure 2.9 illustrates a three-point test rig constructed by the author based on the standards set forth by ASTM D189-09.

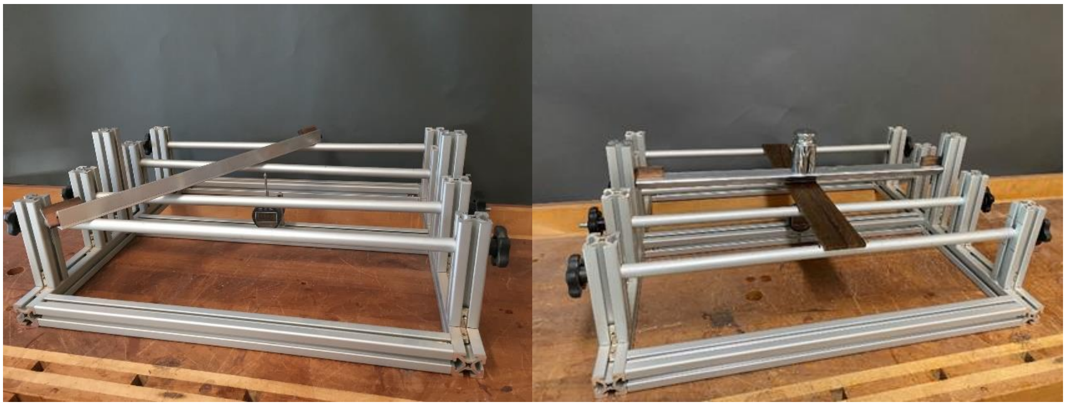


Figure 2.9: Photos of the three-point deflection testing rig used to calculate the modulus of elasticity. The left photo demonstrates the rig with two sets of cross-supports, the center-point weight support, and the digital micrometer. The right photo demonstrates the rig in use utilizing the cross-supports for long samples. Photos by the author.

The three-point test rig uses a digital micrometer to measure the amount of deflection that occurs in the wood sample under a static load, in this case a 1 kg weight. This measured deflection at the mid-point can be used to calculate the modulus of elasticity using the equations provided by the aforementioned elementary beam theory. This is a two-step process that first takes into consideration the implications of the cross-section of the sample. This implication is commonly referred to as the Second Moment of Area (I), and is calculated as follows [Forest Products Laboratory 2010]:

$$I = \frac{bh^3}{12} \tag{2.2}$$

where b is the measured base, and h is the measured height. Having obtained $I,$ the modulus of elasticity is then calculated via the equation [Forest Products Laboratory 2010]:

$$E = \frac{PL^3}{48(\Delta)(I)} \tag{2.3}$$

where P is the applied load, L is the distance between end supports (in units of meters), and $\boldsymbol{\Delta}$ is the measured deflection (in units of meters). The calculated modulus of elasticity is most often recorded in units of gigapascals (GPa).

Alternatively, the dynamic testing method uses the fundamental frequency of a particular grain direction along with the sample's measured dimensions to calculate the *MOE* in the long grain and cross-grain directions as follows [Caldersmith 1984]:

$$E = \frac{\rho\, L_x^4\, f_x^2}{1.05\, h^2} \tag{2.4}$$

where ρ is the density of the sample plate, L_x is the length in the direction being tested, and h is the thickness of the sample material, and f_x is the fundamental natural frequency when the material is excited perpendicular to the plane of the wood specimen.

In addition, the *MOE* in the diagonal direction can be computed with the following equation:

$$E_{x.y} = \frac{2.43\, \rho\, L_x^2\, L_y^2\, f_{x,y}^2}{h^2} \tag{2.5}$$

where $f_{x,y}$ is the natural frequency associated with motion transverse to the twisting/diagonal direction.

While the static method will be used for the purposes herein, the dynamic method is outlined above for the sake of demonstrating an alternative method. The reason for utilizing the static method for determining material stiffness is due to its similarity in approach to the traditional subjective hand-flex method already familiar to most luthiers.

2.6.3 Damping

In lutherie woods, damping refers to the dissipation of vibrations due to internal friction at the cellular level [Bucur 2006]. The traditional method used by luthiers for centuries to estimate damping is often referred to as checking the “tap-tone”. Essentially, this method is akin to treating a wood sample like a marimba bar. Marimba bars are supported at a distance of 22.4% of the bar’s length from each end. This location coincides with the nodal point for the fundamental longitudinal bending mode. See figure 2.10.

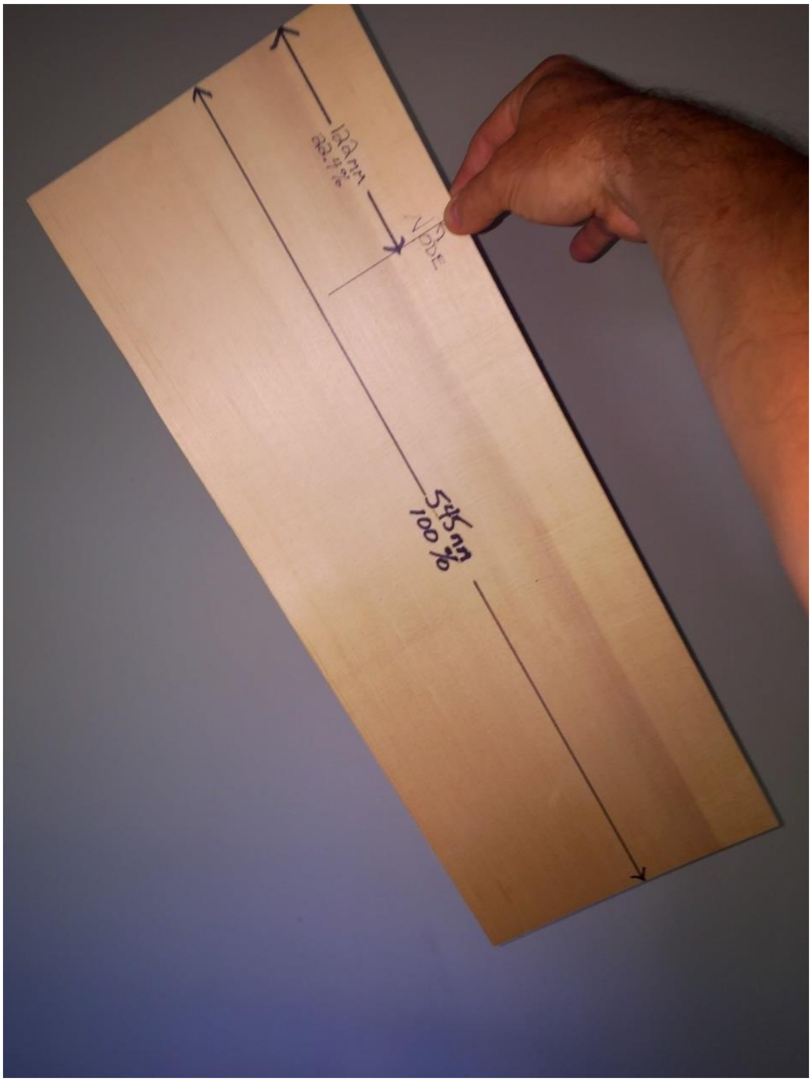


Figure 2.10: A photo demonstrating the technique to hold a tonewood plate at a node to test the tap-tone in the longitudinal direction.

Because a node is characterized by a void of vibration, supporting a wood sample at this location will have minimal interference with its ability to vibrate. Once held in this fashion, the luthier will tap the wood with a knuckle, fingertip, or other small striking device to initiate a vibratory response. The tone produced by the tap is then judged as to its frequency and sustain. The analysis of the sustain component is in effect the attempt to determine the damping characteristics indicated by the duration of the tone from initiation to final decay [Somogyi 2009a]. The simplest technique to accurately measure vibrational damping in materials is the half-power bandwidth method. This method utilizes a rig to support a wood sample at nodal points similar to the manual method described above. The rig used for this research is shown below in Figure 2.11.

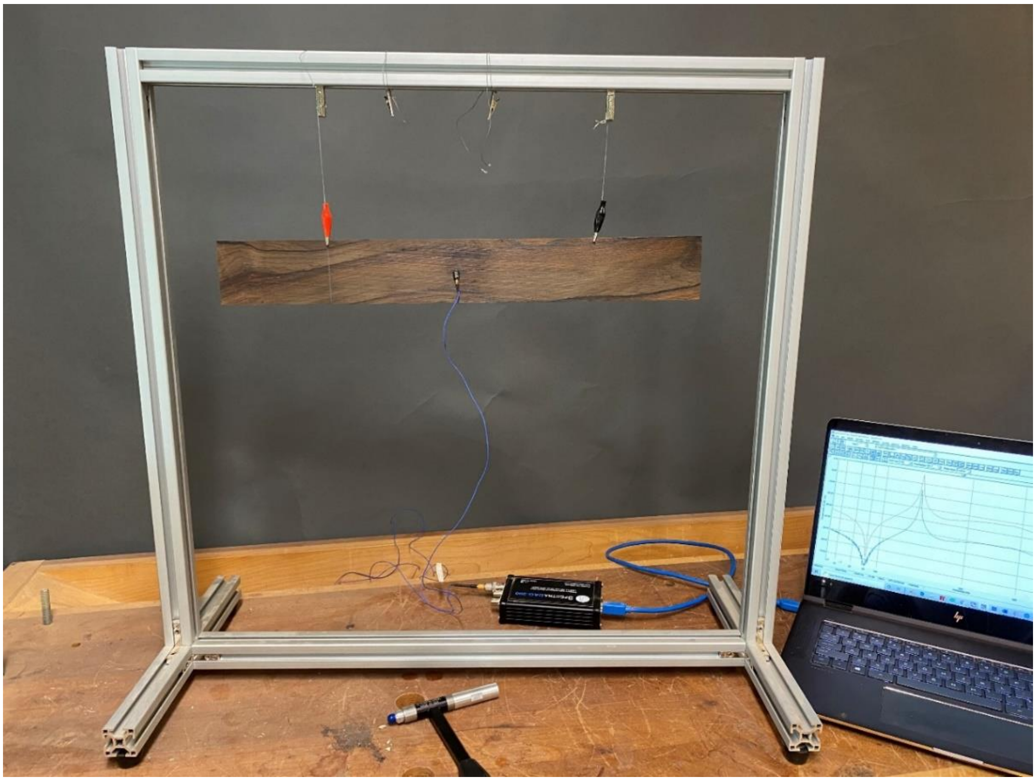


Figure 2.11: Photo of a rig utilized to support a wood sample in the first longitudinal mode. Photo by author.

The vibrations produced by a light tap of an impulse hammer are sensed by a microphone or accelerometer and recorded to a computer file for additional analysis. Computer software with Fast Fourier Transform (FFT) capability can be used to analyze the different resonance frequencies as shown in Figure 2.12. The fundamental natural frequency of this sample, seen at a frequency of 128.48 Hz, is clearly visible with the aid of FFT processing.

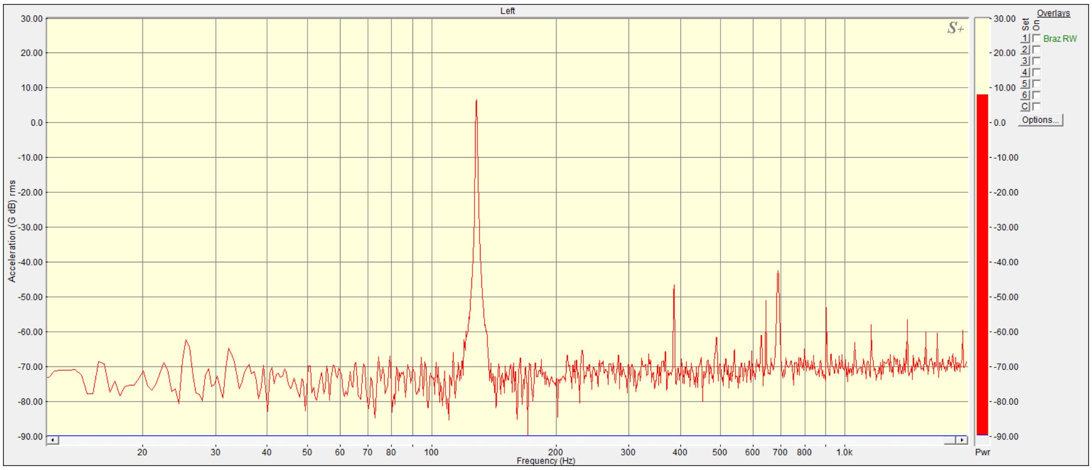


Figure 2.12: A plot of the frequency response for a “tapped” wood sample.

Manually, the half-power bandwidth method of determining damping (*Q*) can be calculated with the following equation [Casiano 2016]:

$$Q = \frac{f_n}{\Delta f} \tag{2.6}$$

Where f_n is the measured frequency and $\Delta f (f_2 - f_1)$ is the bandwidth measured at -3 dB from the peak. This measurement is illustrated in Figure 2.13.

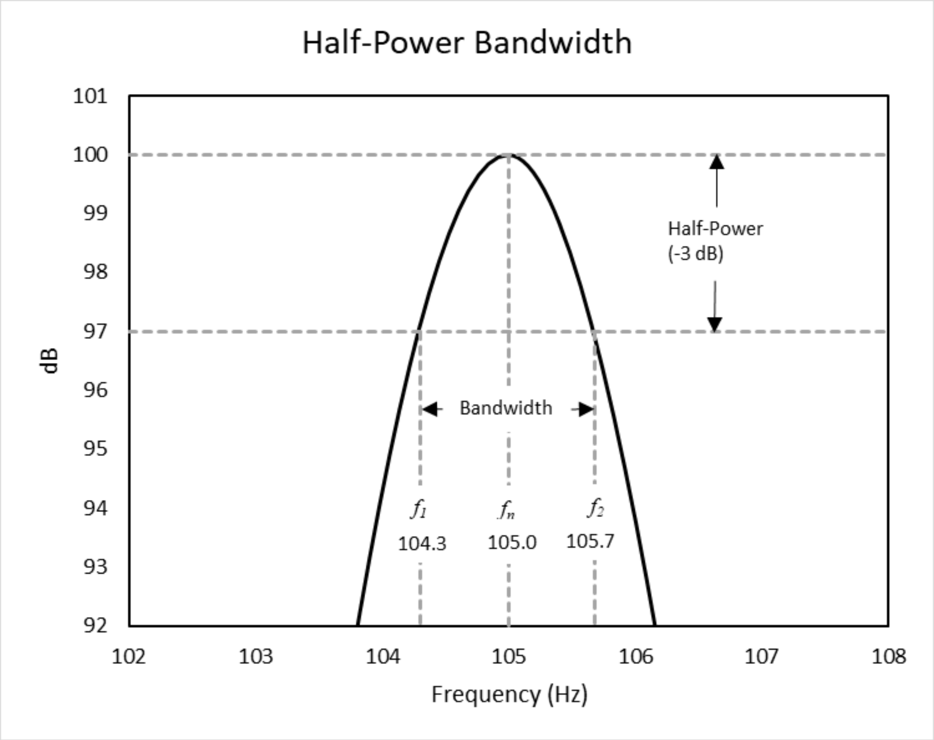


Figure 2.13: Illustration of the Half-Power Bandwidth method for determining damping. Illustration by author.

Q can be solved for the scenario illustrated in Figure 11.1 as follows:

$$Q = \frac{105}{(105.7 - 104.3)} = 75 \tag{2.7}$$

Conveniently, many vibroacoustic analysis software packages offer the additional function of estimating the half-power bandwidth computation to determine the Q factor. Also, it is important to note that the calculated *Q* is inversely proportional to material damping. In other words, a high *Q* (corresponding to a “narrow” peak) indicates relatively low damping, while a low *Q* (corresponding to a wide peak) indicates high damping.

2.6.4 Acoustic Metrics

From the measurements of the physical properties for density, modulus of elasticity, and damping, additional vibroacoustic metrics can be ascertained to further characterize the potential effectiveness of a wood sample . A brief overview of these metrics, as provided in Wegst [2006] is as follows:

The ***Velocity of Sound*** is a measure of the speed at which sound waves travel through a medium, either a gas, liquid, or solid. For thin wood samples, the calculation is as follows:

$$c = \sqrt{\frac{E}{\rho}} \tag{2.8}$$

From this, it can be deduced that wave velocity increases as stiffness increases and decreases as density increases.

Specific Modulus is the relationship of material stiffness to its density and is calculated as:

$$SM = \frac{E}{\rho} \tag{2.9}$$

The specific modulus is often referred to as the strength-to-weight ratio.

The ***Radiation Ratio*** measures the acoustic power of a wood plate by relating the stiffness (E) with the density (ρ):

$$R = \frac{c}{\rho} = \sqrt{\frac{E}{\rho^3}} \tag{2.10}$$

The ***Acoustic Conversion Efficiency*** takes R one step further by recognizing the vibrational losses, at a given frequency, due to internal damping mechanisms as follows:

$$ACE = \frac{\sqrt{E/\rho^3}}{\tan\delta} \tag{2.11}$$

where $\tan\delta$ is the dissipation factor of an oscillating system, or in this case, a vibrating wood plate. The factor $\tan\delta$ is related to the previously defined quality factor Q, (which is defined in terms of a specific natural resonance frequency), as follows:

$$\tan\delta = \frac{1}{Q} \tag{2.12}$$

In considering the acoustic metrics above, it becomes clear that the ratio of stiffness to density (E/ρ) permeates every other property, with a high ratio corresponding to a high property quality. Likewise, a high Q, or low damping, improves the acoustic conversion efficiency (ACE), also benefitting sound production. Therefore, for selecting materials for vibrating systems, the properties of greatest importance would be modulus of elasticity, material density, and damping.

2.6.5 Statistical Terms

The disparity or consensus of physical property measurements between and within species will be mentioned numerous times throughout the remainder of this thesis. In certain cases, it is important to accurately determine measured disparity/consensus in order to demonstrate the magnitude by which sample measurements differ. For the sake of simplicity, this research limited the scope of utilized statistical terms to **arithmetic mean**, **standard deviation**, and **coefficient of variability**. The definition and implication of each term is defined as follows as provided in Illowsky and Dean [2018]:

The **arithmetic mean, $\bar{x}$,** is simply the average value for a set of measurements. The equation associated with determining the mean is written as:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} X_i \qquad 2.13$$

Often, the measured mean will imply what can be expected from a typical wood sample or for a generalization for a species.

The **standard deviation, σ**, measures the disparity of a set of measurements relative to its mean. The equation used to determine the standard deviation is as follows:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad 2.14$$

This measurement indicates how spread out the data is from the mean. In other words, a large standard deviation indicates a large disparity within the data set while a small standard deviation indicates the samples are somewhat similar.

The **coefficient of variability** takes the standard deviation one step further to emphasize the impact of the disparity. The equation to determine the coefficient of variability is as follows:

$$c_v = \frac{\sigma}{\bar{x}}$$

The coefficient of variability demonstrates the extent to which the standard deviation deviates from the mean. In other words, a standard deviation of 5 on a mean of 10 is dramatic, whereas a standard deviation of 5 on a mean of 1000 is relatively miniscule. The coefficient of variability illustrates the true disparity in this scenario calculating a c_v 50% and .5%, respectively.

2.7 Summary

Chapter 2 provided a preliminary overview of the structural components, the vibratory systems that facilitate the guitar's functionality, and the physical properties that impact the ability of a material to effectively vibrate. To illustrate the different components that make up the instrument, a deconstructed view of the guitar, Figure 2.2, was included to demonstrate many of the instrument's essential aspects that would otherwise be obstructed from view in a completed form. The vibrations from a plucked guitar string was examined and followed through the entire guitar system to illustrate effective uses and losses of the energy responsible for creating sound. The primary vibratory components responsible for generating sound were broken down into systems to define how they each contributed to the overall sound in terms of their frequency response and their relationship to each other regarding effective coupling. Next, the physical and acoustic properties that affect material vibration were defined in terms of their consequence on vibratory systems. Finally, a brief overview of statistical terms to determine measured property disparity were defined in anticipation for the testing and analysis chapters in Section II.

Chapter 3

The Guitar: Historical Background and Development

3.1 Assumptions

The one caveat that needs to be considered when studying history through museum and collection pieces is that pedestrian pieces have a low chance of surviving past their original era. By their nature of fine/lavish artistry, collection pieces, or their association with a famed artist or patron, are more likely to be preserved for posterity. Common instruments are probably more likely to be discarded rather than be kept or collected, and therefore there would be a gap in the full account of the guitar over the last five centuries [Arriaga 1991b]. However, because an instrument is considered valuable enough to be “collected”. there might be even more reason to consider its importance in reflecting the material influence that it demonstrates within its era and, subsequently, its role as a part of tradition. In other words, the fact a specific guitar is preserved within a collection is a testament to its success, while those instruments that have been discarded over time alludes to some failure, whether it be material selection, design, or craftsmanship, or maintenance. With these considerations in mind, the evolution of the guitar will be examined based on the surviving specimens and documentation of both gut/nylon-string (classical) guitars and steel-string guitars.

Appendix I lists a selection of instruments from the sixteenth century to the present from various collections. While this is not a complete listing of all surviving guitar-type instruments since the 1520 vihuela, it should still provide a useful overview of wood materials used in the art of lutherie, the trends of their popularity, and their prominence in use.

Defining tradition is complicated at the outset by the very need to determine the point of its origin. One might argue that guitar traditions ultimately date back to pre-history when hunters sat about the fire plucking bow strings [Alves 2015]. A more conservative view would trace the traditions back to the mid-nineteenth century when Antonio de Torres amalgamated many best practices into what we today call the modern classical guitar. Since many of the best practices utilized by Torres and his colleagues existed centuries prior, it would seem appropriate to at least begin when the guitar as we know it today came to exist in a form recognizable to anyone familiar with the instrument. While it is tempting to consider the lute as part of the guitar tradition, this would necessitate nearly 5000 years of instrument history to consider. Besides, the lute did not evolve into the guitar and then cease to exist but instead continued in popularity alongside with its own distinct form [Dumbrill 1998; Burkholder et al 2010].

3.2 In the Beginning

The first known publication to describe a plucked chordophone with guitar shape characteristics is Johannes Tinctoris' *De Inventione et Usu Musicae.* Published ca. 1487, Tinctoris describes the instrument as follows [Hiroyuki 2004]:

> …invented by the Spanish, which both they and the Italians call the *viola*, but the French call the *demi-luth*. This viola differs from the lute in that the lute is much larger and tortoise-shaped, while the viola is flat and, in most cases, curved inwards on each side.

And later:

> …while some play every sort of composition most delightfully on the lute, in Italy and Spain the viola *without a bow* is most often used.

To further distinguish this instrument, Romanillos and Winspear [2002] contend:

> The importance of the invention of the vihuela de mano does not rest on the novelty of a new plucked instrument with a waisted shape but in the implicit suggestion made by Tinctoris that the body of the vihuela de mano was constructed out of separate elements and not made from a solid block of wood in keeping with the prevailing method of making the body of plucked and bowed instruments in the Middle Ages.

This distinction of using separate components to build the instrument from parts would allow material choices beyond what would otherwise be practical if the body were carved out of a solid block. The cost savings in materials notwithstanding, this new method of bending sides from thinned hardwoods and attaching to a separate thinned backplate would allow extremely dense hardwoods to be used, which would otherwise not be considered if the body had to be hollowed out with sharp-edged carving tools [Romanillos and Winspear 2002].

Further evidence of the time origin of a guitar-shaped instrument comes from the iconography at the turn of the sixteenth century. Marcontonio Raimondi clearly illustrates in his engraving *Suanatore Viola de Mano* [1510], an instrument easily recognizable by today's standards of having a typical guitar shape. See Figure 3.1.

Figure 3.1: This ca. 1510 engraving ca. by Marcantonio Raimondi, *Suonatore di viola da mano,* illustrates a five-course instrument with the distinctive “waisted” soundbox characteristic of the guitar family. Accessed March 19, 2020, https://commons.wikimedia.org, public access scan.

While no specific date can be attached to the first guitar type instrument, it would be reasonable to consider the end of the fifteenth century as the earliest guitar-shaped instrument's inception and, therefore, the earliest era at which this research will consider. While the *vihuela de mano* is known regionally by other names such as the French *demi-luth* and the Italian *viola alla Napoletana*, this instrument will be referred to for the sake of simplicity herein as the *vihuela*. The English word *guitar* also had other names by which it was known across Europe, such as the German *gitarre* and French *guitare*, all from the Spanish *guitarra*.

However, *guitar* will be used within this text to reference any of these instruments.

3.3 Development by Era

Going forward, in order to separate the instruments by eras to analyze material usage trends, the commonly accepted periods of music history will be used and delineated as follows; Renaissance era 1400-1600, Baroque era 1600-1750, Classical era 1750-1820, Romantic era 1820-1900, and Twentieth Century 1900-2000 [Sachs 1940].

3.3.1 The Renaissance Era (1400-1600)

The relative peace and events of the fifteenth century provided conditions conducive to a burgeoning art scene, whether graphic, architectural, or musical. An expanding middle class prospered due to increase trade between cities over greater distances. With this period of general increasing affluence, wealth was spent on extravagances instead of just war and basic necessity. Nobility, looking to raise their stature with their subjects and contemporaries, built palaces and churches, purchased artwork to adorn the walls, and employed musicians and singers for both worship and entertainment [Burkholder 2010].

With the development of a movable type printing press by Johannes Gutenberg (1400 -1468), ca. 1450, and its subsequent employment to print musical scores, the availability of notated music allowed for amateur musicians to both learn and perform music for their own pleasure [Burkholder 2010; Arriaga 1991]. This advancement created a new market for the publishers of printed musical notation and musical instrument manufacturers who would need to satisfy a demand for instruments far beyond the limited scope of court and church musicians [Wade 2001]. In the painting *Woman Playing the Guitar* [1627], artist Gerard von Honthorst demonstrates the guitar's popular reach in his depiction of a musician likely performing as part of a theatre troupe [Krén and Marx 2020]. See Figure 3.2.

Figure 3.2: Gerard von Honthorst's painting titled *Woman Playing Guitar* dated 1627. This work depicts a musician outside of the church or a noble court performing music. Musée du Louvre, Paris. Accessed March 20, 2020, https://commons.wikimedia.org/, public access scan.

Towards the beginning of the Renaissance era, there was a musical shift from monophonic to polyphonic expression. The rise of polyphonic musical styles bolstered the popularity of instruments capable of playing more than one note at a time, such as the harpsichord, virginal, lute, vihuela, and guitar [Sachs 1940; Burkholder 2010]. Near the end of the Renaissance, music written explicitly for plucked string instruments to accompany the voice started to become prominent [Rey 1991]. John Dowland's (1563-1626) compositions for the lute spawned an increasing interest in a single voice accompanied by a single instrument. During this era, the lute was the most popular household instrument in the sixteenth century [Burkholder 2010].

Whereas the popularity of the guitar and vihuela would, from this point, increase, the popularity of the lute would start to decline, finding its way out of popularity by the 1800s [Heck 1970]. A possible explanation for the demise of the lute may lie in its evolution into over-complexity. Whereas the medieval lute usually consisted of four string courses, the late Renaissance lute would likely be fitted with ten or more courses of strings [Bouquet 2010]. To undertake such an instrument as a novice would be likely daunting and make the six-course vihuela or four-course guitar much more approachable. This allure of simplicity may have, in turn, precipitated the relatively quick demise of the six-course vihuela in favor of the four-course guitar [Alves 2015]. In Donald Gill's [1981] Vihuelas, *Violas and the Spanish Guitar,* he emphasizes this notion quoting Sebastian Covarrubias Orasco from *Tesora de la Lengua Castellana o Espanola* (Madrid, 1611):

> Until our times this instrument (the *vihuela*) has been highly esteemed and had most excellent musicians, but since the invention of the guitar there have been very few who have devoted themselves to the study of the *vihuela*. It has been a great loss, because all kinds of notated music was played on it, and now the guitar is nothing more than a cow-bell, so easy to play, especially in *rasquado* (strumming) that there is not a stable-boy who is not a musician of the guitar.

In lamenting the vihuela's demise, Orasco inadvertently provides a possible explanation for the guitar's continued success versus the vihuela and the lute: the four-course guitar was simple to play and would therefore have a broader appeal to aspiring musicians.

The distinction between the vihuela and guitar is relatively modest but seems to be mostly a function of the instrument's size and how many courses with which the instrument is strung. The vihuela is larger in size and strung with six double courses of strings, while the guitar of this era is relatively smaller with typically four double courses of strings [Arriaga 1991].

Despite its widespread use in sixteenth-century Spain and Italy, there remains today very few surviving examples of the early vihuela and no four-course guitars [Arriaga 1991]. Only two definite instruments from that century have been identified thus far. The most famous early vihuela is the “Guadalupe”, which currently resides in the Musee Jacquemart-Andre of the Institut de France in Paris. See Figure 3.3. While specific wood identification is somewhat subjective, there is enough agreement in speculation to characterize the instrument components as follows [Prynne 1963; Corona-Alcade 1984; Bermudez 1991; Libin 1991]:

- Spruce (*Picea spp.)* or pine (*Pinus spp*.) soundboard.
- Alternating darts of European Boxwood (*Buxus sempervirens*) and possibly Kingwood (*Dalbergia cearensis*) for the back).
- Interlocking panels of Boxwood, Kingwood, and Pear (*Pyrus communis*) for the bent sides.

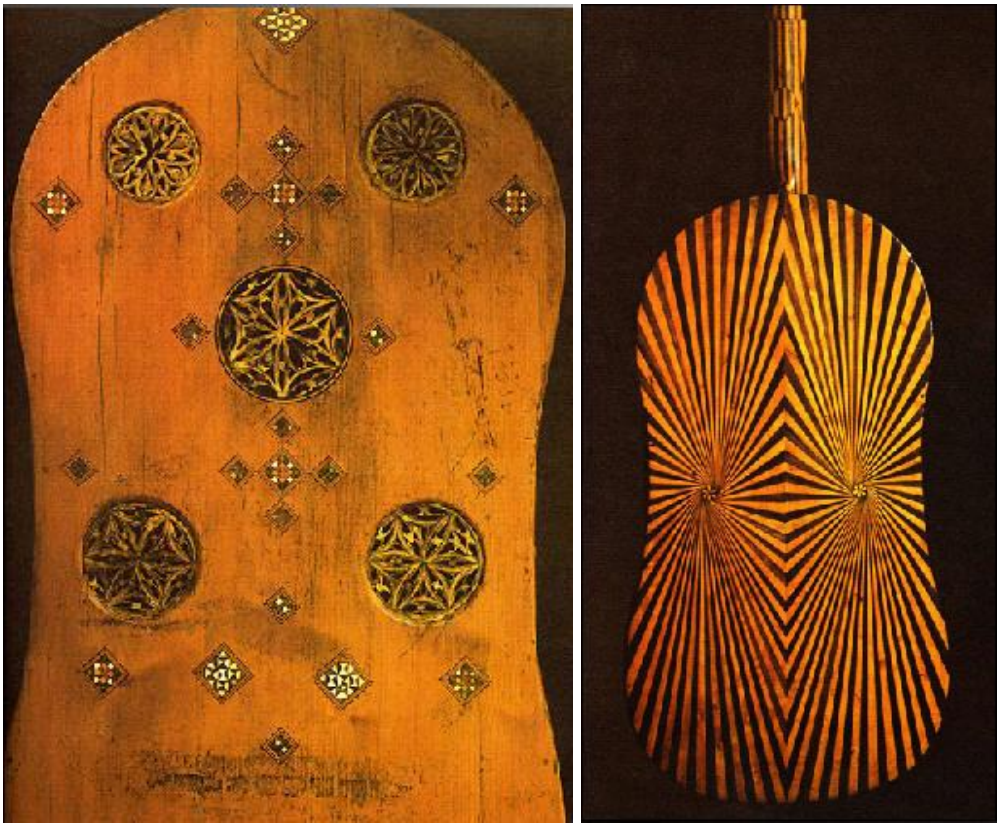


Figure 3.3: *The “Guadalupe”* vihuela by an unknown luthier from the fifteenth century. Musee Jacquemart-Andre, Paris. Accessed March 20, 2020. http://www.lutesandguitars.co.uk/htm/cat12.htm.

The second surviving vihuela, known as the “Chambure” vihuela at the Cité de la Musique, was recently recategorized from a guitar to a sixteenth-century vihuela. Madame de Chambure acquired the instrument at the end of the 1960s before entering the Museum's collections in 1980. Characterization of the instrument's structural materials are varied but include boxwood and Mediterranean cypress (*Cupressus sempervirens).* The soundboard is reported to be spruce or fir [Schreiner 2020].

It should be mentioned there is a third early vihuela referred to as the “Quito”. The “Quito” vihuela currently resides at the church Iglesia de la Compañia de Jesús de Quito in Ecuador, where it is held as a holy relic believed to be once owned and played by Saint Mariana de Paredes (1618-1645). Originally thought to be a sixteenth-century European vihuela, recent evidence suggests the “Quito” was made locally in Ecuador sometime in the early seventeenth century based on the design principles of actual sixteenth-century vihuelas [Koonce 2015; Bermudez 1991]. It is suggested that the soundboard and back were made from pine while the sides were made from possibly alder or maple [Libin 1991].

Despite the limited number of surviving instruments from this era, written instrument descriptions and inventories of instrument makers from this era provide some evidence in lieu of physical specimens. Additionally, transcripts of sixteenth-century luthier guild ordinances precisely specify what materials could be used in instrument manufacture and repair [Arriaga 1991].

The Vihuela de mano and the Spanish Guitar, Romanillos and Winspear [2002] compile a number of sixteenth-century archived documents specifying the woods that were important enough to mention by name.

- An instrument inventory of the Marques de Camarasa dated 1576 lists a “guitarra de ebano con costillas” (an ebony guitar with ribs) and a “vihuela de ebano con costillas” (an ebony vihuela with ribs).
- A mid-sixteenth century account by Cristobal de Villalon describes a vihuela with “sides made of ebony.”
- An inventory of the violero (luthier) Mateo de Arratia of Toledo from 1564 included “a box full of spruce…a round thick bole of sandalwood…a large round bole of Castille ebony…another round bole of similar ebony…a sawn piece of Portuguese ebony…a round piece of boxwood…two vihuelas in Portuguese ebony”.
- Violero Francisco Bejarano made a valuation of instruments belonging to banker Andres de Ecija in 1958, having “one vaulted-back ebony vihuela…another fluted ebony guitar…one beech cittern…another ebony cittern”.

Romanillos and Winspear also include additional archives from the early seventeenth century, such as:

- The examination of Francisco de Lipuste by the Guild of violeros dated 1619 reads, "…the said examiners exhibited and demonstrated in my presence as notary, one instrument which at the moment is being strung as a guitar but was constructed by Francisco de Lipuste as a vihuela…it has ebony ribs, back and soundboard in white wood [spruce?], a rose with three black and white rings, black and white fillets in the bridge and sides, purflings and bindings in ivory and ebony pegs".
- The testament of Pablo de Herrera dated 1622 that declares, "…the Marques de Alcanices owes me for a guitar made in cocobolo (a new-world rosewood) which is worth at least eight hundred reales and he also owes me for a vaulted-back guitar in beech, worth one hundred and fifty, and four ducats for a guitar without inlays. I beg your lordship to be so good as to pay my wife and children who otherwise will be left very poor. I made two guitars for the count of Navalmoral, one of cocobolo worth five hundred reales and another worth twenty-four reales".
- From the "Proposals of Ordinances for the Craft of Violeros of Toledo, 1617", "That if anyone were to bring an ebony vihuela to have a soundboard fitted, this soundboard must be of spruce with a rose of boxwood and not of parchment."

These archives and analysis of the surviving instruments would support inferences regarding material selection in guitar type instruments from the sixteenth and early seventeenth centuries. Consistent with the earlier described vihuelas is the preference of spruce for the soundboard. The use of spruce for the primary vibrational plate is not surprising as it coincides with its use on other chordophones from that era and prior such as lutes and the bowed instruments [Whiteley 2008; Boyden 1969; Haines 1980]. While the vihuela and subsequent guitar may have found its unique origin of shape in the early sixteenth century, the material selection for the soundboard is anything but unique as it replicates that which has been used successfully on other stringed instruments. The reason for spruce's widespread appeal for chordophones, in general, is attributable primarily to two factors: (1) the tonal spectrum of the sound produced by coupling string vibration to a spruce soundboard had appeal within cultural musical preferences [Sturgill1974; Brémaud 2012)], and (2) spruce is very efficient at transferring string vibration to acoustic sound [Bennet 2016; Haines 1979; Busknowitz et al. 2007; Gore 2011]. The successful use of spruce for soundboards was most likely discovered by trial and error throughout the five-thousand-year history of chordophones. Suffice it to say that the use of spruce for the soundboard made for what was considered a pleasing sound, and spruce did the job efficiently.

Ebony (*Diospyros spp.)* seems to be another important wood in use on these early instruments. There are several ebony species distributed about equatorial Africa, Southeast Asia, and Indonesia. With its striking black appearance, strength, and durability due to its surface hardness, ebony would be a natural choice for the instrument's structural "box" components. Additionally, thinned ebony slats are relatively easy to bend when heated or steamed and tend to hold the shape with minimal spring-back, a superior characteristic for waisted instruments such as the vihuela and guitar. Considering trade with equatorial Africa and Indonesia was still in its infancy, having only commenced in the early sixteenth century, the allure of using exotic wood species as part of a musical instrument probably lent some prestige for both the maker and owner of the instrument.

The frequent inclusion of boxwood (*Buxus sempervirens*) in the luthier archives mentioned above speaks to its prominence of use in the musical instruments of this era. Because boxwood also scores very high in strength and surface hardness, its use would ensure a durable instrument [Meier 2016]. Also important to consider is that boxwood is indigenous to much of Europe, which means it would be readily available. However, the *Buxus spp.* is characterized somewhere between a shrub and a tree, rarely growing taller than 10 meters and 20 centimeters in diameter. The lumber from even a large tree would be better suited to smaller parts and fittings than the larger plates required for an instrument back. Accordingly, boxwood is better recognized as a primary wood for smaller woodwinds and stringed instrument fittings such as tuning pegs, tailpieces, and chin rests [Meier 2016]. The “Guadalupe” vihuela pictured above in Figure 2.3 demonstrates a means by which the small boxwood pieces can be incorporated effectively into the instrument structure. Small samples are glued together to make the larger instrument components such as the back, sides, and neck. Unfortunately, there can be no certainty whether this was done for visual appeal or due to the vihuela maker’s inability to procure wood materials large enough to make these components.

The mention of “cocobolo” in the testament of Pablo de Herrera dated 1622 is significant as it might refer to *Dalbergia retusa,* a true rosewood species from Central America. While various rosewood species are distributed throughout global tropical regions, the new-world rosewoods, Brazilian rosewood (Dalbergia nigra) in particular, would later become one of the preeminent hardwoods used in guitar making. In fact, Belchior Dias of Lisbon was known to have used Brazilian rosewood in the late sixteenth century, evidenced by the guitar he made in 1581, which currently resides in the Royal College of Music in London [Romanillos and Winspear 2002].

3.3.2 The Baroque Era (1600-1750)

Characterized by five courses of two strings, the guitar of the baroque era was considered to be of Spanish origin, evidenced by its designation in the cultural centers of France and Italy as *chitarra spagnuola* [Wheeldon 2017]. This was also the period that the popularity of the guitar spread beyond southern

Europe and into the countries of Germany, England, the Austrian Empire, and even the Americas [Alves 2015].

Ironically, the word *baroque* was used initially in the mid-eighteenth century as a pejorative to describe the art, architecture, and music trends that gained popularity in what is now affectionately called the Baroque era. Originally intended to describe that which is “abnormal, bizarre, exaggerated, or in bad taste”, baroque developed a more positive connotation a century later when the ornate art forms of the seventeenth century found greater appreciation [Burkholder, Grout, and Palisca 2010].

The Baroque era guitar pictured in Figure 3.4 demonstrates the lavish ornamentation that the mid-eighteenth-century art critics found contemptuous.

Figure 3.4. A five-course guitar by Jean-Baptiste Voboam from 1697. This instrument demonstrates the lavish use of tortoiseshell, mother-of-pearl, and ivory marquetry and inlay typical to the Baroque era. Metropolitan Museum of Art. Photo accessed March 22, 2020, https://www.metmuseum.org/, used with permission.

While the soundboard is spruce in adherence to expectation, the rest of the instrument is an extravagant display of inlay and marquetry. Using tortoiseshell, mother-of-pearl, ivory, and ebony, Voboam essentially uses the guitar's structural components as a canvas for artistic expression. There can be little question that this guitar was meant to be seen as much as heard.

Reviewing Appendix I from 1600 to 1750, it becomes apparent that the instruments in these collections are most often heavily adorned with inlay and marquetry. These lavishly decorated instruments accurately reflect the Baroque era’s predilection for grand ornamentation. With few exceptions, at no other point in the guitar tradition have there been before, nor since, guitars manufactured *en masse* to match the Baroque guitar's intricate inlay and marquetry.

As for the wood components of these guitars, while spruce is still used for the primary vibrational soundboard, exotic hardwoods are most often used on the other structural components such as the back, sides, and neck. Notably, New World hardwoods play prominently in these selections. Brazilian rosewood (*Dalbergia nigra*) and snakewood (*Brosimum guianense*) from the northeast of what is now South America compete with ebony for structural and adornment use.

It is worth noting the maple (*Acer spp.*) guitars of the Baroque era listed in Appendix I on two levels; (1) that the relatively common maple was used for the backs, sides, and necks, and (2) the instruments are almost entirely devoid of the ornamentation common to the other Baroque guitars.

Quite possibly, the highly adorned guitars preserved from this era would undoubtedly be labor-intensive to produce and subsequently carry a commensurately high price. These instruments were likely commissioned by wealthy patrons intending to display their affluence on what may otherwise be considered a common item [Bucur 2016]. A working musician or middle-class patron would likely not have the means to procure such artistically crafted pieces. As the guitar was gaining in popularity, there would have been a demand for unadorned instruments by those of modest means that merely filled the primary purpose of producing music [Russell 2011]. Not only is maple a common hardwood distributed throughout Europe, but maple also responds well to the heat and steam bending required to shape the ribs and has strength characteristics appropriate to withstand the tensions of taut strings. Its low cost, workability, and availability make maple a prime candidate for use on the affordable instruments suitable for the middle-class and working musician budget.

Additionally, maple also had a reputation for successful use on other chordophones such as the lute, violin, cittern, to name a few. Indeed, at this point in history, it would seem that there was little to distinguish guitar woods from violin and lute woods. The likely explanation is that while an instrument maker might specialize in a particular instrument, there would undoubtedly be acceptance of commissions beyond that maker's primary scope [Arriaga 1991b; Van Amersfoort 2018]. Antonio Stradivari is a perfect example. Various research suggests Stradivari produced over 1,100 instruments in his lifetime. Of these, it is estimated that 960 were violins, for which he is best known. The remainder consists of cellos, violas, and oddly enough guitars. While around 500 Stradivarius violins have survived to this day, only four verifiable guitars are still known to exist [Metropolitan Museum of Art 2020]. The lack of surviving guitars suggests plucked chordophones were not a significant focus of Stradivari. Additionally, the lack of ornamentation and material selection of Stradivari's guitars are in stark contrast to the highly ornate guitars of the baroque era and more akin to the conventions of a typical violin from that era, as shown in Figure 3.5 [National Music Museum 2020].

Figure 3.5. The “Rawlins” guitar by Antonio Stradivari. The woods selected for this instrument are also typical of those used for this luthier’s violins. Photos accessed March 28, 2020, https://emuseum.nmmusd.org/, used with permission.

The surviving Stradivarius guitars were made using spruce tops, maple back and sides, and either solid-maple or maple-veneered neck. The only ornamentation is a simple rosette inlaid around the soundhole [Pollens 2003]. Quite simply, the Stradivarius guitars are what one might expect of a Cremona violin maker: an austere instrument made from the woods that would be on-hand in a violin shop [M.M.A. 2020; Heck 1970]. The austere nature of these guitars suggests that they were intended as true musical performance instruments rather than an ostentatious display of wealth by an upper-class patron. Despite the lack of remaining instruments, it is quite possible the guitars produced in the Baroque era would have had more in common stylistically with the Stradivarius guitars than to the elaborate instruments preserved in private and museum collections [Metropolitan Museum of Art 2020].

3.3.3 The Classical Era (1750-1820)

The beginning of the Classical era saw a continuance of music patronage dependent on the general public and the traditional support of the aristocracy and church. General expanding affluence of the European population produced an increasing market for music consumption, whether it be listening aficionados or amateur musicians. Amateur performance of music continued to grow as it became popular within the middle- and upper-class to perform for the enjoyment of one’s family and friends [Burkholder, Grout, and Palisca 2010].

In the wake of wars and revolutions, the onset of the Classical era was a period of upheaval that brought a sea change within which the arts existed in Europe and the New World. With the elimination of the French aristocracy and dwindling financial resources of Europe’s other noble states, musicians, composers, and instrument makers experienced declining financial support from their traditional patron. However, as peasants and serfs increasingly transformed from subject to citizen and were able to participate in economic trade, a new consumer class started to develop. Additionally, the aristocracy's declining influence and authority was the beginning of the end for the guilds that once controlled both musicians and instrument craftsmen. This new freedom meant anyone with talent and a paying customer could pursue their craft without government restriction [Burkholder, Grout, and Palisca 2010; Romanillos 2002; Arriaga 1991b].

The Classical era instruments included in Appendix I reflect a departure from the extravagant instruments preserved from the Baroque era. In general, ornamentation and inlay are used more sparingly. The exotic materials commonly used to cover the Baroque instruments' structural components are absent in favor of unadorned wood, as depicted in Figure 3.6.

Figure 3.6: Front and back of a spruce and cypress guitar made by Sanchez de Aguiler, 1797. Photos accessed March 21, 2020. https://www.metmuseum.org/, used with permission.

The lack of highly ornamented guitars preserved in these collections suggests a shift in consumer demand. While the Baroque guitar was as much a showpiece as a musical instrument, the Classical era instrument was primarily intended for the primary purpose of making music. The potential consequence of the preservation of labor and financial resources on these more spartan instruments would allow the reallocation of these resources into building a superior instrument with a greater focus on sound propagation rather than visual appeal [Usher 1956].

Throughout the Classical era, spruce continues to be exclusively used for the soundboards while local pedestrian woods predominate the selections for back, sides, and necks. In addition to maple, Mediterranean cypress (*Cupressus sempervirens)* shows up prominently with the Spanish luthiers. Unlike maple, ebony, rosewood, and other species commonly used for instrument back and sides, cypress is a conifer as opposed to a true hardwood. In addition, cypress was once plentiful in the regions surrounding the Mediterranean Sea and would have been easily accessible to the luthiers in those areas [Somogyi 2016]. Due to its relatively plain appearance, cypress most often ended up on lower-priced instruments as it lacked the visual appeal of higher prized hardwoods [Romanillos 1987].

Brazilian rosewood is utilized for back and sides during the Classical era but not to the extent of the more commonly available maple. Considering imported rosewood would have cost considerably more than locally harvested maple and cypress suggests either a fiscally conservative clientele of this period or a lack of supply [Romanillos 1987].

3.3.4 The Romantic Era (1820-1900)

The Romantic era begins amid the first industrial revolution. This period is marked by a progression of innovations that transformed nearly every aspect of life for European communities directly and communities with connections to Europe subsequently.

Significant advancements in steel-making technology by England’s Benjamin Huntsman (1704-1776) in 1742 were likely the fundamental component of industry's subsequent mechanization in the nineteenth century [Wray, Hawkins, and Giles 2001]. Of particular importance to the onset of the industrial revolution is the advancement of machine tools and the steam engine to power them. James Watt (1736-1819) and his business partner Mathew Boulton (1728-1809) are credited with the improvement of the steam engine in 1776 not only for its original intended use of pumping water but also for engines dedicated to producing powered rotational motion [Lira 2013]. Industries that once relied on the wind, water, or beasts of burden to power their mills, such as flour mills, wool mills, and sawmills, now had a consistent source of power no longer dependent on their proximity to a moving waterway or being subject to weather and wind conditions or dealing with the health and temperament of livestock [Wray, Hawkins and Giles 2001]. In fact, it was the replacement of twelve horses by a Boulton-Watt steam engine at a sawmill in 1782 that led to Watt’s characterization of energy output of a machine relative to that of an average draft horse as “horsepower”; an energy output measurement still commonly used today for virtually every type of motor or engine whether it be steam, gas or electric [Lira 2013].

In conjunction with the ability to command power-on-demand came advancements in “machine tools” at the turn of the eighteenth century. While there is a tendency to characterize machine tools as “…power-driven machines used to cut, form or shape metal” [Carlsson 1983], the development of rigid, powered machines has, in fact, far-reaching implications for other industries. The lumber industry greatly benefited from machine tool advancement and proliferation with improved machinery and blades to process logs into lumber. As a result, sawmills experienced increased productivity and utilization of raw materials leading to lower costs to wood consumers [Kirkham 1988]. This advantage was likely even more critical when processing expensive imported tropical woods [Anderson 2012]. In addition to its being a valuable commodity, tropical hardwoods are notoriously difficult to process due to their density and hardness characteristics. The use of industrial machinery outfitted with the latest cutting tool technology would undoubtedly help facilitate tropical hardwoods' growing popularity in Europe and America.

While the machine tool historically gets much more academic attention, the hand tools favored by musical instrument craftsmen would have also improved within the Industrial Revolution context. The improvements in steelmaking technology from the prior century that spawned mechanized industry wonders also shared benefits to the conventional tools of the nineteenth century. Control over steel alloys allowed precise application of steel with specific properties to a given application. Edge tools such as chisels, hand-planes, and saws saw a dramatic increase in quality as steel chemistries were identified to best maximize cutting-edges for sharpness and durability [Evans and Withey 2012]. Moreover, the utilization of machine tools for hand tool production provided superior cost-benefit and higher quality. The largest center of mechanized tool manufacturing in the nineteenth century was the city of Sheffield, England. The steel and tool manufacturing advantage enjoyed by Sheffield firms allowed it to dominate the global market well into the twentieth century [Wray, Hawkins, and Giles 2001].

Simultaneously, lumber shortages endemic to much of Europe since the seventeenth century from over-harvesting necessitated continued wood imports from timber rich regions of the world. The New World's tropical hardwoods were highly coveted primarily for shipbuilding, textile dye-making, and furniture manufacturing [Anderson 2012]. The absence of literature on the timber trade specifically for instrument making suggests it to be an inconsequential market for the nineteenth century's exotic wood importers. Luthiers likely capitalized on the timber imports intended for ships and furniture and incorporated the *avant-garde* exotic species from Africa, Asia, and the New World into their own works. This serendipitous effect of exotic lumber availability would eventually transform the guitar to nearly complete reliance on tropical hardwoods for every component except the soundboard and bracing. By the end of the nineteenth century, there was a complete paradigm shift in material preference from domestic to exotic hardwoods. Other than a spruce soundboard, the guitar's wood components, whether New or Old World, became dominated by the tropical hardwoods of Africa, Central America, and South America. With increasingly fewer exceptions, ebony, mahogany, Spanish cedar, and rosewood displaced the commonly used domestic species of maple, walnut, boxwood, and cypress.

Up until the onset of the nineteenth century, guitars were generally strung with pairs of strings, called courses. However, the advent of metal-wound bass strings precluded the need for duplicated strings to produce sufficient soundboard vibration [Sparks 2002]. Even though four-, five-, and six-course guitars continued to be produced, the six-string guitar became the most popular stringing convention for this point onward [Turnbull 1974].

As far as guitar design is concerned, the most significant event in guitar construction since its inception occurred in the mid-nineteenth century by the luthier Antonio de Torres (1817-1892). Torres is widely credited with transforming the guitar into the concert instrument that exists relatively unchanged to this day [Morrish 2002; Usher 1956]. While most guitar historians agree that the novel attributes of his instruments can be found singularly in other instruments of even the early nineteenth century, Torres amalgamated the best practices of the time to create an instrument that would be so superior that his designs would be emulated by nearly every guitar maker going forward [Evans and Evans 1977]. Most apparent is that the soundboard of the Torres guitar is approximately 20 percent larger than the standard size of that time. Torres also utilized fan braces to allow for a thinner, lower mass top that would subsequently be more responsive to string vibrations. He also popularized a bridge with a separate bone or ivory saddle that could be adjusted for string height [Morrish 2002; Romanillos 1987]. Figure 3.7 demonstrates the size difference between the Torres model and typical guitar from the early nineteenth century.

Figure 3.7: The guitar on the left is Torres serial number 112 guitar dated 1888. The instrument on the right, ca. 1840, is a guitar by the French luthier Guiot. Both images accessed March 21, 2020, https://www.metmuseum.org/, used with permission.

In addition to the design elements introduced by Torres, the tonewoods he predominately used eventually became the standard selection for most concert instruments going forward [Romanillos 1987]. In *The Classical Guitar Book: A Complete History,* Dr. Paul Sparks [2002] contends, “Torres established the use of Brazilian rosewood for the back and sides, ebony for the fingerboard, cedar for the neck and spruce for the table, a combination that became dominant for the next 150 years.” While it is true that these wood species did, in fact, become the *course de rigueur* for concert instruments going forward, their use was already sporadically established, as evidenced by the instruments listed in Appendix I.

The widespread notoriety of the Torres guitar was likely due largely to the patronage of Fancisco Tarrega (1852-1909). Considered by some as the "father of the classical guitar", Tarrega was not only a guitar virtuoso but also a successful composer. Tarrega found in the Torres' guitar an instrument that produced greater expression and nuance versus what was previously being produced by other luthiers [Libin 2001; Arriaga 1991b]. There was an additional musicality in the Torres guitar that stood in contrast to the "brash" instruments otherwise common in the Romantic era [Alves 2015; Morrish 2002]. As the most influential guitar player of his time, Tarrega's touring with a Torres guitar probably had much to do with Torres' notoriety and the proliferation of his advancements [Usher 1956].

Tarrega owned three instruments made by de Torres. The first was serial number FE 17, which was acquired by Tarrega in 1869. This instrument had a spruce top, figured maple back and sides, and a cedar neck. His second acquisition, serial number SE 49, was similar in construction to FE 17 and was meant to replace the previous instrument that suffered from the structural degradation caused by years of use and string tension. The final acquisition, SE114 from 1888, differed from the previous two de Torres guitars in that the back and sides were made from Brazilian rosewood. While there is little doubt Tarrega was fond of the first two acquisitions, the Brazilian rosewood guitar was said to be his favorite [Romanillos 1987].

Another significant event of the Romantic era for the future of guitar manufacturing was the emigration of Charles Frederik Martin (1796-1873) from Saxony to New York City in 1833. Having apprenticed with the venerable guitar maker Johann Stauffer (1778-1853) in Vienna, Martin is much credited with establishing the American guitar making industry that has survived to this day [Johnston, Boak, and Longwirth 1988]. From its humble beginning in New York and subsequent move to Pennsylvania in 1839, C.F. Martin and Co. would become one of the most successful guitar-making concerns in history, producing over one-million guitars to date [Johnston, Boak, and Longwirth 1988]. While initially building gut-strung guitars typical of European instruments, C.F. Martin and Co. would eventually become best known for producing high-end steel-string guitars.

In addition to American luthiers' eventual focus towards steel-string instruments, there was a fundamental difference in the guitar manufacture approach between the European and American luthiers by the end of the nineteenth century. While primarily individual lutherie continued in Europe, the American approach was to modernize manufacturing by employing a production line of workers who carried out specific tasks within the guitar making process [Teagle 1996]. In contrast, European shops were either a one-person affair, who engaged in every building detail of every instrument or small shops that allowed workers or apprentices to build instruments start to finish, yet carry the name of the shop owner [Dawe and Dawe 2001]. In the end, while both may have benefitted from advancements of the industrial revolution, the European luthiers resisted the mass production model while the American's fully embraced worker-task specialization [Somogyi 2009a]. Henceforth, European guitars would maintain an identity to a specific luthier's name while American instruments would maintain an identity to a company. However, even within the small European shops, the luthier responsible for a guitar's construction would usually sign the guitar somewhere within [Kai 2019].

Towards the close of the nineteenth century, one final event marked the end of the Romantic era—the introduction of the steel-string guitar. While steel-strings can be traced back to the late sixteenth century and used most notably on the cittern and Neapolitan mandolin, it was not until the last decade of the nineteenth century that steel-strings were introduced to the guitar [Martin 2014]. Prior to this debut, guitars used strings made from animal intestines' natural fibers, often referred to as catgut (even though it was most often sheep or goat intestine and not that of a cat). This event delineates the formal separation of what is differentiated today as the “classical guitar” and the “western steel-string guitar.” Even though the steel-string guitar is of relatively recent development, there is a dispute about who might be attributed the credit of its introduction. While Orville Gibson (1856-1918) is often considered the first to introduce steel strings to the guitar, many argue that it was, in fact, the Swedish immigrants Carl and August Larson of Chicago that should be given credit. Since Gibson used steel strings on an archtop guitar while the Larson’s modified their flat-top guitar designs in the 1890s specifically to withstand the additional tension produced by steel strings, it would be reasonable to, at the very least, conclude that the Larson brothers were the first to employ steel-strings on flat-top acoustic guitars [Gruhn and Carter 1993; Bacon 2001; Somogyi 2009a].

The span of the romantic era marks an undeniable coming of age within the evolution of the guitar. Luthiers had full access to the world's wood resources and demonstrated a proclivity for tropical hardwoods to replace domestic offering for structural components. The industrial revolution brought advancements for lumber processing and tools for instrument manufacturing, whether it be steel-edge tools for the traditionally oriented European luthiers or industrial machinery for the factory-focused American guitar manufacturers. Additionally, guitar performance continued to flourish not only as a personal pursuit in the home parlor but also in the concert halls of Europe by virtuoso musicians. Furthermore, perhaps the most important events for the instrument's future were twofold: the development of the modern classical guitar by Torres and the modern steel-string guitar by the Larson brothers.

3.3.5 The Twentieth Century to Present (1900+)

Although the classical guitar as we know it has seen little change since de Torres’ standardization in the mid-nineteenth century, the guitar as a broader instrument family has seen tremendous divergence starting at the turn of the twentieth century. While the classical guitar exists at the top of this new family tree, the branches below include in no specific order: the archtop guitar, the steel-string flat-top guitar, the gypsy-jazz guitar, the Hawaiian slide guitar, the bass guitar, the resonator guitar, the pedal steel guitar, and of course, the electric guitar in its numerous forms. In addition, the materials used for these instruments expanded beyond the traditional wood products seen up to this point. The use of plastic, Formica, plywood, fiberglass, metals, and carbon fiber were all implemented during the twentieth century with multiple intentions; sometimes to further the instrument, sometimes to make it as inexpensive as possible. While most of the material substitution attempts to reduce cost inevitably failed, some of the novel material experimentation succeeded in gaining acceptance to some extent. For instance, the Ovation company successfully introduced fiberglass to replace the back and sides in 1965 and continue to build instruments for amateur and professional musicians to this day [Martin 1998]. Another example is the use of metal “cones” to effectively replace the guitar's soundboard in the attempt to increase volume - and so was born the “resonator” guitar [Martin 1998]. As there is much research available on each of these topics specifically, this overview will limit its scope to flat-top guitars. This section will also briefly discuss some of the key players, makers, and events of the twentieth century that furthered the popularity and success of the guitar.

3.3.5.1 Prominent Musicians and Music Forms

No discussion of prominent twentieth-century guitar players would be complete, or even credible, without first starting with Andrés Segovia (1893-1987). At a time when the guitar was at risk of being relegated to the folk music of taverns, cabarets, and *tablaos*, Segovia was principally responsible for elevating the instrument to concert hall credibility [Alves 2015; Tannenbaum 2003]. Segovia not only performed the familiar music of his predecessors but also inspired composers to produce over 500 new works intended explicitly for his repertoire [Turnbull 1974; Tanenbaum 2003]. Throughout his nearly eighty-year performing career, Segovia toured relentlessly bringing his music to every continent's concert halls save Antarctica [Wade 2002; Tanenbaum 2011]. During his performance and recording career Segovia played primarily four guitars; a Manuel Ramirez (1864-1916) that is accredited to his apprentice Santos Hernandez (1873-1943), a Herman Hauser (1882-1952), and Ignacio Fleta (1897-1977), and a José Ramirez III (1922-1995) purportedly made by Paulino Bernabe (1932-2007) [O'Hara 2014]. Famously, it was of his Hauser guitar that Segovia claimed; this is “the greatest guitar of our epoch” [Courtnall 1993]. Segovia was not only the dominant guitar player of the first half of the twentieth century, he is also credited with helping bring the invention of nylon strings to fruition with Albert Augustine (1900-1967) in 1949; an invention that effectively replaced the use of gut strings and remains in use today [Tanenbaum 2011; Alves 2015; Turnbull 1974].

Even though Segovia continued to perform publicly until his death in 1987, his legacy was furthered by numerous performers by the middle of the twentieth century. Fortunately, there is a tremendous amount of literature available on the talented multitudes of late-twentieth-century guitarists as the scope of this research only allows for the mention of two: English born Julian Bream (1933-2020) and Australian John Williams (1941-). While there is little question to these two musicians' virtuosity, their inclusion is made here to point out the reach of their work as much as the quality of it. It is the consumption of their music, live and recorded, that demonstrates the popularity of the classical guitar and its importance in this era.

It has been said that Bream is better known for his musicality than for his technical achievements [Tanenbaum 2003]. Nevertheless, like Segovia, composers were eager to write music for his *repertoire*. Indeed, one of the significant contributions Bream made to the music catalog as a whole was to move away from the predominant Spanish influence that existed for the classical guitar in the first part of the century [Tanenbaum 2003]. Bream toured extensively, bringing live performances to Europe, the USA, Australia, Southeast Asia, and beyond. Besides his live performances and nearly ninety record and CD releases, Bream also engaged the video realm with his DVD *Julian Bream: My Life in Music* in 2006 [Alves 2015].

The guitarist John Christopher Williams, not to be confused with film composer John Towner Williams (1932-), is often mentioned in the same breath as his contemporary Bream and is noteworthy for many of the same reasons [Tanenbaum 2003]. Since the beginning of his recording career in 1958, Williams has released over 150 albums and has traversed the globe for live performances And, like Segovia and Bream, composers were eager to write new material for him. Of particular note is Williams's performance of Cavatina by Stanley Myer for the soundtrack of the film The Deer Hunter [Wade 2002]. However, perhaps the most important aspect of Williams's career is how he managed to straddle multiple musical genres and even crossed over to pop music with his quasi-rock band Sky [Tanenbaum 2003].

While these three classical guitar icons are mentioned partially for their prominent celebrity status, the true impact of their work cannot be understated. Segovia, Bream, and Williams brought guitar music from its traditional western-hemisphere boundary to the rest of the world. Through performances, recordings, video productions, film soundtracks, and radio play, classical guitar music became available to a world audience. Also significant is the twentieth-century advent of audio and video recording technology, the performances of these artists and their contemporaries can be captured and experienced in perpetuity. Moreover, recording technology exposed the world to the classical guitar and was fundamental in disseminating new guitar musical genres that arose during the twentieth century.

Arguably the most significant musical genre to develop in the twentieth century is American folk music. While rooted in the traditional ballads, hymns, and working songs of the nineteenth century, American folk music does not have a specific definition but, instead, covers the multitude of musical styles that mutated, evolved, and transcended from the previous century. From humble, informal beginnings, there developed Delta blues, country and western, bluegrass, gospel, Cajun, jazz, and, of course, rock and roll. Furthermore, in them all, the steel-string guitar played prominently [Gerken et al. 2003].

Throughout the transcendence of the blues, the guitar was the prominent accompaniment. Especially in the early decades' Delta blues recordings of the prominent artists such as Robert Johnson (1911-1938), William “Lead Belly” Ledbetter (1888-1949), Freddie Spruell (1893-1956), and Elizabeth Cotten (1893-1987), to name a few, were mostly solo ballads accompanied by a single guitar. Towards the middle of the twentieth century, blues often relied on small ensembles, likely incorporating a bass guitar, piano, drums, and sometimes brass instruments. A notable example is the 1956 recording of “Smokestack Lightning**”** by Howlin’ Wolf (1910-1976). Accompanied by bass, drums, piano, and harmonica, the song's central musical theme is carried most conspicuously by the guitar. Of additional significance is that “Smokestack Lightning” has been recorded by innumerable blues and rock & roll artists since its original release.

Another American folk music genre with which the steel-string guitar found prominence is that of the “Singing Cowboy” popularized in the Hollywood films of the 1930s and 40s. These films portrayed guitar playing actors whose songs romanticized the cowboys of the old American West. Gene Autry (1907-1998) was arguably the most famous appearing in over ninety movies. He made over 640 recordings during his career and hosted *Gene Autry’s Melody Ranch* show weekly on CBS radio from 1940-1956. In addition to the number of young “buckaroos” Autry inspired to play the songs he made famous in his movies and recordings; he was also one of the pioneers of the burgeoning country music genre [Lacy 2010].

What was initially referred to as hillbilly music in the first decades of the twentieth century morphed into multiple musical styles; country, western swing, and bluegrass were the most familiar. Much like the blues, country music developed out of the previous centuries, musical traditions often combining folk influences from American immigrants’ home countries [Holt, Green and Wilson 2013]. In Bluegrass, for example, one can hear the influence of the Irish in the fiddle, the Italians in the mandolin, the Africans in the banjo, and of course, the Spanish in the guitar. Characterized by simple lyrics and simple chord progressions, country music was the music of the common man and could be performed and enjoyed without adherence to any formal musical education. Country music is often characterized as being the music of the working class and, as such, had a broad audience with which to gain popularity. Due to its foundation of simplicity, the music could be performed by nearly anyone with the knowledge of three to four guitar chords. With relative ease, amateurs often learned by listening to records their favorite tunes by artists such as The Carter Family, Johnny Cash, Willie Nelson, or Emmylou Harris, to name a few. However, while country music may be characterized as simple in general, this is not to say the genre did not have its share of guitar paragons. One need only hear the flatpicking of Arthel Lane “Doc” Watson or the fingerstyle of Clarence White and Chester “Chet” Burton Atkins to realize the level of virtuosity to which a simple music form can ascend.

While Country was the music of the working man, the mid-century birth of Rock & Roll was the music of America's young generation that would eventually transcend its geographic border and age demographic and become the most popular music form in the world [Dredge 2019]. Once again, at its core, was the guitar. Although predominated by the electric guitar, the steel-string acoustic was conspicuous within sub-genres of folk- and country-rock artists like Neil Young, Bob Dylan, James Taylor, Paul Simon, John Denver, Dave Mathews, to name a few. Even hard-rock bands such as The Who, Led Zeppelin, the Grateful Dead, and the Rolling Stones sprinkled in acoustic guitar accompanied songs amidst their quintessential electric guitar offerings. What is more, beginning in 1989, eight years after its inception, the cable television channel MTV further popularized acoustic performances by producing televised coverage of rock bands performing predominantly on acoustic instruments. Electric guitar-centric performers like Eric Clapton, Stevie Ray Vaughn, The Eagles, Pearl Jam, and Nirvana played full sets with the uncharacteristic use of steel-string flattop guitars. Many of these performances were additionally released as records and CDs and found additional commercial success in that format as well. The popularity of these performances indicates that Rock & Roll was not limited to electrification. The acoustic guitar could in fact feature prominently with audience approval; not to mention the new way amateur guitar players could discover new interpretations for their favorite rock songs.

Curiously, the twentieth-century artists that most conspicuously promoted the guitar's musical potential are arguably the number of sub-genres that will be grouped together here and referred to as "New Age" music. The category New Age is often used as the label applied to music produced in the latter part of the twentieth century that does not fall under other headings yet does not have the breadth of material to warrant its own category. For the scope of this research, New Age will be used narrowly to define the acoustic instrumental music produced from the late 1960s onward and not the broader definition of New Age music that often includes electronica and recorded or synthesized sounds of nature.

New Age music developed in stark contrast to the highly commercialized and popular Rock & Roll that dominated radio play and record sales in the latter part of the twentieth century. A singular definition of the music style is difficult as it draws influence from folk, classical, jazz, and ethnic music [Coffey 2013]. The music is best described as solo instrumental pieces that did not rely on the multiple tracks or overdubs that were common in the music production industry. Thus, musicianship was of greater importance as the recording process did not rely on the production techniques to improve the outcomes. Most often, the recording process relied solely on an instrumental performance played straight through and recorded simply with microphones [Whitesel 2010]. In turn, this technique made greater demands on the quality of performance instruments as they were indeed played acoustically and did not rely on sound processing equipment to change or improve the sound output. In a sense, the New Age genre's acoustic instrumental music was more akin to previous centuries' classical music than it was to the pop music of its own era. Because these musicians had very demanding and specific needs of their guitars, they often turned to the emerging independent American steel-string luthier community that was just barely gaining momentum in the early 1970s in search of superior instruments. Fingerstyle-guitar pioneers such as William Ackerman, Alex De Grassi, Michael Hedges, Andrew York, and Phil Keaggy, to name a few, sought out the finest handcrafted guitars in lieu of the mass-produced factory instruments that dominated the steel-string industry up to this point. Over the following decades, luthiers such as James Olson, Ervin Somogyi, Jeff Traugott, Linda Manzer, and others went on to elevate a cottage industry into prominence in close resemblance to the artistry that has eternally existed in the classical guitar traditions of Europe.

3.3.5.2 The "Golden Age" of Luthiery

What might be most remarkable is the fact that individual lutherie came to exist outside of Europe without the benefit of formal training or traditional apprenticeship practices. As American luthier pioneer Ervin Somogyi remembers, "We were just a bunch of eccentric odd-ball misfits, operating between the cracks [Shaw 2008]." For the most part, the early luthier community came from an instrument repair background and honed their skills and knowledge through dismantling and re-assembling damaged guitars [Shaw 2008]. The only early assistance to actual instrument construction came from Irving Sloane's [1964] treatise *Classic Guitar Construction*. Thereafter followed other volumes to add to the luthier library such as Arthur Overholtzer's [1974] *Classic Guitar Making* and David Young's [1975] *The Steel String Guitar: Construction and Repair*.

Individual success lead some of these independent makers to venture into formalized production to compete against the established factories of C.F. Martin, Gibson, Guild, Harmony, etc. Early entrepreneurs such as Michael Gurian, Stuart Mossman, and Jean Larrivée established small-scale production companies maintaining the "boutique" quality ethos that attracted consumers to works of individual luthiers. In addition to producing high quality, well-crafted instruments, these concerns inadvertently made an even greater contribution to modern luthiery – the propagation of highly skilled guitar makers that would eventually build instruments under their own labels. In addition to making guitars, these small-scale companies made luthiers. A few of the most highly regarded luthiers started their distinguished careers apprenticing for these small manufacturers. Some of these notable individuals are Joe Veilette, William Cumpiano, Sergei de Jonge, William "Grit" Laskin, Linda Manzer, Michael Millard, and Thomas Humphrey, to name a few.

In addition to the knowledge and skill transfer that coincides with an apprenticeship tradition, this developing community of luthiers bucked the industrial trend of trade secrets, opting to share knowledge, methods, techniques, and areas of success freely with other guitar makers. One of the early forums for this exchange was the Guild of American Luthiers, which started in 1972. In contrast to historical guilds that protected the secrets of limited members, this novel guild was open to anyone interested in furthering their knowledge regarding lutherie. An excerpt from the guild's webpage [2020] explains their mission and contribution best:

> Started by a group of budding craftsmen in 1972, the Guild of American Luthiers has grown to become a driving force in the current "Golden Age" of lutherie through its constant commitment to a free exchange of information among luthiers of all areas and experience levels. Makers and repairers of guitars of all types, mandolins, violins, lutes, and other stringed instruments have found in the Guild's publications and meetings a place to share their expertise and developing techniques, and to learn from the experience, successes, and trials of others in the field. In over forty years, we have published almost 200 journals, ten books, and dozens of instrument plans. Thousands of members and hundreds of authors and presenters, including many of the world's foremost luthiers, have supported the Guild's free exchange of information and created a culture of openness that has helped advance the craft to the incredibly high level we see today.

As indicated in the text above, the guild not only shared expertise with practicing professional luthiers but amateurs as well. This dissemination of knowledge brought luthiery to thousands of other individuals who wished to build instruments even if just for a hobby or merely for making an instrument for ones personal use.

This is not to say that success for the independent luthiers was an easy road. Makers of "boutique" instruments lacked the distribution network and marketing budgets of the established firms like Martin and Gibson. The makers had to overcome the consumer reluctance to spend more money on an instrument made by someone with whom they were unfamiliar [Turner 2000]. This task was eventually made easier in the 1990s with the proliferation of the internet. The ubiquitous website became the virtual storefront of anyone wishing to reach a consumer market beyond the limitations of a printed ad or word of mouth. Another advent was the boutique guitar shop that specifically represented the works of individual luthiers. In addition to having an internet presence, shops such as Classic Guitars International, Dream Guitars, Guitar Gallery, and Fine Guitar Consultants carried inventory, allowing potential customers the ability to compare and evaluate an instrument before purchase. In a single location, a potential customer might have dozens of luthiers' guitars to assess. This ability to experience the sound, playability, and craftsmanship firsthand undoubtedly helped overcome any insecurity of taking a chance on an otherwise unknown commodity.

Another benefit for luthiers provided by the internet was a means to promote boutique guitar shows, often drawing international attendance. At no other time did luthiers have foot traffic numbering in the thousands inspecting their wares. At no other time did guitar enthusiasts have access to hundreds of luthiers displaying their finest works. These shows facilitated a considerable assemblage of makers and customers that would not be practical in any other way.

3.3.5.3 Music Genre Lines Blurred

Just as the Spanish classical guitar expanded its reach across the globe, the American steel-string guitar has also found international prominence with both players and makers. Fingerstyle guitar music expanded its reach to encompass and build on the folk traditions in other countries around the world. One of the more interesting developments that occurred in conjunction within "World Music" fingerstyle guitar playing was the exploration of alternative guitar tunings. With open-chord style tunings, musicians were able to evoke emotive arrangements otherwise unattainable with standard tuning. Probably the most prominent use was in new arrangements of traditional Celtic tunes. A few of the more prominent artists to have success with this style were England’s Martin Simpson, Scotland’s Tony McManus, France’s Pierre Bensusan, and Ireland’s Paul Brady. Other notable world-music guitarists outside of the Celtic revival were Australia’s Tommy Emmanuel, South Africa’s Tony Cox, and Benin’s Lionel Loueke, to name a few. And finally, taking the steel-string guitar to the music before its inception, was John Renbourn. Renbourn, in addition to his folk repertoire, recorded Renaissance era lute music using the steel-string guitar [Kemp 2021].

Another twentieth-century development worth noting is the cross-over use of steel-string and classical guitars. Classical guitars, once the limited purview of traditional classical and flamenco music, became prevalent in broader musical styles such as Brazilian Bossa Nova, Argentinian Tango, Mexican Mariachi, and various Cuban genres. The classical guitar also moved into the jazz realm with players such as Chet Atkins, Al Di Meola, and Earl Klugh. Moreover, despite early dominance by electric and steel-string guitars, the classical guitar can also be found in country music and rock & roll; early on to evoke the signature sound of Willie Nelson to most recently in the stadium concerts of Zac Brown. In like manner, the steel-string guitar has been embraced to perform the music once relegated to the classical guitar. John Renbourn and Michael Chapdelaine are two prominent musicians that performed classical arrangements on the steel-string guitar; however, many modern steel-string-instrumental compositions could arguably be characterized as modern classical music as well.

In 1962 Decca Records’ Dick Rowe passed on a recording contract with The Beatles having infamously prophesized to their manager, “Guitar groups are on their way out, Mr. Epstein” [Viner 2012]. Using any metric, there has never been a prophecy so wrong. By the end of the twentieth century, it would seem that all music can be guitar music, and the lines that once distinguished the classical guitar from the steel-string guitar have, at the very least, been blurred, if not obliterated. Moreover, the instrument needs of the world’s guitarists are as varied as the music being performed. The guitar manufacturing industry has correspondingly developed to meet those needs, from inexpensive beginners’ guitars costing under $50 to custom made concert instruments that reach well into the tens of thousands. In addition to these are the highly ornate collector instruments reminiscent of those from the baroque era. While there are factories that mass produce instruments without much concern for sound or artistry, the high-end luthiers maintain the pursuit of advancing the art. With thousands of luthiers around the world actively aspiring to build the elusive “best” guitar, esteemed luthier Rick Turner [2000] contends, “Now, at the beginning of the twenty-first century, the state of lutherie is right up front and in the present tense. Don’t look back; you are living in the Golden Age of Lutherie.” Chris Martin IV of C.F. Martin & Co. echoes this sentiment saying of the luthier renaissance, “There have never been guitars built on Earth as good as the ones being built today” [Shaw 2008].

3.3.5.4 The Quintessential Modern Acoustic Guitar(s)

After six centuries of evolution, it might seem that the guitar should have attained some coalesced paradigm. However, at the dawn of the twenty-first century, nothing could be further from the truth. While it might seem the instrument had attained such a paradigm after the standards popularized by de Torres, the arrival of the steel-string guitar at the turn of the twentieth century certainly complicated things. Nevertheless, even the choice of stringing material aside, the differentiation of the instrument continues to expand with novel shapes, bracing designs, and alternative building materials. Yet, despite the multitude of models to choose from, there seems to be one aspect of the guitar that has remained in singular high regard amongst its enthusiasts; the quintessential materials with which the instrument is made.

Generally accepted within the guitar community, the instrument at its apex is made with a spruce soundboard, Brazilian rosewood back and sides, mahogany or Spanish cedar neck, ebony fretboard, and either an ebony or rosewood bridge [Romanillos 1987; Usher 1956]. For most of the twentieth century, the finest instruments of luthiers and factories alike were made as such [Johnston, Boak, and Longworth 2009; Somogyi 2009a; Wegst 2006]. The irony, of course, is that the instrument of Spanish origin no longer uses any materials from its native land – with the exception of Mediterranean cypress for traditional flamenco guitars. With the advent of global trade, the guitar was able to take advantage of specific woods for optimal function, visual aesthetic, or the combination of the two. Freed from the constraint to rely solely on domestic offerings, the premier woods used to make high-end guitars are sourced globally; the spruce for soundboards come from the European Alps and North American mountain ranges; the ebony from Africa, India, and the Indonesian archipelago; the various rosewoods from the world's tropical regions; Spanish cedar, and mahogany from South America, Central America, and the West Indies.

3.4 Summary

Chapter 3 explored the guitar's development from its first distinguishable form, the fifteenth-century vihuela, through five centuries of evolution. Existent historical instruments provided the basis for illustrating the broader changes in material selection during this span. This section also explored the historical events that led to the ultimate coalescence of a standardized instrument in its highest form. While spruce remained firmly the quintessential choice for the guitar soundboards throughout, the tonewoods selected for the other components went through significant transformations. With the advent of trans-oceanic trade in the sixteenth century, tropical hardwoods were quickly adopted into the structural components of even late Renaissance instruments. The preserved instruments from the Baroque era demonstrated an affinity for the ostentatious, exploiting the instrument's body as an artistic medium to execute lavish inlays and marquetry of tortoiseshell, ivory, and mother-of-pearl. The classical era saw an aesthetic movement towards the austere that has generally prevailed from this point onward. In addition, European maple was prominently selected for instrument back and sides, likely the consequence of local availability and its common use for other stringed instruments that were part of a luthier's repertoire. While maple has seen continued use throughout the Romantic era and twentieth century, Brazilian rosewood eventually established itself as the preferred soundbox tonewood by the middle of the nineteenth century. Concurrently, Spanish cedar and Honduran mahogany became the typical selection for guitar necks. With the standardization of the modern acoustic guitar by Torres in the mid-nineteenth century, the instrument at its apex consisted of a spruce soundboard, Brazilian rosewood back and sides, and a mahogany or cedar neck. Temperate hardwoods, on the other hand, were most often relegated to the secondary offerings or introductory models.

Advancements of the twentieth provided an optimal scenario for the increase in the guitar's popularity, be it the gut/nylon-string classical guitar or the recently inaugurated steel-string guitar. The guitar's music reached a global audience early through touring musicians, recordings, radio, movies, and eventually TV and video. Additionally, populist ethnic folk music's advent in the early twentieth century spawned a multitude of guitar-centric genres such as Blues, Bluegrass, Country, and Rock & Roll. This music was simple in form and easily performed by would-be guitarists without the need for any formal training. Modern manufacturing practices enabled instrument production for virtually every affordability level, from cheap toylike children's instruments to more serious musicians' higher quality instruments. By the end of the twentieth century, the guitar became one of the world's most popular instruments. Out of this popularity, contrary to the factory model that has dominated twentieth-century production practices, arose a new "Golden Age" of luthiery. The individual luthier model that has endured in Europe was finally realized in the United States as musicians sought specialized guitars outside the scope of what was offered by factory-made instruments. Subsequent demand for artistically hand-crafted guitars broadened the support for an expanding independent luthier production model. This independent luthier model fostered a guitar quality renaissance that until then suffered under the constraints of the mass-production model.

Chapter 3 – The Guitar: Historical Background and Development

Chapter 4

Guitar Woods

4.1 The Woods of the World

We may take for granted the ease with which materials are sourced in the modern era. With the click of a computer key, a transaction from the other side of the world can be consummated, paid, and arrive in a week. Needless to point out, this was not always the case. Indeed, at the time of the guitar’s inception, the other side of the world was merely a theory. Prior to the voyage of Bartholomew Diaz (1450 – 1500) in 1488 around the southern tip of Africa and on to India, trade with the Near or the Far East depended solely on draft-animal driven carts on the “Silk Road”; hardly conducive for unwieldy timber shipments. Serendipitously, the dawn of the guitar’s evolution arrived at the same time world trade on a grand scale also saw its onset. Transportation aside, another consideration is why the woods that ultimately make up the guitar’s structural components were chosen out of thousands of potential wood species to make their way to the luthiers of Europe.

4.2 New World Exports

Timber resources from the New World commenced shortly after Christopher Columbus’ (1451-1506) “discovery” in 1492. Warren Dean contends in *With Broadax and Firebrand* [1995], a treatise on the exploitation of Brazilian resources:

> This (first) messenger ship (of 1500), or perhaps the next expedition of 1501, was the first to bring back samples of the earliest of Brazil’s treasures. This was a dyewood, called *ibirapitanga* – red tree – by the

> Tupi, who colored their cotton fibers with it. The Portuguese called it *pau-brasil*, probably from *brasa* – glowing coal.

Coincidentally, in addition to becoming the primary export of early Colonial Brasil, pau-brasil is also known today as Pernambuco, the favored wood used for the bows of concert string instruments.

In addition to brazilwood, merchants fetched other hardwoods from the Brazilian Atlantic Forest primarily for France's markets. Their penchant for brightly colored fabrics and cabinetry made from the visually stunning Brazilian hardwoods caused deforestation that even alarmed the Portuguese crown near the end of the sixteenth century. By 1607, Portugal limited brazilwood imports to 600 tons a year; a drastic reduction from an estimated 12,000 tons removed in previous years by “concessionaires” and smugglers combined. Often, the large non-dyewood logs traveled free of charge on ships returning to Europe as means of ballast [Dean 1995].

By the eighteenth century, the Brazilian hardwoods came to be recognized for their advantage in shipbuilding. Compared with temperate climate European hardwoods, the New World tropical hardwoods possessed superior strength to weight characteristics and, in some cases, high resistance to marine parasites [Revels 2002]. By the mid-eighteenth-century Brazilian shipyards became a primary producer for both naval and merchant ships [Dean 1995]. In addition, as pointed out by Y. Eyüp Özveren [2000]:

> “…it went without saying that the location of shipyards was determined primarily by proximity to timber resources. Thus, not surprisingly, all shipyards in this era had, at one point or another in their history, benefitted from a relatively easy access by navigable rivers to forests in their hinterland. Depletion of these resources correlated strongly with the downgrading or virtual elimination of shipyards”.

In other words, as Europe depleted the oak forests once venerated for shipbuilding, the Brazilian coast was a conspicuous location for shipbuilding with easy access to the superior timbers of the Atlantic Forest. Moreover, with shipbuilding came the infrastructure to process trees to lumber. In Sau Paulo alone, there were fifty-three sawmills by 1838 [Dean 1995].

Ironically, some of the prized Atlantic Forest woods that started as components of warships were subsequently repurposed to other uses. According to Craig Revels [2002], "Even extremely old mahogany Spanish ships captured by the English were broken up and the pieces redistributed." Perhaps the re-purposed keel of a Portuguese man-of-war found new life as a guitar.

4.3 The Ebonies of Africa and Asia

Ebony made its way into lutherie in a fashion somewhat similar to the hardwoods of the New World. However, rather than being a byproduct of dyewood shipments, ebony found its way onboard as a tag-along to the highly profitable commodity of spices from the Asian sub-continent. In particular, it was the pepper trade that initially lured the Portuguese and later the Dutch and English to the Malabar coast's port markets in southwest India beginning in the late fifteenth century [Disney 1977].

In addition to the ebony found in the Indian markets, the European traders also exploited ebony resources from the countries where they possessed ports of call on the sea route between Europe and India. For the Portuguese, their trading posts in Mozambique provided a substantial source of ebony. By the early seventeenth century, each Portuguese ship was instructed to return with roughly 12,000 kg of ebony along with their more lucrative cargo of pepper [de Silva 1974].

The Dutch notably sourced their ebony from Mauritius, an island in the Indian Ocean, which they held as a trading post. According to Vilhelm Slomann [1934], "The Dutch East India Company took possession of Mauritius in 1638, but in 1710 gave it up because there was no more ebony left.” Much like the hardwoods of the New World, ebony’s primary market was for the high-end furnishings of Europe’s upper class. Slomann also notes, “The first *maîtres ébéniste* (ebony craftsmen) in Paris are mentioned in 1638, and from about that date, ebony became one of the most appreciated kinds of *‘Bois des Indies’* for furniture in Europe.”

Surprisingly, there exists virtually no mention of systematic ebony timber exportation during this period to England. While the early English East India Company did indeed partake in the timber trade and the more lucrative spice trade, it appears their efforts were primarily restricted to materials critical to shipbuilding, teak in particular [Cross 1994]. Even so, as English ships visited ports of call with inventories of ebony, it would be reasonable to assume that ships procured smattering quantities, if only on a novelty level [Erikson 2014].

4.4 Summary

Ultimately, the hardwoods that came to dominate the guitar's structural elements became available through events well outside the context of lutherie itself. The advent of foreign exploration and trade made it possible to introduce exotic woods to markets once relegated to local species alone. The fact that larger industries, warship and furniture manufacturing, in particular, created a market lucrative enough to warrant the cost of extraction and transportation allowed the relatively meager supply needs of guitar makers to be fulfilled. By the time de Torres developed what is known as the modern guitar, luthiers had access to the woods of the world to advance their craft.

Chapter 5

Tonewood Evolution

5.1 Background

As alluded to earlier, the guitar's visual aesthetic changed over time in periods almost conforming to the commonly accepted musical eras. While the lack of surviving instruments from the Renaissance leaves a bit of a void at the onset, the instruments preserved in collections give some evidence of the prevailing tastes of each era. The only material constant throughout the guitar's history is spruce, which never wavers as the preferred wood used for the soundboard. Though, the other structural materials go through a series of changes before settling on a rather consistent formula from the end of the Romantic period to the present. Historically, conventional wisdom presumed the soundboard was the primary, if not exclusive, sound-producing element, whereas the other components were merely structural in nature. Of course, this would allow for some artistic license by the luthier to present those components in an attractive manner for marketing purposes. While the Baroque era employed the abundant use of exotic materials such as tortoiseshell, ivory, and ebony veneers, the Classical era was much more subdued, predominantly utilizing maple; perhaps to emulate the violin, which was the most highly regarded instrument in the concert halls of that era [Burkholder 2010]. However, at the dawn of the nineteenth century, the East and West's exotic woods started to predominate the guitar’s structural components. By this time, European wood importers had access to the four corners of the globe and seemingly unending choices of woods to market. Nonetheless, there rose to popularity a select few that were held in the highest regard. As the luthier market was relatively small compared to other exotic wood demand industries, likely, any development of aesthetic preferences started elsewhere before progressing to the guitar. This section will review the woods predominantly employed as structural components in luthiery using photographs of samples to demonstrate visual impact and correlate their popularity with the largest consumer of exotic timber, high-end furniture, and cabinetry [Cross 1994].

5.2 Temperate Hardwoods

Prior to the opening of global trade routes at the end of the fifteenth century, luthiery depended on the tree species indigenous to the regions where manufacturing took place. Locally sourced maple, cypress, and a lesser amount of beech and walnut were used for chordophones' structural components before tropical hardwood supply became available. While the tropical hardwoods eventual came to replace the domestic offerings, cypress and maple have continued to be used to some extent even to this day. For instance, cypress is still synonymous with the flamenco guitar while maple is sporadically utilized for both classical and steel-string guitars, not to mention frequent use on modern lutes and complete dominance throughout history in the violin family. The following explores the two most prevalently used temperate hardwoods that have been used throughout the history of the guitar.

5.2.1 Cypress

Figure 5.1: These photos show a closeup of a typical Mediterranean cypress sample (left) and its use on a guitar by Sanchez de Aguiler, 1797 (right). Wood photo by author. Guitar photo accessed March 21, 2020, https://www.metmuseum.org/, used with permission.

Mediterranean cypress is by far the plainest of the woods used for guitar backs and sides. Its straw-yellow coloration and plain, straight grain are without distinction from many other common temperate hardwoods, as shown in Figure 5.1 above. Native to the eastern Mediterranean regions, cypress was transplanted to Spain and Italy as an ornamental specimen. Due to its natural resistance to weather rot, cypress was historically often used for the ignoble purpose of fence posts [Meier 2016]. Nonetheless, cypress wood has become synonymous with flamenco guitars. As cypress guitars came to prevalence in the nineteenth century, luthiers did not differentiate between concert and flamenco guitars but instead used the relatively inexpensive cypress on their lower-priced instruments. Since the flamenco tradition grew from the working-class *barrios* of southern Spain, the less-expensive cypress instruments were most commonly acquired by its musicians [Somogyi 2016; Gerken et al. 2003]. Cypress guitars are thought to have a loud, percussive, and articulate sound that helped cut through the din of a Roma *gitano* or Spanish *tablao* [Morrish 2002]. Ironically, due to the overexploitation of cypress, the wood procured for a modern flamenco guitar in the twenty-first century costs as much as Indian rosewood (*Dalbergia latifolia*), approximately $150 U.S. [LMII.com 2020]. However, in the early days, cypress was employed purely as an inexpensive yet functional wood without concern for visual aesthetic [Romanillos 1987].

5.2.2 Maple

Figure 5.2: Photographs of a figured maple sample and its use on a guitar by José Massague, ca. 1755-1760. Sample photo by author. Guitar photo accessed March 22, 2020, https://www.metmuseum.org/, used with permission.

Historically, maples (*Acer spp.*) have been used extensively across many forms of chordophones, including lutes, citterns, violins, and guitars. While there are few surviving instruments before the end of the medieval era, surviving instruments held in collections suggest maple was a favored tonewood prior to the evidence available of physical specimens. See Figure 5.3.

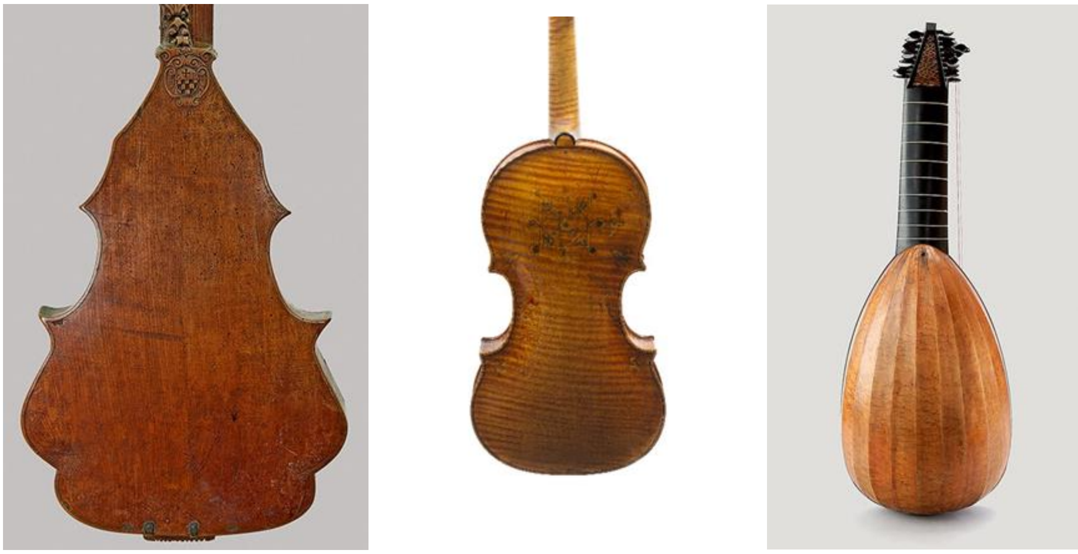


Figure 5.3: Photographs demonstrating the use of maple on, from left to right, a Rafaelo a Urbino cittern (ca. 1540), Andrea Amati violin (ca. 1560), and Thomas Edlinger lute (1728). Photos accessed March 22, 2020, https://emuseum.nmmusd.org/ (left, right) and https://www.metmuseum.org/ (center), used with permission.

During the Renaissance in lute construction, its prominence is proffered by Jonathon Santa Maria Bouquet [2010] in an essay where he states, “The Renaissance lute typically had a body constructed of nine to thirteen ribs, mostly made of maple.” This is not to say that the early lute used maple exclusively as there are many examples preserved that have used rosewood, beech, ebony, and even ivory for their bowl-backs. Similarly, other early plucked chordophones such as the cittern, citole, harp, etc. often employed maple in their construction. However, with few exceptions, the violin has never strayed from maple for its use in the instrument’s back, sides, neck, and bridge. Rarely, and never systematically, have any other woods been employed so consistently than those of the violin from its origin onward [Stoel and Borman 2008]. Moreover, while the guitar has wavered in its wood selections, it is not surprising that with all its popularity with other instruments, maple would be used in guitar lutherie. In fact, the guitars referenced in Appendix I during the eighteenth century were predominantly made using maple backs and sides.

While rosewood eventually replaced maple's prominence on classical guitars beginning in the nineteenth century, maple would eventually be used extensively on steel-string guitars in the twentieth century. Of all the major steel-string guitar manufacturers, the Gibson Guitar Company was most associated with maple models. It is suggested that the company's location amidst the vast maple forests of Michigan prompted their use of maple, which was for them cheap and readily available [Whitford, Vinopal, and Erlewine 1994]. It also worth noting the prolific use of maple for solid-body electric guitar necks beginning most notably with Leo Fender's introduction of the "Telecaster" in 1950. The guitar's design has remained relatively unchanged through the years and currently still utilizes a maple neck. Indeed, the various maple sub-species are abundant in all the continents of the northern hemisphere, indicating maple would be readily available in any temperate location. Traditionally the most common species for lutherie are European maple (*Acer pseudoplatanus*), Big-leaf maple (*Acer macrophyllum*), and Sugar maple (*Acer saccharum*).

Visually, maple can range from plain to extraordinary depending on whether the sample exhibits any grain figuration. Generally, the maple trees' inner fibers grow straight, resulting in a very plain appearance when cut into lumber. Occasionally though, the wood fibers grow in an undulating pattern that, when cut, displays a chatoyance due to the varying grain angle. The most common figuring in maple is curly (also referred to as flamed or fiddleback) and quilted.

Maple has a long history of use as a component in furniture manufacturing. Its inherent strength, stability, and abundance ensured a dependable raw material for this application. Figure 5.4 shows two very disparate uses of maple in furniture construction. The left image depicts a chair made from plain maple and stained to mimic perhaps the darker tones of higher regarded walnut, mahogany, or even rosewood. The image on the right demonstrates the use of figured maple veneer to enhance the furniture piece's aesthetic wholly outside of any structural function. Throughout history, highly prized figured woods were often cut into veneers and used as an overlay or inlay with plain structural component woods in order to maximize the valuable resource.

Figure 5.4: Photos demonstrating maple use on a ca. 1700 American chair and ca. 1780 desk by David Roentgen. Both images accessed March 24, 2020, https://www.metmuseum.org/, used with permission.

Similarly, in instrument usage, plain maple is often stained or shaded to enhance its otherwise unassuming appearance. The aforementioned Gibson Guitar Corporation is probably most notable for the shading of maple instruments to elevate their appearance. From its first flat-top guitars in 1926 to the present (along with archtop guitars and mandolins from the turn of the century), Gibson guitars have eternally been recognized by their “sunburst” aspect on both plain and figured maple instruments [Whitford, Vinopal, and Erlewine 1994]. See Figure 5.5.

Figure 5.5: Photo of a sunburst finish on a maple guitar made by Gibson Guitar Corporation, ca. 1933. Accessed May 14, 2020, https://www.dreamguitars.com/, used with permission.

5.3 Tropical Hardwoods

Initially, many of the tropical hardwoods made their way to Europe and America due to the need for ballast on ships carrying the shrubby branches of the commercially important dyewoods such as brazilwood and logwood. Merchant ships required the heavier woods to prevent cargo shifting during the heavy seas commonly incurred during Atlantic crossings. Although the hardwood logs were secondary in value to valuable dyewoods, a market developed for their lumber. Any material not needed for shipbuilding was auctioned off for other purposes [Dean 1995]. Anderson [2012] explains,

> English ships also returned home from the East and West Indies carrying so-called ‘fancy woods’ (including mahogany, ebony, rosewood, and cedar, as wells as other unnamed species) but in such small quantities at first that artisans used them only for ornamentation, such as marquetry, a technique of gluing tiny jewel-like pieces of contrasting woods in elaborate designs on cabinet doors, tabletops, or small boxes. Ownership of such rarefied objects, however, remained exclusive to the aristocracy.

The eventual consequence of Brazilian rosewood's prestige as a decorative element likely initiated the demand for further importation and subsequent use on larger pieces such as the desk shown below in Figure 5.6.

Figure 5.6: Photo of a rosewood library table by the Herter Brothers, ca. 1879. Metropolitan Museum of Art. Accessed January 14, 2020, https://www.metmuseum.org/art/collection/search/4785, used with permission.

Therefore, it is not surprising that rosewood would also find its way into the musical instrument realm, as demonstrated by Figure 5.7.

Figure 5.7: Photo of a Robert Nunns 1853 rosewood piano. Accessed February 21, 2020, https://www.metmuseum.org/, used with permission.

The intricate carving and ornamentation on this piano indicate it was made not only as a musical instrument but also as a showpiece. As it seems no expense was spared, rosewood usage is a testament to its visual aesthetic.

Between the seventeenth and nineteenth centuries, rosewood was commonly utilized merely as a veneer when used for guitar backs [Romanillos 1987; Usher 1956]. This practice indicates rosewood's visual regard versus any contribution to acoustics as solid woods tend to have better acoustic properties over veneered woods [Sharpe 1963]. However, if visual appeal is indeed a contributing factor for the preference of the tropical hardwoods, this preference has persevered over two centuries of changing style and fashion.

5.3.1 Ebony

Figure 5.8: Photos of ebony from India (*Diospyros ebenum*), Indonesia (*Diospyros celebica*), and Cameroon (*Diospyros crassiflora*). Photo by author.

Ebonies (*Diospyros spp*.) may have been coveted longer than any other wood in history. Evidence of ebony furniture and coffins in ancient Egyptian tombs from 3000 B.C.E. suggests the wood was important enough to travel with its buried dignitary on into the afterlife [Dixon 1961]. More recently, ebony is commonly used for piano keys, chess sets, pool cues, and, of course, guitar parts. While there exist over 700 different ebony species, only a handful of the trees grow large enough to produce viable lumber.

The most prominent ebony sub-species for instrument making are Macassar (*Diospyros celebica*), Gabon (*Diospyros crassiflora*), Ceylon (*Diospyros ebenum),* and Madagascar (*Diospyros perrieri*) [Meier 2016]. As might be evident from the preceding list, the common name used for the different ebony species is generally the geographical place from which it comes; Macassar, or Makassar, is a port city and capital of South Sulawesi in Indonesia, Gabon, sometimes Gaboon, refers to the equatorial region of West Africa including its namesake country, Ceylon is the colonial name of Sri Lanka, and

Madagascar is the island nation in the southern Indian Ocean off of eastern Africa. One notable exception to this naming convention is the New World species persimmon (*Diospyros virginiana*). However, the persimmon of the eastern United States is known more for its fruit than for its uncharacteristically blonde-colored wood [Meier 2016].

Early usage of ebony on guitars was primarily in veneer form, covering structural woods in a dramatic black backdrop, often to accentuate the light aspect of ivory and mother-of-pearl inlay work as demonstrated in Figure 5.9.

Figure 5.9: Photo of an Italian ivory inlaid ebony guitar, ca. 1800. Accessed January 13, 2020, https://www.metmuseum.org, used with permission.

The instruments from the seventeenth and eighteenth centuries in Appendix I indicates the esteem for ebony veneered guitars. In fact, ebony veneered necks continued in popularity into the nineteenth century, evidenced by the work of German maker Johann Stauffer (1778-1853) and his protégé Christian Frederick Martin (1796-1873).

As referenced earlier, most of the ebony trade bound for Europe was predominantly destined for the French *ébénistes.* The exquisite pieces produced by these furniture craftsmen were made even more dramatic by their use of ebony in both solids and veneers, as shown in Figure 5.10. Worth noting is the similarity of inlay work between the guitar in Figure 5.9 and the two furniture pieces in Figure 5.10. Clearly, luthiery adornments, at least during the Baroque era, drew their inspiration from what was popular in high-end furniture.

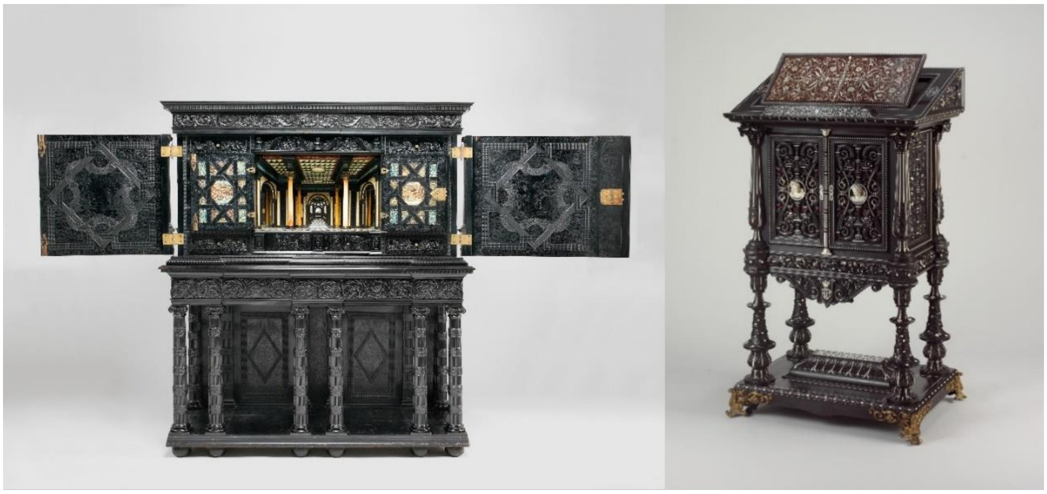


Figure 5.10: Photos of French-made ca. 1645 ebony cabinet and ebony bookstand from 1839. Both photos accessed May 19, 2020, https://www.metmuseum.org/, used with permission.

While the regular use of ebony on the guitar's corpus fell from favor by the middle of the nineteenth century, it found regular use as the preferred material for guitar fretboards. Moreover, while this usage has more to do with the function of the wood, owing to its compression strength and resistance to wear, the black fretboard became so identified with the guitar that low-end factories usually dyed or painted white-wood fretboards black in the attempt to emulate ebony [Fouilhe, Houssay, and Brémaud 2012].

5.3.2 Rosewood

Figure 5.11: Photo of a Brazilian rosewood sample. Photo by the author.

Often referred to as the “holy grail” of tonewoods, Brazilian rosewood (*Dalbergia nigra*) possesses esteem greater than any other guitar wood. See Figure 5.11. Even though the back and sides contribute a relatively small amount of sound compared to the soundboard, guitar aficionados are willing to spend thousands of dollars extra for an instrument made from Brazilian rosewood [Huber 1994]. As Brazilian rosewood came to dominate the concert quality instruments of the late-nineteenth century, there developed an expectation that high-quality instrument backs and sides utilized this particular rosewood. To reinforce this convention, American steel-string guitar makers also used Brazilian rosewood on their flagship models substituting maple or mahogany for their entry-level, affordable product lines [Whitford, Vinopal, and Erlewine 1994; Johnston & Boak 2009]. And while there are other rosewoods suitable for instrument construction, there exists a general consensus that none approach the beauty of Brazilian. Figure 5.12 offers several rosewood species for comparison.

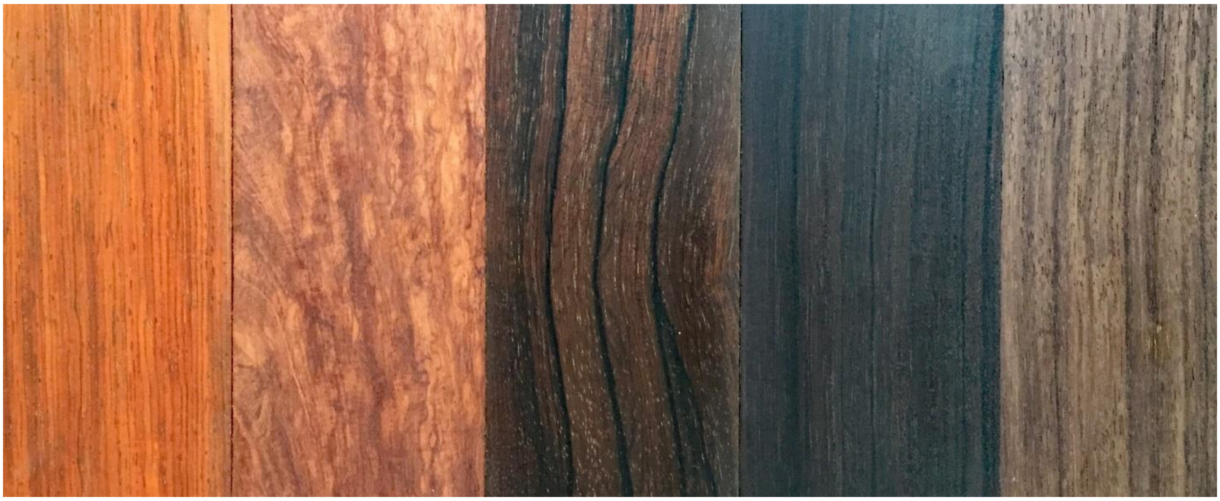


Figure 5.12: Photos of commonly available rosewood species. Depicted from left to right are Cocobolo (*Dalbergia retusa*), Honduran rosewood (*Dalbergia stevensonii*), Brazilian rosewood (*Dalbergia nigra*), African blackwood (*Dalbergia melanoxylon*), and East Indian rosewood (*Dalbergia latifolia*).

While there exists to this day the argument that the "best" sounding guitars are made with Brazilian rosewood, early usage of this wood indicates it was chosen more for its visual aesthetic than any concern for tonal contribution to the instrument. According to Johnston and Boak [2009], "Many of the guitars made in the 1830s had a layer of spruce on the inside of the guitar's back, with only a thin veneer of rosewood or maple on the exterior. Spruce-lined rosewood backs continued on some models into the 1850s and perhaps later, although no Martin guitars with the post-1867 label have been reported with this feature." Indeed, this practice was also common with European luthiers where "In the 1800s, it was common for luthiers to make the back out of a wood like spruce or cedar and to laminate a veneer of maple or rosewood over it…" [Gerken et al. 2003].

This practice of utilizing a veneer for the sake of outward appearance dates back well before the luthiers of the nineteenth century. The ornate instruments typical of the baroque era were often made with common woods for the backs and sides to act as a canvass for the ebony, rosewood, tortoise, mother-of-pearl, and ivory inlay and marquetry. However, even with the more austere sensibilities of the nineteenth century, an instrument's visual aesthetic was still valued. This use of highly esteemed rosewood veneers indicates the recognition of the instrument's appearance for marketing purposes.

As the practice of using veneers diminished, the use of solid Brazilian rosewood came to predominate the high-end instrument offerings from the late nineteenth century onwards. Appendix I clearly demonstrates that rosewood was the most popular wood selected for back and sides from the late nineteenth century onward. Also, when rosewood was used, it was most likely Brazilian. Perhaps the preference for Brazilian rosewood is best expressed by the following:

> Martin's catalogs from the early 20th century give us the first public pronouncements about the company's choice of woods and their origin. The rosewood, of course, came from Brazil. In fact, there's little point in describing a pre-1960s Martin as being made with Brazilian rosewood, simply because all the rosewood used, apparently without exception, was of that species. [Johnston, Boak, and Longwirth 2009]

Unfortunately, the extreme overutilization of Brazilian rosewood for all of its industrial uses has led it to the highest protection status by the Convention on International Trade in Endangered Species (CITES) [Herrod 2016]. Since its listing in Appendix I by the Convention on June 11, 1992, logging of Brazilian rosewood became illegal, and the trade of lumber, even from trees cut prior to the ban, is highly regulated. Except for the fortunate few who still have inventories from before the ban, luthiers have been obligated to find a suitable substitution for the iconic Brazilian rosewood. Even though there are other rosewood species that serve the structural purpose well, none can match the visual aesthetic of Brazilian, as demonstrated by Figure 5.13.

Figure 5.13: Photo of pre-ban Brazilian rosewood on a guitar made by James Olson. Image accessed April 28, 2020, http://olsonguitars.com/, used with permission.

5.3.3 Mahogany and Spanish Cedar

From the eighteenth century onward, the insatiable appetite for mahogany furniture and cabinetry developed on both sides of the Atlantic Ocean from the New World to the Old. Cabinet makers appreciated the wood's strength and stability and the ease with which intricate carvings could be achieved. In addition to the stylizing possibilities due to mahogany's density, consumers admired the natural range of colors the wood exhibited. Mahogany was so highly regarded that owning a piece became a "status symbol of the social elite" [Anderson 13].

For the less fortunate, common woods were stained in hopes of imitating the rich hues found naturally in mahogany. However, mahogany also exhibits a natural chatoyance or shimmering light refraction. While the beauty of chatoyance is subjective, it in no way can be duplicated by the use of dyes nor stains. Jennifer Anderson [2012] equates the natural light refraction of mahogany to "…silks that were specially woven or passed between iron rollers to create iridescent effects".

Similar in natural hue to mahogany is Spanish cedar. The Spanish cedar tree is a close relative to mahogany, with both species belonging to the *Meliaceae* family [Meier 2016]. Being similar in appearance, Spanish cedar was often found and harvested during mahogany hunts [Camille 2000]. While the wood coloration is quite similar, Spanish cedar lacks the chatoyance found in mahogany. This lesser visual appeal, along with its characteristic insect-repelling scent, might explain its often relegation to the interior components of fine furniture while the visually superior mahogany was used for exterior components [Kukachka 1964].

Figure 5.14: Photos of a Mahogany English bureau table, ca. 1750, and Spanish cedar-lined rosewood tea chest by Abraham Roentgen, ca. 1750–55. Images accessed June 26, 2020, https://www.metmuseum.org/, used with permission.

While mahogany and cedar were certainly prized in high-end furniture, its use as a guitar component was more likely due to the wood's physical characteristics. These woods have outstanding strength to weight ratio and are able to withstand the stress of tensioned guitar strings without undue mass. The lower neck mass ensures a well-balanced instrument that would be comfortable to hold and play. Additionally, their characteristic stability regarding humidity changes mitigates dimensional changes that would affect fretboard playability [Gore 2011]. Finally, both Spanish cedar and mahogany are well known for their ease of carve-ability, an attribute especially important when a guitar neck is shaped with only hand tools.

While these two wood species found immediate appreciation for their use in neck construction, they also eventually found their way to be used as back and side components: mahogany's use for steel-string guitar bodies in particular. Martin & Co. introduced its Style 18 guitar in 1917 that replaced the traditional rosewood for Honduran mahogany on this specific model. According to Johnston, Boak, and Longwirth [2009], "For the next several decades, most of Martin's growth was in mahogany, not rosewood models. This was due primarily to the lower retail price of the mahogany versions." Gibson guitars utilized mahogany to an extent even greater than Martin. Beginning with their introduction of flat-top guitars in 1926 to the present, Gibson has used mahogany on more of their models than any other hardwood [Whitford, Vinopal, Erlewine 1994]. Despite its reputation of use in lower-end models, mahogany can sometimes demonstrate spectacular figure in its grain, resulting in a stunning appearance, as shown in Figure 5.15.

Figure 5.15: A photo of a quilted mahogany guitar made by the Santa Cruz Guitar Company. Image accessed April 28, 2020, https://themusicemporium.com, used with permission.

Tragically, Honduran mahogany and Spanish cedar are precariously close to following in the footsteps of Brazilian rosewood as overharvesting has diminished the population to critical levels. Mahogany has been listed in Appendix II of CITES since November 16, 1995, and Spanish cedar in Appendix

III since December 12, 2001, to “ensure that trade in that species is based on sustainable harvest and to address the threats of unregulated trade and illegal harvest [FWS 2020].”

However, again, like Brazilian rosewood, the luthier community expects high-end guitars to be outfitted with necks made from Spanish cedar or Honduran mahogany [Somogyi 2009a]. However, should these tree populations continue to decline, it is quite possible that they will no longer be available for commercial usage and necessitate an adequate substitute.

5.4 Summary

The wood species most prominently employed in luthiery were examined individually with respect to their value outside of any potential acoustical contribution. By drawing parallels with their usage outside of lutherie, it was shown that the use of certain woods could enhance the quality perception of an instrument based on their inclusion. The cultural appetite for the exotic timbers of rosewood, mahogany, and ebony was reflected in their usage for fine cabinetry and furniture items. The possession of items made from these woods was a symbol of wealth and status. The fact that rosewood and ebony were commonly used in lutherie as veneers over cheaper structural woods suggest their inclusion was partly due to enhance the instrument's visual aesthetic. Furthermore, on guitars and furniture items alike, “white” woods were often dyed or painted to mimic the highly coveted tropical hardwoods' darker coloration. Ultimately, luthiers delineated their top models by the inclusion of esteemed tropical hardwoods, while their lower-priced lines most often utilized the more common temperate hardwoods such as maple and Mediterranean cypress. This section also introduced the ramifications of natural resource overutilization. Many of the wood species iconic to guitar luthiery have seen population depletion due to overuse coupled with poor timber management. Quite possibly, the future of luthiery might need to contend with the loss of the woods that have played a prominent role in its ascension to its popularity and reverence in a multitude of musical genres.

Chapter 6

Material Selection Criteria

6.1 A Symbol of Status

The implicit prestige of tropical hardwoods in the art of lutherie would have likely transcended from the cultural adoration for its use in furniture and cabinetry in both Europe and America. As alluded to earlier, furniture and decorative household items made from these woods in the sixteenth and seventeenth centuries were seen as iconic status symbols for the affluent. As symbols of status, it is not surprising that the desire to own such pieces would permeate lower social strata as well. With the rise of the merchant and middle classes, the ownership of “objects of social value” became the equivalent of landed gentry titles of the previous centuries [Anderson 2012; Revels 2002]. In lieu of aristocratic titles, materialism came to define the socio-economic classes. This is especially true in the post-industrial revolution era when luxury goods became not only more affordable but also widely available [Burkholder, Grout, and Palisca 571].

To further illustrate, consider the piano shown previously in Figure 5.7. In addition to its contribution to the visual aesthetic, the use of rosewood contributes to the piece's value due to the cultural status of the materials used for its construction as well. The inclusion of this highly prized wood elevates the piano's intrinsic value beyond what could have otherwise been achieved using locally harvested hardwoods.

Since the quantity of wood required to build a guitar pales in comparison to that needed for a larger item, such as a piano, the perceived prestige of the guitar could be enhanced with a relatively small increase in cost. As a result, a luthier could enhance an instrument's quality perception simply through the utilization of mahogany, Spanish cedar, ebony, and rosewood [Kies 2013].

While historically the perceived prestige of tropical hardwoods likely contributed to their introduction and subsequent widespread use in guitar making, the loss of these resources, whether immediate or in the future, is creating a covet mentality of the woods that in the middle of the twentieth century were largely taken for granted. Since Brazilian rosewood's harvest ban in 1992, CITES Appendix II listing for Honduran mahogany in 2003, entire rosewood (Dalbergia spp.) Appendix II listing in 2017, Spanish cedar Appendix II listing in 2020, and all Madagascar specific ebonies (*Diospyros spp.*) Appendix II listing in 2011, demand has increased for these threatened species due to two primary factors; perceived superiority of quality over potential wood species substitutes and human nature's tendency to hoard that which is rare. This, of course, only reinforces the prestige of owning an instrument made from the dwindling availability of woods iconic within the traditions of guitar making.

6.2 Workability

While the visual appeal and prestige of the guitar's components would benefit the marketing of the instrument, the functionality of a wood species in manufacture will also help determine its long-term popularity within lutherie. Since the art of lutherie has historically depended on the use of simple hand tools, the ability to effectively cut, plane, bend, and carve individual guitar components is of significant importance to the luthier. Assuming the luthier's tools are of reasonable quality, the physical characteristics of the intended woods will primarily determine their practicality within the manufacturing process [Gore 2011].

Around the time Torres popularized the modern incarnation of the classical guitar, spruce, maple, cypress, rosewood, Spanish cedar, mahogany, and ebony were the primary woods used in guitar lutherie in both Europe and the Americas [Romanillos 1987; Johnston, Boak, and Longwirth 2008]. Little has changed over the last 150 years as these species still hold prominence into the twenty-first century. In addition to their visual appeal, the attributes that determine a wood's ability to be processed into guitar parts undoubtedly contribute to their widespread use in lutherie. Table 6.1 identifies the workability attributes for lutherie tonewoods. The Janka hardness number represents the amount of applied mass necessary to press an 11.28 mm diameter steel ball into the wood to half the ball’s diameter, most often denoted in Newtons (N). The measured Janka score helps predict the ease with which wood can be cut or machined. It is important to note; the figures provided indicate what is typical for a species but can vary substantially from sample to sample [Gore and Gillet 2016]. The other four workability scores are a subjective assessment of how that wood responds during the manufacturing process. This score is an amalgamation of conventional wisdom within the luthier community, published perspectives in various woodworking books, and the author's personal experience [Cumpiano and Natelson 1987]. A score of 1 indicates difficulty for a particular process, while a 5 indicates high suitability.

Species	**Density kg/m^3**	**Janka (N)**	**Hand Dimen-sioning**	**Hand Carving**	**Steam/Heat Bending**	**Gluing**
Spruce (*Picea abies*)	405	1,680	5	5	2	5
Maple (*Acer pseudoplatanus*)	615	4,680	3	3	3	5
Cypress (*Cupressus sempervirens*)	535	2,490	5	5	3	5
Ebony (*Diospyros celebica*)	1,120	14,140	1	1	4	3
Rosewood (*Dalbergia nigra*)	835	12,410	2	2	5	3
Spanish Cedar (*Cedrela odorata*)	470	2,670	5	5	4	5
Mahogany (*Swietenia macrophylla*)	590	4,120	5	5	4	5

Table 6.1: Workability properties of various tonewoods used in luthiery.

To fully appreciate the subjective scores, it is essential to understand how each wood species behaves in the specific tasks undertaken by a luthier. The following observations are from the author’s culmination of over twenty years of experience as a luthier:

- Spruce is very conducive to dimensioning with hand planes and chisels making it relatively easy to thickness soundboard plates and braces to exacting dimensions. Its reluctance to steam bending is not an issue as spruce is not used for guitar sides.
- Maple has moderate shaping and carving characteristics. While not as easy to dimension as spruce, maple cuts well with both chisel and plane without excessive dulling of tool cutting edges. It tends to bend readily with typical heat/steam methods. However, maple tends to spring-back towards its original flat state, requiring subsequent bending operations. In addition, scorch marks from heating irons can sometimes be visible

on this light-colored wood due to the bending process. In figured specimens, the undulating grain direction tends to increase the difficulty of dimensioning, carving, and bending the wood.

- Cypress dimensions and carves easily owing to the fact that it is actually a conifer rather than a true hardwood. The ease with which cypress can be worked with hand tools also makes it an appropriate candidate for a guitar neck as long as the stiffness properties of that particular specimen are adequate to resist deformation under string tension. Cypress will often demonstrate some spring-back after bending and is also subject to scorching if overheated.
- Due to the higher surface hardness of rosewood, dimensioning and carving this species provides additional challenges to the luthier. Planing and carving rosewood necessitate extremely sharp tools that will require frequent redressing on sharpening stones. The high resin and oil content allows for this very stiff wood to be easily bent with heat. Rosewood does not experience the same issues of spring-back that are inherent with the lower resin woods. However, the high resin content interferes with glue adhesion.
- When straight-grained, Spanish cedar responds exceptionally well to planning and carving. Despite its low Janka score, Spanish cedar has a remarkably high stiffness to weight ratio. The combination of stiffness and carve-ability makes Spanish cedar an obvious choice for a guitar neck.
- Mahogany is almost as easy to dimension and carve as is its cousin, Spanish cedar. Having decent bending properties, mahogany became the secondary choice for guitar back and sides in the American market in the nineteenth and twentieth centuries. Mahogany is used occasionally as a neck wood in Europe and almost exclusively for necks in America [Johnston, Boak, and Longwirth 2009].
- What ebony lacks in ease of manufacture is made up for in its appropriateness for purpose. Ebony’s hardness has a dulling effect on

cutting tools requiring frequent re-sharpening. However, this hardness makes ebony a perfect candidate for a guitar fretboard [Gore 2011]. Not only will ebony hold up to years of finger and guitar-string friction, but it will also maintain its characteristic black sheen without the aid of oil or finish. Surprisingly, ebony responds well to heat bending, making it a good candidate for back and sides (more so, however, in the current age of machine aided dimensioning).

6.3 Suitability to Purpose

The final, and possibly most important, consideration of why certain woods became *de facto* in lutherie is their suitability to purpose. To analyze this, the guitar will be broken down into the major components that make up the instrument: the soundboard, bridge, back and sides, neck, and fretboard. Each component will then be defined as to its function and physical requirements, whether it be vibrational, structural, or both. Finally, the suitability of each species will be examined for its typical application in a guitar.

6.3.1 The Soundboard

The soundboard, along with its attached braces, is unique. In addition to its role as the primary vibratory component of the guitar, it also serves as a significant structural component. Although it is impossible to quantify precisely, most scientists and luthiers expect between 80-90% of the sound produced by the guitar is directly attributable to the soundboard [Richardson 1992; Gerken et al. 2003]. The vibration response of a flexible plate excited by strings is analogous to the paper cone on a typical stereo speaker. However, when strung to concert pitch, the soundboard anchors 400 newtons of tension on a classical guitar and up to 890 newtons on a steel-string guitar [Somogyi 2009b; D’Addario 2020]. This dichotomy of duties required by the guitar’s soundboard necessitates a balance between strength and flexibility [Wheeldon 2017; Gore 2011; Somogyi 2009b]. An excessively rigid soundboard would resist vibration, while an unreasonably flexible soundboard would eventually succumb to the forces of string tension and fail on a structural level. These conflicting requirements are central to the compromise between a guitar's responsiveness and its structural longevity [Gore 2011]. Therefore, it would seem imperative to have a clear understanding of a given soundboard's stiffness characteristics to best achieve the luthier's goal of this balance. This compromise can be controlled during the guitar's construction by thinning the soundboard plate to achieve target stiffness/flexibility [Somogyi 2009b].

Another consideration is the soundboard's mass. As established in Chapter 2, the lower the soundboard's mass, the more responsive it will be to the energy of a vibrating string. Because the luthier has control over the thickness dimension of a soundboard, it is most appropriate to consider mass and stiffness together as a single characteristic, commonly referred to as the strength to weight ratio [Richardson 2010]. The argument to consider mass and stiffness as a single characteristic stems from the fact that as material is removed during the plate thinning process, mass is reduced.

The final consideration for the soundboard is internal damping. Internal damping for tonewoods refers to vibrational energy loss through internal friction [Bucur 2006]. A practical example of a low damping system is a brass bell that rings for a long time after being struck by an impulse mechanism. Similarly, different woods will respond in varying degrees to an impulse based on a particular specimen's internal damping characteristics. Traditionally, potential soundboard woods that exhibit low internal damping, or a good "tap tone", are generally preferred for use on a guitar [Kies 2013; Somogyi 2009a]. Luthiers have typically favored wood samples producing a sustaining clear tone while those exhibiting a dull thud may cause a sample to be forsaken [Somogyi 2009a].

While subjective, this tapping procedure attempts to measure the internal damping of a specific piece of wood. A long ringing tone produced by the tap indicates a piece of wood that returns vibrations to the system, much like the brass bell mentioned above. In fact, the luthier community commonly refers to such wood as having “a bell-like” tap tone and considers it a characteristic of quality. Conversely, a sample that produces a short, dull thud sound indicates the wood is internally absorbing vibrational energy, which would be in opposition to the goal of efficiently producing sound and sustain [Haines 1980; Somogyi 2009a].

6.3.2 The Guitar Neck

The guitar’s neck serves a structural function primarily to anchor the strings at one end and provide a surface onto which a fretboard is adhered. In addition, several specific material selection criteria need to be satisfied to ensure the wood's immediate and long-term success in use. Most obvious is the call for a wood species that provides the stiffness required to withstand the continual stress of tensioned guitar strings while maintaining a sense of instrument balance for proper performance ergonomics. Careful consideration of the prospective species’ stiffness and density will help ensure success in this regard. Whereas a high strength to weight ratio was the primary goal in selecting a soundboard, these properties need to be viewed separately when considering a neck wood's success. Since the dimensions of the guitar neck are constrained by fixed parameters to ensure proper playability of the fretting hand, the dimensioned neck's eventual mass and stiffness needs to be considered in their own right. In other words, the stiffness and the mass need to be appropriate once the neck-wood is dimensioned to its appropriate size. For example, consider the strength and density properties of Balsa (*Ochroma pyramidale*), Katalox (*Swartzia cubensis*), and Honduran mahogany listed in Table 6.2.

Species	**Density (ρ) Kg/m^3**	**Specific Gravity (SG) $\rho/1000$**	**Modulus of Elasticity (E) GPa**	**Specific Modulus (SM) E/SG**
Balsa	150	.15	3.71	24.73
Katalox	1150	1.15	25.62	22.28
Honduran Mahogany	600	.60	10.06	16.77
Spanish Cedar	470	.47	9.12	19.40
Hard Maple	705	.71	12.62	17.77
European Maple	615	.62	9.92	16.00

Table 6.2: The density and modulus of elasticity properties for Balsa, Katalox, Honduran mahogany, Spanish cedar, Hard maple, and European maple [Meier 2016].

While the specific modulus of Honduran mahogany is towards the lower end of the six candidates, its practical use over the last centuries has proven its stiffness is adequate to withstand the tension of guitar strings while at the same time being of appropriate mass to succeed on an ergonomic level. Even though it demonstrates a superior strength to weight, Balsa would undoubtedly fail under tension once in practice within the appropriate dimensions of a guitar neck. Conversely, Katalox, though it succeeds based on strength, would weigh approximately 2x the mass of Honduran mahogany resulting in an unbalanced, neck-heavy instrument. While slightly more massive than the mahogany and cedar, the two maple species demonstrate a modulus of elasticity score sufficient for consideration, which would explain their early use on gut-string guitars and later use on steel-string guitars.

Another consideration for a guitar neck's long-term success is its stability within a range of humidity conditions [Gore and Gillet 2011a]. By its very nature, wood is hygroscopic and will gain and lose moisture depending on the atmospheric conditions within which it exists. The ramifications of this condition are explained by Meier [2016] as follows:

> …wood, almost like a sponge, will gain or lose moisture from the air based upon the conditions of the surrounding environment. But not only does wood gain or lose moisture, but it will also *expand or contract* according to its moisture level. It is this swelling and shrinking in finished wood products, often referred to as the wood's movement in service, that is responsible for so much mischief and malfunction in woodworking.

The hazard for the guitar neck is the potential for the neck to bow, twist, or otherwise deform during service from changes in humidity. Additionally, wood dimensional deformation would likely also occur if the wood is not fully seasoned prior to manufacturing to its equilibrium moisture content, usually accepted as 8% moisture content at 70° F. To complicate matters is the anisotropic nature of wood that results in different expansion or contraction in the wood depending on grain direction. While longitudinal expansion and contraction are relatively negligible, radial, and tangential initial volume shrinkage can amount to upwards of 16% for some species [Meier 2016]. The potential ramifications for stability are exacerbated by the rate at which the wood moves tangentially versus radially or the T/R ratio. A T/R ratio of 1.0 indicates identical volumetric movement across the board width and thickness and would mitigate the potential for twisting, cupping, and bowing. A high T/R ratio, sometimes upwards of 3.0, indicates the wood will shrink or expand in one direction more than the other, causing dimensional distortions. Meier [2016] offers:

> In addition to the volumetric shrinkage, the T/R ratio serves to measure the uniformity of the shrinkage and is another good indicator of a wood's stability. Ideally, a wood species with good stability would have both low volumetric shrinkage and a low T/R ratio.

However, Meier [2016] adds to this the caveat:

> …just because a particular wood species experiences a high initial shrinkage during drying does not always correlate to an equal swelling after it has been dried. For instance, Basswood (*Tilia americana*) has fairly high initial

> shrinkage values—6.6% radial, 9.3% tangential, and 15.9% volumetric—yet its movement in service is relatively low. Using shrinkage and T/R ratio data simply offers woodworkers the best means of making an educated guess.

Because Honduran mahogany, Spanish cedar, and maple have a history of success in service, their "shrinkage" data can at least be used to establish a standard by which other woods can be measured. See Table 6.3.

Species	Radial Shrinkage	Tangential Shrinkage	Volumetric Shrinkage	T/R Ratio
Honduran Mahogany	2.9%	4.6%	8.0%	1.59
Spanish Cedar	4.1%	6.2%	10.3%	1.51
Hard Maple	4.8%	9.9%	14.7%	2.06
European Maple	4.5%	7.8%	12.3%	1.73

Table 6.3. Shrinkage data for Honduran mahogany, Spanish cedar, Hard maple, and European maple [Meier 2016].

According to the data in Table 6.3, both Honduran mahogany and Spanish Cedar score better than the maples in both volumetric shrinkage and T/R ratio. This, in turn, indicates these two species would be more stable in varying humidity situations than maple, which was the early choice of guitar neck wood.

In summation, Spanish cedar and Honduran mahogany demonstrate high suitability to purpose based on necessary stiffness, appropriate density, and superior dimensional stability. Even though maple scores reasonably well in these metrics, the superiority of mahogany and cedar might help explain their eventual preeminence in use as neck woods for both classical and steel-string guitars.

6.3.3 Guitar Back and Sides

The back and sides of the guitar are, at the very least, structural in purpose and, arguably, a vibratory contributor to the guitar's overall sound. Therefore, wood selection needs to consider suitability on two levels: the strength of the wood to support the neck and soundboard in a state of tension and the potential effect on the guitars sound.

If a guitar existed in a hermetically sealed environment with a padded floor and foam furniture, wood selection for mere structural integrity would be made simpler. However, since the guitar likely exists in a world of changing weather, sharp corners, and careless owners, an individual instrument will depend on its structure's physical properties to mitigate the disasters of daily life. At its basic level, the guitar's back and sides are required to be a durable box to which a neck and soundboard are attached. Indeed, many prominent luthiers believe the back and sides as nothing more than structural components whose only sound contribution is made by the mere fact it encloses the air cavity inside the guitar body. Antonio de Torres was one such proponent and attempted to demonstrate this by building a guitar with back and sides made from *papier-mache*. Unfortunately, that instrument's success cannot be judged today as it ultimately failed on a structural level—at the very least proving the importance of the back and sides needing strength to avoid an untimely demise.

To establish a benchmark for strength and durability, Table 6.4 compiles the physical properties of woods traditionally used for back and sides. The fact that many centuries-old instruments are still playable, the Stradivari "Rawlins" guitar of 1700 being a notable example, is a testament to traditional woods' successful use and using them as a benchmark. Of particular interest to this section are surface hardness, stiffness, density, and dimensional stability [Gore 2011]. Table 6.4 compiles the mechanical properties for the woods traditionally selected for guitar back and sides.

Species	**Surface Hardness (Janka) (N)**	**Density (ρ) kg/m^3**	**Modulus of Elasticity (*MOE*) (GPa)**	**Stiffness/ Weight Ratio $MOE/\rho(10^3)$**	**Total Volumetric Shrinkage %**	**T/R Ratio**
Mediterranean Cypress	2,490	490	4.7	9.60	9.60	2.4
European Maple	4,680	640	9.92	15.50	12.30	1.7
Brazilian Rosewood	12,410	810	16.61	20.50	8.50	1.6
Honduran Mahogany	4,020	480	9.94	20.70	7.50	1.5

Table 6.4: Important mechanical property measurements for the traditional woods used for guitar backs and sides [Meier 2016; Brémaud et al. 2011].

The Janka surface hardness determines how well the wood will resist dents, dings, and scratches. The measurements that are provided characterize what is typical for the species. Unfortunately, since this is a destructive test that renders the sample useless, it would not be practical to test individual specimens prior to utilization. Even so, the Janka score provides a good rule of thumb on how a species will generally respond to surface wear over time. A high Janka score represents a hard, durable surface. Based on the data provided, Brazilian rosewood would be the most durable, while Mediterranean Cypress would be the most susceptible to dings, dents, scratches, and cracks from handling abuse.

The modulus of elasticity measures the stiffness of wood. Specifically, this metric measures the resistance to deformation under a given load for a determined geometry of the sample being tested. The modulus of elasticity allows the stiffness comparison of different species regardless of their dimensions. Additionally, the stiffness to weight ratio, or specific modulus, considers the stiffness relative to the sample's density. This metric is particularly important when the objective is to minimize mass. For example, even though Brazilian rosewood possesses a higher modulus of elasticity versus Honduran mahogany (16.61 GPa vs. 9.94 GPa, respectively), it does so at the expense of more mass (810 kg/m^3 vs. 480 kg/m^3, respectively). If the two wood samples were thinned to respond to a load with an identical deflection, the higher specific modulus of the Honduran mahogany (20.70 GPa/SG) versus the Brazilian rosewood (20.50 GPa/SG) anticipates that it will provide the same strength but with slightly lower mass.

As mentioned in the previous section, dimensional stability measures the woods' susceptibility to dimensional shrinkage or expansion depending primarily on fluctuations in humidity. Of particular concern is the potential for wood failure due to cracks caused by humidity levels far below the ambient levels when the guitar was manufactured. This failure is most common in the guitar's top and backplates due to their nature of having their entire edges fixed in place by the guitar’s sides. As humidity levels decrease, the wood will shrink in tangential and radial grain directions. Because the plate edges are fixed, the plate will split to release the pulling stress caused by the shrinking fibers if the stress becomes too great. There are four ways to mitigate low humidity-induced cracks: (1) make sure wood has been seasoned to its equilibrium moisture content, (2) build the instrument in an ambient humidity level below its expected future environment, (3) dome the backplate to allow for some contraction during low humidity periods, and (4) maintain the instrument in a static humidity environment. However, since most guitars, particularly those belonging to travelling musicians, will encounter variably humidity conditions due to regional and seasonal variability, the wood's dimensional stability will help dictate the instrument's longevity in terms of wood vulnerability [Gore 2011]. Paradoxically, Brazilian rosewood, despite having low volumetric shrinkage and T/R ratio scores, is notable for developing cracks attributable to humidity changes [Somogyi 2016].

Structural integrity aside, there is a strong case to be made for sound contribution by the guitar’s backplate. Renowned luthier Ervin Somogyi [2009a] refers to backs that contribute sound as “acoustically active” while those that do not contribute as merely a sound “reflector.” Somogyi further contends the following criteria will in some way affect the back's ability to contribute: (1) the lower the mass, the easier it will be for the backplate to couple with the vibrations instigated by the soundboard, and (2) the higher the "*Q*" (i.e., long sustaining tap-tone) of the wood being used, the more vibrational energy the backplate will return to the coupled system. Gore and Gillet [2011a] echo this sentiment, adding as long as "the backplate is sufficiently flexible and of low enough mass to couple with the top and leave an impression in the top's response. Somogyi, Gore, and Gillet's views suggest the importance of a high stiffness to weight ratio so that a structurally adequate backplate can be employed at the lowest mass possible. Table 6.4 indicates that three of the traditional woods have a remarkably similar stiffness to weight ratios, while Mediterranean Cypress is relatively deficient in this regard. Even though Cypress is a rather light wood, in order to provide the same structural integrity as the other woods, it needs to be dimensioned to a thickness causing the plate to be relatively higher in mass versus the other specimens. Conversely, if the Cypress were to be dimensioned to an identical thickness, which was often the case historically, it would be a very light instrument but with a likely short lifespan.

As for *Q*, defined previously in Chapter 2.6.3, consensus in lutherie endorses the notion that wood samples that exhibit a long sustaining tap tone will return vibrational energy to the coupled system. A low *Q* wood specimen, by its nature, dampens vibration due to internal friction at the cellular level. Rather than returning vibration energy back to the system, the internal friction dissipates the energy through heat [Brancheriau, Kouchade, and Brémaud 2010]. As a result, vibration that could have been used to produce sound is effectively wasted by the wood's internal damping characteristic [Haines 1980]. Because producing sound is the ultimate goal of a guitar and a plucked string is a singular force event, it follows that to produce sound most efficiently, the intent would be to direct vibrational energy to produce sound rather than be consumed by the internal friction of any vibratory plate.

While the determination of sustain through a tapping and listening process is purely subjective in practice, the concept has been gaining scientific attention in recent decades, likely due to technological advancements that allow for objective analysis of physical vibrations. While once purely the purview of well-funded scientific laboratories, the technology is now within reach of anyone with a computer, soundcard, microphone, and audio analyzing software [Gore and Gillet 2011a]. The two most common ways to objectively determine the *Q* of wood specimens are the half-power bandwidth method and the logarithmic decrement method. To define the *Q* of the traditional tonewoods in this section results from Brémaud et al. [2011] will be used to populate Table 6.5.

Species	**tanδ**	**tanδ(10^3)**	***Q*** **1/tanδ**
Mediterranean Cypress	.0153	15.3	65.36
European Maple	.0161	16.10	62.11
Brazilian Rosewood	.0070	7.00	142.85
Honduran Mahogany	.0064	6.40	156.25

Table 6.5. Damping coefficients for traditional woods used for guitar backs and sides. Results were calculated using the half-power bandwidth method [Brémaud et al. 2011].

The conclusions that can be inferred from the damping coefficient data in Table 6.5 are that all other things equal, guitars made from cypress and maple would demonstrate shorter sustain due to higher damping mechanisms. Conversely, the rosewood and mahogany guitars would exhibit longer sustain due to a higher *Q* as vibrational energy is returned to the coupled system rather than being consumed by internal damping [Errede 2016]. Taken one step further, the high Q backplates' ability to remain vibrating suggests they will have a higher contribution to sound generation than a backplate that is effectively damped. The selection of the wood used for the backplate is then dependent on the intent of the luthier and subsequent instrument owner. To help facilitate a musicality with notes of quick decay, woods demonstrating high damping should be utilized. This is the case for flamenco and jazz guitarists who prefer short note duration according to those musical styles [Somogyi 2009a].

Altogether, the physical characteristics of the guitar's back can impact the success of the instrument in terms of resistance to wear, structural integrity, and contribution to sound production. Specifically, the Janka hardness will help evaluate a wood specimen's resistance to wear, and the modulus of elasticity will help determine how thin a piece of wood can be made while still providing the necessary structural requirements of a guitar under tension. The resulting mass and damping coefficient will affect how the back might contribute to sound enhancement.

6.3.4 The Fretboard

While the fretboard serves primarily as a structural component, it does so in ways specific to its purpose. The fretboard needs to possess a hard surface to withstand the abrasion of strings being pressed and rubbed against its surface, have a longitudinal-grain compression strength to hold frets in sawn slots securely and possess dimensional stability to maintain fixed dimensions. Also, the need for a high modulus of elasticity serves two functions of stiffness: (1) strengthen the neck system to withstand string tension, (2) enhance the neck's function of acting as fixed-end support to mitigate vibrational energy loss [Gore and Gillet 2011a].

Throughout history, there have been three primary species used for the fretboard role. Ebony, rosewood, and maple have all been used to at least some extent. However, as demonstrated by its conspicuous dominance as part of the guitars listed in Appendix I, ebony appears to have been favored above any other species. Table 6.6 lists the properties of the three primary species used for fretboards to determine the suitability for these species in use.

Species	**Janka (N)**	**Density (kg/m^3)**	**Modulus of Elasticity (GPa)**	**Compression Strength (MPa)**	**Tan. Shrinkage (%)**	**Rad. Shrinkage (%)**
European Maple (*Acer pseudoplantanus*)	4,680	615	9.92	55.00	7.80	4.50
Hard Rock Maple (*Acer saccharum*)	6,450	705	12.62	54.00	9.90	4.80
Brazilian Rosewood (*Dalbergia nigra*)	12,410	835	13.93	67.20	4.60	2.90
Macassar Ebony (*Diospyros celebica*)	14,140	1,120	17.35	80.20	N/A	N/A
W. African Ebony (*Diospyros crassiflora*)	13,700	955	16.89	76.30	11.20	8.30

Table 6.6: Mechanical properties of common fretboard woods [Meier 2016].

By nearly every metric, the ebony species are superior to the other listed woods. One could expect from the use of an ebony fretboard superior: (1) resistance to wear, (2) stiffness to withstand string tension, (3) compression strength to hold frets, and (4) mass and stiffness properties to enhance fixed-end support. The only area that ebony is deficient is susceptibility to dimensional changes with changes in ambient humidity. This is particularly true if the wood sample is used before attaining its equilibrium moisture content or if put into service during a period of high humidity. The likely consequence of post-production wood shrinkage being sharp fret ends that hang over a fretboard after the wood has shrunk across its width and a crack in the finish where the fretboard and neck meet. It should be noted that because radial shrinkage is typically less than tangential shrinkage regardless of wood type, quarter-sawn wood is ideal as it exhibits less dimensional variance across its width with changes in humidity environments. The consideration of mass in a fretboard recognizes a higher mass neck system would resist string energy loss contributing to a maximized fixed-end support. However, the fretboard contributes to the combined mass of the neck system and must be within a range to ensure ergonomic suitability [Bennet 2016].

6.3.5 Bridge

At first glance, the guitar’s bridge may seem a simple component used to anchor the strings and provide a bridge location to determine the guitar's scale length. In practice, though, the guitar bridge performs a multitude of functions critical to the instrument's success. In addition to providing a strong anchor for the strings, the bridge is the point at which string energy is transferred to the primary sound generator, the soundboard system [Campbell, Greated 1987; Somogyi 2009a]. The bridge is, in effect, the gateway for string energy and will affect the transfer of string vibration to the guitar’s soundboard. Table 6.7 lists the properties that will influence the success of the guitar bridge in practice and the woods commonly used for this purpose.

Species	**Janka (N)**	**Density (kg/m^3)**	**Modulus of Rupture (MPa)**	**Modulus of Elasticity (GPa)**	**Tan. Shrinkage (%)**	**Rad. Shrinkage (%)**
European Pear (*Pyrus communis*)	7,380	690	83.30	7.80	11.30	3.90
Indian Rosewood (*Dalbergia latifolia)*	10,870	830	114.40	11.50	5.90	2.70
Brazilian Rosewood (Dalbergia nigra)	12,410	840	135.00	13.93	4.60	2.90
Macassar Ebony (*Diospyros celebica*)	14,140	1,120	157.20	17.35	N/A	N/A
W. African Ebony (*Diospyros crassiflora*)	13,700	955	158.10	16.89	11.20	8.30

Table 6.7: Important mechanical properties of woods used for guitar bridges [Meier 2016].

It might seem odd to include European Pear in this list as it does not appear specifically as a bridge wood in Appendix I. Its inclusion is based on the possibility that some of the bridges represented as ebony might, in fact, be pear that has been dyed or “ebonized” to appear as the more esteemed ebony. Since pear has a tight grain appearance similar to ebony, artisans employed a process of dissolving iron shavings in vinegar to make a solution that could dye the wood to a black appearance indistinguishable from ebony. Because the coloration penetrated the wood's surface, the only means by which its identity could be determined would damage the historical piece in question. Therefore, pearwood is included based on the likelihood that some of the historical bridges identified as ebony are, in fact, pear [Wheeldon 2019; Fouilhe, Houssay, and Brémaud 2012].

The concept of considering moisture stability of woods used for bridges has been rarely considered in previous research. However, conventional wisdom amongst luthiers contends that quarter-sawn wood will perform better in service due to the generally lower dimensional movement across the radial (quarter-sawn) grain direction with humidity changes. Long-term grain swelling and shrinkage due to humidity changes will affect the glue joint holding the bridge as the bridge wants to expand and contract while the soundboard is relatively stable in the longitudinal grain direction. In addition, deformations in the bridge shape will cause a consequential deformation of the soundboard that will be at the least unsightly and, at its worst, catastrophic [Somogyi 2009]. With this in mind, logic would suggest using quarter-sawn wood for the bridge and selecting species that demonstrate superior moisture stability characteristics. The Janka hardness score is vital due to direct string contact with the bridge at the point of anchor. For steel-string guitars, this is where the bridge pin seats the ball-end of the string in a conical hole cut perpendicular through the bridge, and for the classical guitar, where the strings are tied to a block just behind the saddle [Gore and Gillet 2011a]. A high Janka score is more important for the steel-string guitar due to the strings' hard nature and the additional tension needed to bring steel strings to proper pitch. Also, classical guitar makers often reinforce the top of the string tie block with a bone veneer to mitigate string damage to the wood. Figure 6.1 illustrates these conditions in detail.

Figure 6.1: Photos demonstrating the characteristics of a classical (top) and a steel-string (bottom) guitar bridge. Photos by the author.

Figure 6.1 also illustrates the importance of the modulus of rupture when considering some wood for a guitar bridge. In both cases, the strings pass over the saddle at an angle, causing pressure against a saddle slot. The sharper the angle the string transitions at the saddle, the greater the pressure will be on the wood supporting the saddle. A high modulus of rupture score will ensure the wood will not fail due to long-term torsional fatigue. Figure 6.2 demonstrates this unfortunate outcome.

Figure 6.2: Photo of a cracked bridge due to wood failure at the saddle slot. Photo by the author.

In addition to acting as an anchor for the strings and providing a structurally secure slot to hold the saddle, the bridge also acts as a major brace for strengthening the soundboard [Somogyi 2009a; Gore and Gillet 2011a]. This bracing function indicates the importance of a high modulus of elasticity for any wood being considered for the bridge. A high modulus of elasticity is also essential to ensure effective transmission of string vibration to the soundboard. String vibrations will act as a force on the saddle to create a rocking motion in both longitudinal and transverse directions [Gore and Gillet 2011a]. Assuming a well-seated saddle, a non-flexing bridge will transfer that string energy to the soundboard with less loss than a flexible bridge. A flexing bridge would damp string energy, much like a spring damping device. Of course, high stiffness often comes at the price of high mass, which might be the most crucial consequence as far as sound production goes.

Mass will affect the string energy transfer in two ways: (1) a massive bridge will require more energy to accelerate and keep in motion, and (2) mass will affect the impedance (resistance) of energy transfer from the strings [Somogyi 2009a; Campbell and Greated 1987]. Regarding acceleration Gore and Gillet [2011a] assert:

> As the bridge is in the most active region of the soundboard, it undergoes the highest levels of acceleration on the guitar. To make it easier for the

> bridge (and hence the soundboard) to accelerate, it makes sense to make the bridge as light as possible, as higher accelerations produce higher velocities and hence more sound. It is impossible to make a sufficiently strong bridge too light.

Somogyi [2009a] offers the following analogy to illustrate this concept further:

> The inertial (i.e., rise-of-tone) action of the strings pulling on the bridge can be thought of in terms of a horse pulling a wagon: if the wagon is loaded with hay the horse will have little trouble pulling it; but if the wagon is loaded with rocks, the horse would not be able to start the wagon moving when the driver cracks his whip.

In addition to the energy loss, another condition exists concerning a massive bridge; this condition is described as impedance. In this scenario, impedance measures energy transfer resistance from one medium to another, specifically from the strings to the bridge to the soundboard. A common example in textbooks uses the scenario of two strings of differing mass connected together. Campbell and Greated [1987] describe the outcome succinctly as:

> Waves are produced in the first length of string using a vibratory mechanism, and these travel along the string until they meet at the join. If the second length of string is much heavier than the first, it will act as a fixed end, and nearly all the incident wave energy will be reflected, only a small amount being passed on to the heavy string.

The result of a high mass bridge will be a reduction in the rate of vibrational energy transfer to the soundboard and an increase in sustain as vibrations are reflected back to the string. Since it has been well established that the primary damping mechanism in steel strings is air viscosity, and in nylon strings, internal damping rather than conductance to the soundboard, a closer impedance match utilizing a low mass bridge would likely improve the sound production of the guitar [Errede 2016]. Therefore, the ideal wood choice for the bridge would be characterized by high stability with changes in ambient humidity, superior hardness (Janka score) to resist string wear, a high rupture modulus to support the long term torque pressure of a slotted saddle, a high modulus of elasticity to perform the dual purpose of bracing the top and effectively transferring string energy, and low mass to reduce inertia and improve impedance. Because ebonies and rosewoods have successfully been used for bridges over the last 600 years, it is safe to assume their suitability to purpose provides a benchmark by which other replacement woods can be measured.

6.4 Summary

This section developed the criteria by which material selections should be made for the guitar's primary components: soundboard, neck, back and sides, fretboard, and bridge. Woods traditionally used for luthiery tonewoods were assessed in terms of their workability and suitability to purpose. Workability scores were based on the ease with which a particular species responded to the manufacturing processes required to transform a raw material into a finished part. Suitability to purpose assessed each component in its role as a structural component, vibrational component, or a combination of the two. The component was then defined by the mechanical properties important to best function in its defined role. Previously published mechanical property data was used to compare the wood species traditionally used for each component.

Section II

Section II uses the foundation of vibroacoustic theory and historical material selection established in Section I to objectively analyze the use of traditional and alternative tonewoods for a number of specific components used in the construction of an acoustic guitar.

Chapter 7

Analysis of Woods Suitable for Guitar Necks

7.1 Background

The woods that eventually became the iconic species utilized for guitar neck construction initially made their way to markets as an adjunct commodity to fill out ships returning from the New World carrying the more treasured dyewood species [Dean 1995]. The initial market for the *C. odorata* and *Swietenia spp.* was primarily the established shipyards of Europe and developing New World colonies [Özveren 2000]. Their high strength-to-weight characteristics and the availability of large board sizes made them ideal candidates for the shipbuilding boom occurring in the sixteenth century [Anderson 2012]. Soon thereafter, as Anderson points out regarding mahogany, “Cabinet makers and carvers deemed it excellent as well for furniture making, lending itself especially well to the art and mystery of their crafts.” Likely, the shipbuilding and cabinetmaker demand for cedar and mahogany provided the impetus of supply that was eventually employed by the less consequential luthier market. However, the use of tropical hardwoods for guitar necks was somewhat sporadic until the classical guitar found a state of standardization through the works of Antonio de Torres in the mid-nineteenth century [Sparks 2002]. After Torres, Spanish cedar became the predominant guitar neck species utilized by European luthiers, while American manufacturers were more likely to employ mahogany [Gerken et al. 2003]. The one notable exception was the use of maple (*Acer spp.*), primarily by archtop guitar makers, and secondarily by steel-string manufacturers on limited models [Benedetto 1994; Whitford, Vinopal, and Erlewine 1994; Gruhn and Carter 1993].

While there is no recorded historical testament as to the adoption of these species into luthier conventions, their eventual preponderance in use can be logically theorized based on their availability of supply for cabinet shops (luthiery and cabinetry were historically crossover occupations). Spanish cedar and mahogany are famously easy to carve with hand-tools, and both of these species possessed the optimal strength and density to produce a well-balanced instrument while maintaining structural integrity under the stress of tensioned guitar strings. Additionally, the cultural esteem for exotic hardwoods likely added to consumers' quality perceptions [Anderson 2012; Cross 1994]. The established suitability to purpose, evidenced by 250 years of predominant use, exacerbates the reluctance by those in the luthier community to accept substitutions. However, laying aside sentimental attachments, the success of any wood used for the guitar neck will depend wholly on its inherent mechanical properties [Somogyi 2009a; Gore and Gilet 2011; Haines 1979, 1980; Bucur 2016; Wegst 2006; Barlow 1997]. Therefore, the logical first step would be to determine and define the physical properties that characterize a superior guitar neck.

7.2 Selection Parameters

Academic research on guitar woods has historically been limited to the primary vibratory components of the soundboard and backplate. To date, the various structural components of the guitar have garnered little attention, likely due to the fact that tried and true wood species have demonstrated their ability to perform their duties adequately. Treatises on guitar making at least offer some testimony as to the properties to consider when making material selections for vibratory and structural components. The conventional guidance is well represented with the following excerpts (implied mechanical properties in bold):

In *The Responsive Guitar* [2009a], Somogyi states:

> The best neck blanks are straight-grained and perfectly quartersawn wood, with straight-grained and perfectly slab-cut wood being a close second. The traditional choice for guitar necks are Spanish cedar and Honduran mahogany. These are **stable**, available, **easy to work**, attractive, and relatively inexpensive for those only making a few guitars a year. Besides cost, species, **rigidity,** and **stability**, other factors involved in wood choice can be availability, beauty, **weight/density**, and liveliness.

In *Contemporary Acoustic Guitar Design and Build: Design* [2011a], Gore and Gilet offer:

…the properties required are long term **stability** (i.e., **stiffness**) under load and **ease of carving**. The traditional choices are Honduras mahogany (*Swietenia macrophylla*) for a steel-string guitar and “Spanish cedar” (*Cedrela odorata* – neither Spanish nor a true cedar) for a classical. The maples are an alternative for steel-string guitars, but tend to be both **dense** and **hard**, whilst also being prone to cold creep. The density can make a guitar neck-heavy and unbalance the guitar, whilst the **hardness** makes carving tough work…Any wood used for necks needs to be well **stabilized** prior to use.

Gore adds in “Wood for Guitars” [2011]:

> Critical to the success of the guitar neck assembly is that it remains **stable** over time as relative humidity changes. This cannot be achieved if the fretboard and neck woods have significantly different coefficients of dimensional change with moisture content.

William Cumpiano and Jonathan Natelson advise in *Guitarmaking: Tradition and Technology* [1993]:

> The principal criteria for choosing suitable neck wood for the acoustic guitar are **stability** (limited reaction to environmental changes), **working ease**, and **strength-to-weight** ratio…Of all the tonewoods, far and away the most versatile timber for neckstock is Honduras mahogany…the species is so **stable** and **easy to work** that it is often used as a standard for rating other tropical species.

The characteristics of interest that persist through these treatises are stiffness to determine structural integrity, hardness to determine carve-ability, density to determine neck mass, and stability to determine resistance to dimensional changes from different ambient humidity environments. All of these characteristics can be measured quantitatively using modulus of elasticity for stiffness, Janka scale for hardness, measured density to predict mass, and shrinkage coefficients to estimate dimensional stability. More specific definitions and implications for each metric are offered below:

The **modulus of elasticity** (*MOE*) measures a wood sample's stiffness characteristic in a particular grain direction. For guitar neck applications, this is the longitudinal direction as it replicates the stress applied to the neck in service due to string tension. The stiffness characteristic is considered the single most important characteristic to determine the long-term success of a guitar neck [Somogyi 2009a; Gore and Gilet 2011; Cumpiano and Natelson 1993]. In addition, Somogyi [2009a] argues that a stiffer neck will resist string vibration admittance conserving vibrational energy for the primary sound-producing soundboard.

As previously mentioned, wood surface hardness is typically measured with the **Janka** test. For luthiers, surface hardness is a double-edged sword when considering appropriate woods for guitar necks. A low Janka will carve more easily but be susceptible to surface wear and dents due to mishandling. Conversely, a high Janka will be durable in service but difficult to shape with hand tools. However, two factors can mitigate the negative consequences of a low or high Janka. First, modern instrument finishes provide exceptional wear resistance for a low Janka scenario. Second, the prevalence of inexpensive machining technology has replaced hand-carving in even the smaller luthier workshops. High Janka woods tend to perform better when processed using CNC milling machines. The Janka score's applicability depends on the method by which a luthier processes a wood sample into a dimensioned neck. The low-end Janka threshold for the woods under consideration was established for this analysis at 2,500 N, slightly less than that of Spanish cedar.

Density is a measurement of a sample at a specified dimension, typically kg/m^3. The measured density will determine the ultimate mass of the guitar neck once it is dimensioned. The mass of the guitar neck will affect how balanced the instrument feels when being held in a playing position. This consideration usually only extends to high mass situations deeming an instrument neck-heavy, awkward, or uncomfortable to play. While low mass guitar necks are never a concern in this regard, there is an arguable benefit to neck mass in terms of dynamics. Somogyi [2009a] states:

> Heavy necks take up string energy more slowly than lightweight ones…The reason for this phenomenon is that the strings will want to dump their energies out of whichever of their two ends they most easily can – and we want this release to go as much as possible into the guitar face. If the neck is relatively massive and unmovable and the face is compliant and receptive (i.e., because of being lightly built), then more driving energy will be released into the soundbox. If heavier necks and pegheads will contribute to sustain and volume, then lighter necks will promote quicker onset and decay of tones.

Importantly, as mentioned earlier, the weight balance between the guitar neck and box is a limiting factor when considering additional mass. Guitar neck shapes are fixed by the ergonomic objectives of the potential musician. As such, there is very little ability to affect total neck mass by altering neck dimensions. The neck mass will ultimately be determined by the selected wood sample's density and its finished dimensions.

Neck shapes and designs, though, can differ dramatically between classical and steel-string guitars, and even somewhat within their own classification. Most notably, classical guitar necks are generally designed with larger cross-section profile dimensions than steel-string guitars due in part to playing method and, more importantly, an absence of the steel truss-rod used with steel-string guitar necks to mitigate deformation due to string tension. Also, the soundbox on classical instruments tends to be much smaller than their steel-string counterparts. These parameters dictate the selection of woods exhibiting low density. Steel-string guitars, designed with a smaller neck profile and balanced by a heavier soundbox, can comfortably utilize higher density woods. Still, there is an upper limit based on design restrictions before any instrument type is no longer feasibly ergonomic. While this upper limit is somewhat at the discretion of the intended player, potential alternative wood species were rejected for this study above the density of 750 kg/m^3.

The **shrinkage coefficient** measures the dimensional shrinkage a wood sample exhibits from the moment its harvested to an oven-dry state [Meier 2016]. This measurement, calculated as a percentage (%) change in dimension, indicates a seasoned samples susceptibility to subsequent dimensional movement with a change in ambient humidity. However, Meier points out, “It should be noted that just because a particular wood species experiences a high initial shrinkage during the drying does not always correlate to an equal swelling *after* it has been dried.” Nonetheless, the shrinkage coefficient is the best indicator of this aspect. It is imperative to note that wood, as an orthotropic material, exhibits dimensional movement differently in the longitudinal (L), radial (R) (i.e., quartersawn), and tangential (T) (i.e., slab or flatsawn) directions. Consistently, dimensional movement is highest in the tangential direction and nearly negligible in the longitudinal direction. The ratio of movement between the T and R direction ranges from 1.0 to 3.0 and is typically around 2.0. Woods with a high T/R ratio will have a greater tendency to warp, cup, or twist with changes in ambient humidity [Forest Products Laboratory 2010]. While a finish coating on the neck will help slow moisture absorption, it will not totally seal it out [Meier 2016]. For the purpose of this analysis, the shrinkage coefficient in the radial direction was arbitrarily set at a 5% limit, slightly higher than the conventionally utilized Hard maple. In addition, candidates were excluded if they demonstrated a T/R over 2.0.

7.3 Results

Wood candidates were analyzed based on the published data compiled in *Wood: Identifying and Using Hundreds of Woods Worldwide* [Meier 2016]. Species meeting the thresholds established in Section 7.2, Selection Parameters, were compiled and cross-referenced against the IUCN Red List of Threatened Species to ensure a modicum of current sustainability [IUCN 2020]. Except for Spanish cedar and the mahoganies, species listed as NEAR THREATENED or greater were eliminated from consideration. Port Orford cedar (*Chamæcyparis lawsoniana),* which is currently listed as NEAR THREATENED, was allowed special dispensation and added for consideration due to its increasing population trend. The other remaining candidates are listed below in Table 7.1, woods traditionally used for guitar necks in bold.

Species	**Density (ρ) (kg/m^3)**	**Janka (N)**	**Modulus of Elasticity (*MOE*)**	**Strength-to-Weight ($MOE/\rho(10^3)$)**	**Moisture Stability (R,T) (%)**	**T/R Ratio**
Cuban Mahogany (*Swietenia mahogany*)	**.60**	**4,120**	**9.31**	**15.51**	**3.0,4.6**	**1.5**
Honduran Mahogany (*Swietenia macrophylla*)	**.59**	**4,020**	**10.06**	**17.05**	**2.9,4.3**	**1.5**
Spanish Cedar (*Cedrela odorata*)	**.47**	**2,670**	**9.12**	**19.40**	**4.1,6.2**	**1.5**
Hard Maple (*Acer saccharum*)	**.71**	**6,450**	**12.62**	**17.77**	**4.8,9.9**	**2.1**
European Maple (*Acer pseudoplatanus*)	**.62**	**4,680**	**9.92**	**16.00**	**4.5,7.8**	**1.7**
Kauri (*Agathis australis*)	.54	3,230	11.87	21.98	4.1,6.0	1.5
Albizia (*Albizia spp.*)	.60	4,530	10.91	18.17	2.7,4.6	1.7
Red Alder (*Alnus rubra*)	.45	2,620	9.52	21.16	4.4,7.3	1.7
Port Orford Cedar (*Chamæcyparis lawsoniana*)	.47	2,620	11.35	24.15	4.6,6.9	1.5
Queensland Walnut (*Endiandra palmerstonii*)	.68	7,380	11.42	16.79	4.5,8.6	1.9
Mango (*Mangifera indica*)	.68	4,780	11.53	16.96	3.6,5.5	1.5
Black Cherry (*Prunus serotina*)	.56	4,230	10.30	18.39	3.7,7.1	1.9
African Padauk (*Pterocarpus soyauxii*)	.75	8,760	11.72	15.62	3.3,5.2	1.6
Limba (*Terminalia superba*)	.56	2,990	10.49	18.73	4.3,6.3	1.5
Australian Red Cedar (*Toona ciliata*)	.49	3,130	9.22	18.81	3.8,6.3	1.7
Avodire (*Turræanthus africanus*)	.58	5,180	11.13	19.19	4.2,6.6	1.6

Table 7.1: Mechanical properties of wood species appropriate for use as guitar necks [Meier 2016].

7.4 Analysis

The four traditional and twelve alternative species listed in Table 7.1 represented a 4.3 % success rate for all potential species compiled by Meier [2016]. While many rejected species were eliminated based on a single metric or the failure of sustainability, the objective was to offer woods that could be substituted without compromising the quality standards established by Spanish cedar and Honduran mahogany and without an adverse ecological impact. Specific analysis of each species is offered below:

Cuban mahogany was once considered the premier mahogany species due to its superior color and tight grain. Centuries of overutilization by shipbuilders and cabinet shops have decimated native populations in the West Indies to “the point of utter depletion” [Meier 2016]. *S. mahogany* was added to Table 7.1 merely as a representative of a traditional wood used for guitar necks.

Honduran mahogany has been a traditional neck wood of choice for most steel-string guitar makers as well as a number of classical builders [Gerken et al. 2003]. As referenced earlier, most treatises on steel-string guitar making simply defer to *S. macrophylla* as the obvious choice for use on guitar necks. Reviewing its data metrics in Table 7.1 affirms the regard for which it has earned over the last 250 years. Its stiffness and stability characteristics have become the accepted standard by which all other neck woods are compared [Cumpiano and Natelson 1993]. Also critical to the long-term success of Honduran mahogany’s popularity amongst luthiers is the ease with which it can be shaped with hand tools.

Spanish cedar has historically been the preferred wood selected for use on classical guitars. In addition, *C. odorata* has also successfully been used on steel-string guitars, thanks in part to the use of adjustable truss rods to enhance stiffness characteristics [Johnston, Boak, and Longwirth 2009]. Despite cedar’s relatively low *MOE*, it has proven sufficient for use on lower tensioned nylon string instruments. Its low relative Janka score indicates the ease with which

Spanish cedar can be shaped with hand-tools but also suggests a susceptibility to damage with careless handling.

Hard maple demonstrates its suitability with a high *MOE*. Native to Northeastern North America, maple is the predominant selection for archtop instruments and occasional selection for steel-string guitars*. A. saccharum*’s high density makes it most appropriate for narrower, thinner necks, which would also mitigate eventual mass. Hard maple’s shortcoming is exposed by its poor moisture stability and high T/R ratio. In fact, maple would otherwise be discounted from Table 7.1 due to its T/R exceeding 2.0 if it were not already widely used. Hard maple has a reputation for being difficult to shape with hand-tools, evidenced by its high Janka score. However, this characteristic also illustrates maple’s resistance to dings and dents from mishandling.

European maple has a long history of use in luthiery. Prior to the Torres era, *A. psudoplatanus* was commonly used for classical guitar necks and is still the predominant species found on bowed instruments [Winspear 1991; Campbell, Greated, and Myers 2004]. The relatively low *MOE* of European maple suggests this wood could benefit from larger neck dimensions or assistance from a truss rod. A lower Janka relative to Hard maple indicates this maple species is more conducive to hand shaping.

Kauri is a massive tree endemic to New Zealand [Meier 2016]. Its relatively low density and high stiffness make Kauri suitable for both classical and steel-string guitars. Also, Kauri’s lower end Janka indicates a suitability to dimensioning with hand-tools.

Albizia ranges throughout tropical Asia and Africa. Albizia compares almost evenly with Honduran mahogany in terms of density, Janka, and *MOE*. Albizia is also the only species in Table 7.1 to surpass Honduran mahogany in terms of radial stability.

Red Alder is one of the most common hardwood species in the U.S. Pacific Northwest [Meier 2016]. While Alder has been successfully utilized for electric guitar bodies, the author is unaware of *A. rubra* being systematically used in guitar necks. The mechanical properties of Red Alder indicate it could be a reasonable substitute for Spanish cedar, demonstrating very similar metrics in every property.

Port Orford cedar, found primarily in the Pacific Northwest state of Oregon, demonstrates excellent mechanical properties. Its characteristic high *MOE*, low density, and remarkably straight grain coincidently make *C. lawsoniana* the ultimate wood species for archery arrows. These same characteristics make Port Orford cedar one of the few wood species that could be appropriately selected for either classical or steel-string guitars. Also, an increasing population trend indicates a more promising sustainability future.

Queensland walnut is a commonplace wood in its indigenous growing region of North-Eastern Australia. *E. palmerstonii* likely garnered its “walnut” moniker due to its similar dark brown appearance, despite having no relation to the true walnuts (*Juglans spp.)* [Meier 2016]. Its relatively higher density and *MOE* make this species more suited for use on high-tension steel-string guitars. Additionally, the high Janka score makes Queensland walnut more appropriate for machine-assisted shaping.

Mango grows naturally and on plantations throughout Tropical Asia and Oceania. Known more readily for the fruit it bears, *M. indica* has recently gained favor in the luthiery community for instrument back and sides. Its relatively high density and *MOE* suggest Mango to be most appropriately applied for steel-string necks.

Black Cherry is a common species from the Eastern coasts of North America through the Great Lakes region. Black cherry succeeds on all the measured criteria but was nearly disqualified with a T/R ratio of 1.9, indicating potential deformation issues when subject to changes in ambient humidity.

African Padauk is another species that was nearly discounted due to a singular metric. Its characteristically high density makes African padauk more suitable for steel-string applications. In fact, *P. soyauxii* has already shown occasional use by small scale luthiers primarily on electric guitars. With the highest Janka of all woods listed in Table 7.1, African padauk is most definitely more appropriate for machining rather than hand-carving.

Limba, from West Africa, is another wood that has been making inroads to luthiery. While currently only typically used for electric guitar bodies, *T. superba's* relatively low density and Janka indicate a reasonable application for hand-dimensioned classical guitar necks.

Australian Red cedar grows not only in its namesake Australia but also in Southern Asia. Sharing the same species family as Spanish cedar, *Meliaceæ*, it is not surprising they share nearly identical mechanical properties. *T. ciliata* would be an obvious alternative for hand-carved classical guitar necks.

Avodire is an African species found in the western and central regions, often near bodies of water [Meier 2016]. Another member of the *Meliaceæ* family, Avodire outperforms the benchmark Honduran mahogany in every aspect except moisture stability. With a moderately high Janka, *T. africanus* lends itself advantageously to steel-string guitar applications utilizing machining methods.

7.5 Conclusions

Spanish cedar and Honduran mahogany have demonstrated over 250 years of predominant use in luthiery for guitar neck applications. Based on that success, it can be reasonably assumed that the mechanical properties inherent to these two species provide the benchmarks by which potential sustainable woods can be compared. The mechanical properties investigated were compiled using the common conventions suggested in guitar making treatises. These treatises had consistent agreement as to the properties of importance: density, stiffness, surface hardness, and moisture stability. While high stiffness and moisture stability were categorically imperative, the importance of density and surface hardness has to be individually assessed based on neck dimensions and manufacturing processes, respectively. Spanish cedar and Honduran mahogany's mechanical properties were used as benchmarks to establish thresholds by which 369 different species were compared. Potential candidates were rejected for failing any single threshold or if they were listed as VULNERABLE or greater on the IUCN Red List. Thirteen sustainable species were assessed alongside three traditional species deemed currently threatened. All of the candidates were found acceptable in at least conditional use. Of all the species listed in Table 7.1, Port Orford cedar distinguished itself by satisfying the criteria for both classical and steel-string guitars and demonstrating a surface hardness conducive to hand-carving.

The acceptance of alternative woods for use in luthiery will depend on the demonstration of equal or superior material characteristics to overcome the bias and prejudice developed towards traditional wood species. By demonstrating the mechanical properties of alternative species objectively, luthiers and consumers will gain confidence that instrument quality will not be diminished with sustainable substitutions. In fact, as in the case of Port Orford cedar, quality could even be enhanced.

Chapter 7 – Analysis of Woods Suitable for Guitar Necks

Chapter 8

Fingerboard Woods: Quantifying the Mechanical Properties of Traditional and Alternative Species

8.1 Background

As previously established, luthiers' choice of woods has remained relatively unchanged over the last two centuries. The woods for specific guitar components have been standardized through tradition, expectation, and suitability to purpose. While spruce (*Picea spp.*) has remained the preeminent soundboard choice dating back to time immemorial, the tropical hardwoods of ebony (*Diospyros spp.),* mahogany (*Swietenia spp*.), Spanish cedar (*Cedrela odorata*), and rosewood (*Dalbergia spp.)* supplanted the temperate hardwoods of Europe after trans-oceanic trade was established with India, Africa, and the New World. From the Torres era onward, the guitar in its apex was typically constructed of a spruce soundboard, Brazilian rosewood (Dalbergia nigra) back and sides, mahogany or Spanish cedar neck, and ebony or rosewood fretboard and bridge [Sparks 2002]. Unfortunately, in the words of B. C. Bennet [2016], “Late 19th century and early 20th century guitars read like an endangered species list.” Indeed, the overutilization of tropical hardwoods has led to the complete ban of harvest for Brazilian rosewood through the Appendix I listing by CITES in 1992. Subsequently, Honduran mahogany (*Swietenia macrophylla*) and Spanish cedar were listed in CITES Appendix II, restricting harvest and trade from certain geographic areas. More recently, in 2017, all rosewood species beyond Brazilian were also listed in CITES Appendix II. While only the ebonies from Madagascar are currently listed in CITES Appendix II, the other commercial ebonies traditionally used in luthiery are currently listed by the IUCN as either “Vulnerable”, “Endangered”, or “Critically Endangered”.

While there is an established body of science concerning the vibratory aspects of luthiery, very little research has been directed at other structural components such as necks, bridges, and fingerboards [Liu et al. 2020]. However, as the timbers that have traditionally been used for these functions become more, if not wholly, unavailable, potential species must be vetted to ensure at the very least a like-for-like substitution in terms of physical properties [Gore 2011]. Because both luthiers and guitar players hold traditional woods to an iconic status, the acceptance of substitutes will require empirical evidence to equitability; the best-case scenario would demonstrate substitution superiority to create demand for substitutes rather than just acceptance. Even so, the potential for acceptance of substitution is further mitigated by the human nature demand for that which is rare [Fouihle, Houssay, and Bremaud 2012]. For example, according to Annah Lake Zhu in “China’s Rosewood Boom: A Cultural Fix to Capital Overaccumulation” [2020], rosewoods have become the number one illegally trafficked endangered species. The demand for rosewood furniture by the “nouveau riche” in China accounts for nearly 90% of the illegal trade in the various Dalbergia spp. Zhu attributes China’s “insatiable demand for rosewood” as a means by which rising cultural circles could demonstrate “prestige” and “sophistication.”

Similarly, the woods used as guitar components are often chosen out of the allure to own something rare and not necessarily according to purpose superiority. In other words, the extrinsic value of the instrument is partly determined by the woods from which it is made [Carcagno et al. 2018]. Guitar makers have long used material selection to help distinguish between their various lines. For instance, while rosewood fingerboards are usually employed on high-quality instruments, ebony is usually selected for manufacturers’ top-of-the-line models, while low-end instruments often employ a black dyed or painted whitewood in the attempt to emulate the standard expectation of a dark wood [Fouihle, Houssay, and Brémaud 2012; Gore 2011].

A growing body of research contends the name of the species is less important than the specific properties of a given wood sample [Gore 2011; Carcagno et al. 2018; Somogyi 2009a; Wegst 2006; Fouihle, Houssay, and Brémaud 2012; Haines 1979]. This contention is well explained in Gore and Gilet [2011] with the following observation:

> It must never be forgotten, however, that even in highly select “good” tonewoods, the within-species variation in material properties can range up to a factor of two, emphasizing the importance of the materials you select.

Therefore, when considering materials for the fingerboard, it behooves the luthier to first identify the properties of importance for that specific function and then test the prospective specimen to ensure it satisfies a threshold of acceptability. Furthermore, by first establishing benchmarks vis-à-vis tried-and-true species, potential substitution species can be compared on a macro level to determine general suitability. Specific specimens can then subsequently be vetted for selection.

8.2 Properties of Importance

There is general consensus between published academic research and practical luthier treatises as to the material properties to consider when selecting wood for an instrument fingerboard; the structural properties of mass, stiffness, surface hardness, moisture stability, and compression strength are found throughout [Somogyi 2009a; Gore and Gilet 2011a; Sloane 1966; Benedetto 1994; Young 1975; Liu et al. 2020]. The specific implication of each property is as follows.

Mass. The mass of the fretboard has two separate implications to consider in terms of use as a fingerboard. First, because the fretboard exists as component of the neck system, the ergonomics of guitar balance is affected by the total mass of the neck versus the total mass of the instrument body. This is particularly true of guitars being played in a seated position. The instrument needs to be balanced so that note and chord fingering is not hindered by any necessity to support a neck-heavy instrument. Second, and in contradiction to the first implication, a higher mass neck-unit provides greater inertia to string vibration. High inertia will resist string energy loss at the neck and allow more energy to be supplied to the vibrating soundboard [Somogyi 2009a]. The goal then would be to strive for the highest mass neck-unit that maintains a balanced feel for the musician. Factors such as scale length and neck dimensions will further impact this consideration.

Stiffness. As a structural part of the neck-unit, fingerboard stiffness contributes to the resistance of string tension that could potentially deform the fingerboard plane and make the instrument unplayable. Steel-string guitars exert upwards of 90 kg of tension, causing a neck of insufficient stiffness to bow. Lower-tensioned classical guitar necks are also susceptible to this as they do not employ the adjustable truss-rod commonly found in steel-string guitars. In addition, higher neck stiffness will increase the mechanical impedance of string energy to preserve it for soundboard admittance [Fletcher and Rossing 1998; Somogyi 2009a]. This, of course, assumes the intent to preserve string energy rather than damping it out of the vibratory system. Stiffness is measured by determining the modulus of elasticity.

Surface Hardness. The fingerboard is subject to the abrasive effect of pressing strings against its surface. While this condition is of greater impact with non-fretted fingerboards, fretted instruments are also susceptible depending on fret height and the finger pressure with which a musician frets a note. Surface hardness is measured by a Janka score; the amount of mass required to “embed an 11.28 mm steel ball into the wood to half its diameter” [Meier 2016]. The Janka is usually reported for a species rather than a specific specimen, as this is a destructive process that renders the sample useless for further utilization. Besides offering a published Janka score for each species, this research also offers an alternative method to measure hardness using a pin Durometer. The Durometer is traditionally employed in testing surface hardness of plastics, rubber samples, and hardwood flooring.

Moisture Stability. Wood dimensional stability in changing humidity environments is important due to primarily three factors. First, dimensional changes in the longitudinal direction can cause deformation in the fingerboard plane. Specifically, moving the instrument to a high humidity environment will cause the outer wood fibers to swell, leading to the fretboard to bow backward, while moving to a low humidity environment causes the fibers to shrink, causing it to bow forward. These ramifications are more detrimental to guitars absent of an adjustable truss rod, which is used to compensate for these deformations. Second, radial dimensional changes can cause an issue with fret ends. In low relative humidity environments, the width of the fingerboard will shrink while the length of a fret remains fixed, causing sharp fret edges to protrude past their usual boundary. Finally, dimensional fretboard expansion and contraction can cause lacquer finish adhesion issues at the seam between the fretboard and the neck. This issue is exacerbated when the shrinkage coefficient for the fretboard wood species is decidedly different from that of the neck wood species. Often a witness line becomes visible in the lacquer finish with moderate humidity changes. Under more severe conditions, the guitar finish will crack along the fingerboard neck joint. It would be impractical to test individual wood samples for compression moisture stability necessitating reliance on published averages for a species.

Compression Strength. Sometimes referred to as “crushing strength”, compression strength measures wood fiber strength in the longitudinal direction [Meier 2016]. This metric is particularly important when barbed frets are seated in fret-slots. A low compression strength suggests the wood fibers would be damaged in this process leading to possible fret failure, i.e., frets falling out of their slots. It would be impractical to test individual wood samples for compression strength necessitating reliance on published averages for a species.

8.3 Fingerboard Candidates

Table 8.1 details published mechanical properties for the five fingerboard candidates and Honduran mahogany. Honduran mahogany was added solely to demonstrate moisture stability compatibility.

Species	Specific Gravity (kg/m^3)	Janka (N)	Modulus of Elasticity (GPa)	Compression Strength (MPa)	Radial Stability %	IUCN Status
Hard Maple (*Acer saccharum*)	710	6,450	12.62	54.0	4.80	N.A.
E.I. Rosewood (*Dalbergia latifolia*)	830	10,870	11.50	59.7	2.70	V
W. African Ebony (*Diospyros crassiflora*)	960	13,700	16.89	76.3	8.30	V
Granadillo (*Platymiscium spp.*)	950	12,030	19.56	80.7	2.80	N.A.
Katalox (*Swartzia cubensis*)	1150	16,260	25.62	105.1	3.90	N.A.
Honduran Mahogany (*Swietenia macrophylla*)	590	4,020	10.06	46.6	2.90	V

Table 8.1: Mechanical properties of woods considered for fingerboards [Meier 2016].

Historically, various ebonies and Brazilian rosewood were the preferred species used for fingerboards. Once Brazilian rosewood became unavailable, Indian rosewood became its de facto substitute [Gerken et al. 2003]. Hard Maple came to prominence with the single-piece neck and fretboard design employed by Leo Fender on his electric guitars of the early 1950s [Balmer 2009]. Species-specific observations based on the data in Table 8.1 and conventional wisdom are as follows:

> **Hard maple** is the least expensive species on the list. However, its material property scores are the lowest in every category except slightly besting East Indian rosewood in modulus of elasticity. Nonetheless, Hard Maple remains a popular fingerboard for electric guitars, primarily.
>
> **East Indian Rosewood** is currently the most common species used for guitar fingerboards [Gerken et al. 2003]. Major instrument producers have relied on East Indian rosewood due to its one-time availability, low cost, and dark appearance, which coincides with consumer expectation for a fingerboard wood. Unfortunately, overutilization by various end-users has resulted in a CITES Appendix II and IUCN VULNERABLE listing. Its mechanical properties are towards the lower end of the species listed in Table 8.1. However, once seasoned, East Indian rosewood demonstrates a moisture stability at the lower end and similar to that of Honduran mahogany.
>
> **West African ebony** is typically used on the top-line offerings of most luthiers. *D. crassiflora* exhibits the consistent jet-black appearance both consumers and luthiers expect to see on a high-end instrument. According to the metrics in Table 8.1, West African Ebony scores towards the average of the species listed for most categories and, surprisingly, worst in terms of moisture stability. Nonetheless, West African ebony will likely remain the preferred choice for high-end instruments as long as visual aesthetic remains the prevailing determining factor.
>
> **Granadillo** is a relative newcomer to the art of luthiery. As a tonewood, it has been touted by Taylor Guitars as being very similar to East Indian rosewood [Taylor 2020]. Most luthier wood supply firms are now offering Granadillo as a “sustainable” alternative to threatened rosewood species.

Judging by the material properties in Table 8.1, the *Platymiscium spp.* holds promise as a fingerboard wood, even superior to ebony in terms of modulus of elasticity, compression strength, and moisture stability.

Due to the dark color of **Katalox,** this species is often referred to as Mexican ebony, even though it is not a *Diospyros spp*. Indeed, between its near-black coloration and reported mechanical properties, Katalox may, in fact, be the best prospect for a fingerboard. Additionally, the advertised price by Luthiers Mercantile International for a first grade Katalox fingerboard is about half the cost of a West African ebony fingerboard [LMII.com 2020].

8.4 Scope of Testing

As previously pointed out, there are no practical means to test individual samples for compression strength and moisture stability. Therefore, data for these properties rely on published figures to indicate wood sample attributes for the sake of comparison and achieving a threshold based on traditional fingerboard species. However, mass, stiffness, and surface hardness can be accurately measured using the methods outlined below. The compilation of the metrics will provide a basis to compare the suitability of tested woods for the application of a fingerboard. Mass was measured in terms of density, kg/m^3. Stiffness is considered only in the longitudinal direction as this is the primary strain on the fingerboard due to string tension. Surface hardness testing was an average of Durometer readings at three different sample locations. All tested samples were dimensioned to 6.35 mm x 68.5 mm x 482.5 mm. These dimensions were chosen simply to ensure the samples could be subsequently used as guitar fingerboards. The samples were procured from luthier supply companies that processed the wood with the intention of being used as high-quality instrument fingerboards. The wood was seasoned and tested in a climate-controlled space at an ambient temperature of 21℃ +/- 1° and relative humidity of 43%-47%. Specific tests were carried out in their entirety for all the species at a consistent climate to mitigate any disparity due to temperature and humidity factors.

8.5 Testing methods

Mass was measured using a jewelry scale. **Density** was calculated based on the dimensions of the specimen and measured in kg/m^3.

Surface hardness was tested using a Shore D-scale durometer. The durometer measures the depth of indentation made by a 1.44 mm steel conical pin under 44.45 newtons of spring pressure. The corresponding D-scale is a dimensionless quantity that allows surface hardness comparisons (ASTM 2017). Because durometer testing is non-destructive, specific samples can be tested and subsequently used in manufacturing.

The **modulus of elasticity** in the longitudinal direction (E_L) was determined using a static three-point deflection rig, as shown previously in Figure 2.9. The equations provided by elementary beam theory were used to determine E_L based on each sample's measured deflection in accordance with ASTM, JIS, and ISO standards [Yoshihara and Tsunematsu 2005].

8.6 Results and Discussion

Table 8.2, below, details the mean density, surface hardness, and modulus of elasticity of ten samples for each of the five fingerboard candidates.

Species	**Density (kg/m^3)**	**Durometer (D Scale)**	**Modulus of Elasticity (GPa)**
Hard Maple	720	69	16.00
E. Indian Rosewood	740	72	12.99
W. African Ebony	1,150	84	17.36
Granadillo	990	79	20.32
Katalox	1,090	82	20.65

Table 8.2: Tested density, Durometer D scale, and modulus of elasticity values for five fingerboard species.

In terms of density, the tested results concur reasonably well with the published figures in Table 8.1 except for East Indian rosewood and West African ebony, which came in 11% lower and 20% higher, respectively. Other than West African ebony scoring slightly higher than Katalox, the surface hardness rankings produced using the durometer are consistent with the expectations established by published Janka scores. In terms of the modulus of elasticity, the major outliers from expectation were Hard maple (+27%), and Katalox (-25%). Factors that might contribute to the differences between the published and tested figures are the relatively low sample size of ten specimens for each species, the growing environment from which the wood was sourced, and radical outliers that dramatically affected the calculated mean scores. To further investigate each sample's specific characteristics, Figure 8.1 displays the tested results for the primary fingerboard functional properties of surface hardness and stiffness.

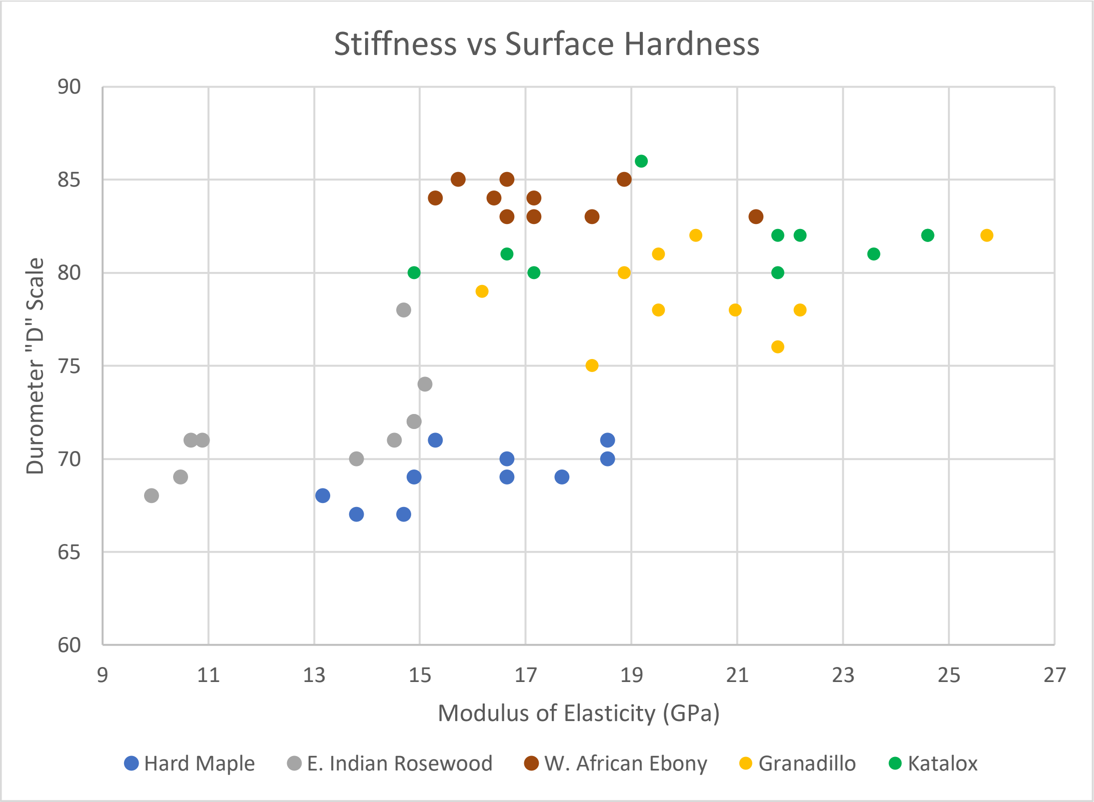


Figure 8.1: Plot comparing the modulus of elasticity and surface hardness of fingerboard samples.

Immediately apparent in Figure 8.1 is the disparity of values demonstrated within species by all of the fingerboard candidates. This aspect demonstrates the importance of testing individual potential components rather than relying on published species' averages. Specific evaluation of each individual species is offered as follows:

> **Hard maple** generally scored the lowest in terms of surface hardness. This result is consistent with the expectation established by the published metrics. Surprisingly, in some cases, maple scored as well as any species in terms of stiffness and generally scored better than East Indian rosewood. Hard maple proved itself to be a reasonable fingerboard candidate, especially if the surface can be protected by an abrasion-resistant surface

finish, as is usually the case when used as an electric guitar fingerboard.

Figure 8.2: Photo of a Hard maple sample. Photo by author.

East Indian Rosewood scored the lowest in terms of stiffness in half of its sample set (the data point just left of the 11 GPa actually represents two identical specimens). Even the best samples barely approach the stiffness scores of West African ebony, Granadillo, and Katalox. This finding suggests East Indian rosewood's choice as a fingerboard wood should be questioned, especially in light of its threatened ecological status.

Figure 8.3: Photo of an East Indian rosewood sample. Photo by author.

West African ebony demonstrated the most consistency in terms of surface hardness and stiffness. It should be noted that the samples used came from a sole supplier that procures their timber from a singular location in Cameroon. Its high scores relative to East Indian rosewood substantiates its preference in use for high-end instruments, particularly when a jet-black visual aesthetic is a contributing consideration.

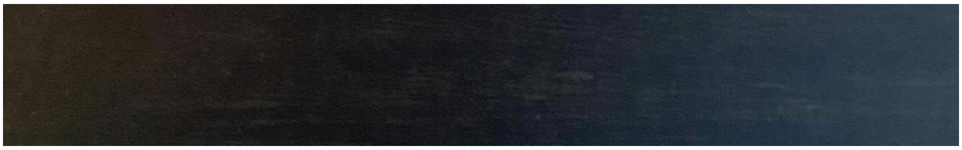


Figure 8.4: Photograph of a West African ebony sample. Photo by author.

Granadillo exhibited a wide disparity of both surface hardness and stiffness. Nonetheless, its surface hardness with every sample tested better than East Indian rosewood. In addition, its stiffness scores were generally higher than those of West African ebony. With testing and selection, Granadillo could prove itself to be a superior fingerboard wood to East Indian rosewood in both surface hardness and stiffness. Also, its dark-brown appearance is similar to East Indian rosewood to satisfy any penchant for that visual aesthetic.

Figure 8.5: Photograph of a Granadillo sample. Photo by author.

Katalox, as with Granadillo, demonstrated vast disparity in individual scores. However, 50% of the samples tested displayed stiffness scores higher than the industry standard West African ebony. Furthermore, due to its natural near-black coloration, Katalox could be dyed to compare on visual aesthetic with the ebonies, a practice already done by manufacturers to enhance the darkness of streaky or mineral spotted ebony.

Figure 8.6: Photograph of a Katalox sample. Photo by author.

8.7 Conclusions

The threat to the continued availability of traditional woods used for instrument fingerboards necessitates the consideration of alternative species. With East Indian rosewood restrictions and dwindling availability of ebony, it is conceivable the two primary wood species used for quality fingerboards may no longer be available for commercial use. The results of the testing contained herein demonstrated the viability of substitution for rosewood and ebony by species not referred to in a CITES Appendix or by IUCN threatened status. The testing also demonstrated the relatively low suitability of East Indian rosewood for use as a fingerboard relative to Katalox and Granadillo. Katalox, in addition to its exemplary mechanical properties, contends well with ebony as far as visual aesthetic is concerned. Beyond the scope of this test, there are likely several other species that could also be considered as potential candidates based on their published material properties. Finally, the testing as a whole demonstrated the importance of considering wood samples on their tested material properties rather than on the published averages for the species. While the suitability of fingerboard woods can be assumed by published generalizations, they can only be confirmed through individual testing.

Chapter 9

Guitar Bridges: Analysis of Important Mechanical Properties to Determine Suitability of Various Wood Species

9.1 Background

The archetypal ebony and rosewood populations common to luthiery have dwindled due to global overutilization. The growing number of international harvest and trade restrictions for these timbers indicate an uncertain future. The International Union for Conservation of Nature (IUCN) currently categorizes the two most prominent species used for guitar bridges, West African ebony (*Diospyros crassiflora*) and East Indian rosewood (*Dalbergia latifolia*), as VULNERABLE [IUCN 2020]. In addition, the Convention on International Trade of Endangered Species (CITES) lists all rosewood (*Dalbergia spp.*) species in Appendix II, regulating their harvest and trade due to global overutilization. Furthermore, CITES specifically lists Brazilian rosewood (*Dalbergia nigra*) in Appendix I, which prohibits any further harvest and trade of this once ubiquitous luthiery wood [CITES 2020]. Conceivably, the wood species that have overwhelmingly been selected for guitar bridges may, in the future, be no longer available for commercial use. Even without a complete harvest ban on these woods, the scarcity of supply and increasing costs are forcing guitar manufacturers to consider alternative timbers.

However, acceptance within the luthiery community will depend on overcoming the prejudices developed over two centuries of fairly static wood material applications for guitar bridges [Haines 1979]. When Antonio de Torres standardized the modern classical guitar in the mid-nineteenth century, ebony and rosewood became the *de facto* woods selected for use on concert quality instruments. So prevalent was the expectation for a dark-wood bridge that cheap instrument manufacturers using a light-colored wood, such as maple, dyed, or painted the wood in order to match the expected visual aesthetic [Gerken et al. 2003; Fouihle, Houssay, and Brémaud 2012]. In essence, the wood species used for the guitar bridge were a partial indicator of the instrument's quality [Gerken et al. 2003; Huber 1994]. Arguably, this convention to establish panache through material selection goes back centuries before Torres when luthiers embellished their instruments with rare and exotic materials to substantiate higher prices, as shown previously in Figure 3.4 and below in Figure 9.1.

Figure 9.1: Photo of a lavishly inlaid guitar from the seventeenth century. Note the tortoiseshell fretboard. Accessed January 16, 2020, https://www.metmuseum.org/art/collection/search/503932, used with permission.

While the lavishly adorned instruments of the Baroque period subsequently gave way to a more subdued visual aesthetic, exotic tropical hardwoods from Africa, India, and the New World saw continued use as specific luthiery components: most notably necks, fretboards, bridges, and backs & sides. Functional attributes aside, the penchant for fashionable exotic wood furniture was a likely contributing factor, rosewood, and ebony being the ultimate statement in style [Anderson 2012; Cross 1994].

Beyond the preferred visual aesthetic and added panache, rosewood and ebony were also ideally suited to perform structurally as a guitar bridge. At a basic level, the guitar bridge needs to: (1) be strong enough to anchor the tensioned guitar strings without breaking, (2) provide a stiff brace to resist soundboard deformation, and (3) resist abrasion wear due string contact [Gore 2011]. Both ebony and rosewood are well known for measuring high values of Modulus of Rupture, Modulus of Elasticity, and Surface Hardness. On the basis of functioning at a structural level AND adding a certain level of prestige, ebony and rosewood are admittedly superior choices. However, current acoustic research contends the property of mass should also be a primary determining factor when selecting components for a vibratory system [Wegst 2006; Torres and Boullosa 2009; Bucur 2006; Fletcher and Rossing 1998; Sedik et al. 2010; Haines 1980]. Other research also suggests that moisture stability has both structural and vibrational ramifications that should also be considered [Gore and Gilet 2011; Somogyi 2009a].

In light of the current ecological dilemma facing ebony and rosewood, there is an imminent need to examine and qualify potential substitutes and re-examine the suitability and presumed superiority of traditional bridge woods. This stance is succinctly articulated by C. Y. Barlow [1997] as follows:

> There are two approaches one can use to when trying to find a substitute material. One is to seek a material which gives the same mechanical properties as what is being replaced. This approach automatically limits the choice of materials…The other approach is to analyse the system to discover what the optimum properties of the material should be for it to function as efficiently as possible.

Current species selections are likely born more out of the habit of adhering to traditional conventions rather than a thorough investigation of comprehensive material properties that would verify suitability. This analysis will first establish and define the properties necessary to evaluate woods for the intended end-use as a guitar bridge. Secondly, using published data, evaluate various wood species' suitability to purpose.

9.2 Material Properties

A review of existing scientific research revealed very little in terms of studies directly relating to acoustic guitar bridges. However, there was consensus regarding musical instrument wood in general and modern treatises on guitar making to establish the properties to be considered herein. The principal properties to be examined when selecting wood species for guitar bridges were **density, surface hardness, strength, stiffness, and moisture stability**. The definition and consequence of each property are listed as follows:

Density (ρ) is the measurement of a specimens' weight at specified dimensions (kg/m^3). Since guitar bridges are generally manufactured to predetermined dimensions due to standardized production methods, the resulting mass cannot be managed through any other means than through material selection. Published data for density reflects a typical measurement for that species [Forest Products Laboratory 2010]. However, the density of a specific sample can vary from published data due to the location where the sample was acquired from the tree and the growing environment from which it was harvested. Sample density and resulting bridge mass affect the bridge's ability to respond to string vibration. A high mass bridge will take longer to accelerate and incur more resistance to vibration energy [Somogyi 2009a]. Gore [2011] contends, "The overall mass of the bridge is a critical design factor in both tailoring the sound of the guitar and in determining its responsiveness." In a separate treatise, Gore and Gilet [2009a] assert:

> To make it easy for the bridge, and hence the soundboard, to accelerate, it makes sense to make the bridge as light as possible, as higher accelerations produce higher velocities and hence more sound. It is impossible to make a sufficiently strong bridge too light.

While acoustical properties are studied predominantly in research regarding soundboards, it is imperative to view the guitar bridge as an integral part of the soundboard that ultimately alters the soundboard's mass affecting its vibrational characteristics. Master luthier Ervin Somogyi [2009a] estimates the typical steel-string guitar bridge ranges in mass between 35 and 60 grams, and typical braced soundboard from 300 to 600 grams. Given these figures, the addition of a typical bridge could increase soundboard mass upwards of 20%. Essentially, a soundboard with a massive bridge will take longer to accelerate and require more energy to keep it in motion [Somogyi 2009a; Gore and Gilet 2011a].

Surface hardness in wood is determined by the Janka test, as detailed previously in Section 6.2. Published Janka characteristics vary greatly between tree species, with Quebracho (*Scinopsis spp.*) scoring a top-end 20,340(N) and Balsa (*Ochroma pyramidale*) registering a low-end 390(N). The two most common wood species used for guitar bridges, West African ebony and East Indian rosewood, score 13,700(N) and 10,870(N), respectively [Meier 2016]. High surface hardness ensures the bridge can effectively resist compression pressure from the saddle and string wear from terminating string-ends [Gore and Gilet 2011]. String wear is particularly prominent with higher tensioned steel-strings. Initially, prior to the advent of the removable saddle in the mid-nineteenth century, the bridge wood also served as the saddle and was further subjected to the wear mechanism of contacting a tensioned, vibrating string. Torres helped popularize the removable saddle, often a strip of ivory or bone, which helped eliminate some of the destructive effects of string contact [Morrish 2002]. For classical guitars, particularly, the addition of the bone saddle and the conventional bone veneer protecting the string tie-block diminishes the requisite need for surface hardness. Likely, these string-wear consequences initially made ebony and rosewood eminently crucial for an individual instrument's long-term viability. However, with the mitigation of string-wear effects, surface hardness has diminished relevance.

The calculation of the **modulus of rupture** is the "generally accepted criterion" for determining wood strength [Forest Products Laboratory 2010]. The modulus of rupture (*MOR*) measures the amount of applied mass needed to cause a catastrophic failure in a wood sample when supported on two ends. High wood strength is of specific importance for guitar bridges to avoid wood failure. This failure is most often caused by the "levering" pressure exerted by the slotted saddle [Somogyi 2009]. Unfortunately, testing a specific wood sample for *MOR* is impractical as the test itself will effectively destroy the sample. Therefore, the analysis of wood strength necessitates the reliance on published data that reports figures typical for a species.

Material stiffness is defined by determining the modulus of elasticity (*MOE*) of a wood sample, also commonly referred to as the Young's modulus. This topic was discussed in detail in Chapter 2. While published data is available to represent a species in general, within-species variation can often differ by a factor upwards of 2x [Gore 2011; Brémaud et al. 2011]. Fortunately, testing methods based on elementary beam theory are non-destructive and can be easily replicated for testing individual samples.

The guitar bridge performs two primary functions: (1) act as a "significant" brace to resist soundboard deformation due to tensioned strings, and (2) provide the means to couple string vibrational energy to the soundboard [Gore and Gilet 2011a; Somogyi 2009a].

Without an adequate bracing structure, the soundboard would eventually fail due to the continued stress of tensioned strings. The guitar bridge acts as part of this structure to distribute this load. According to Gore [2011], the bridge is a "massive cross-grain brace seated right in the middle of the top of the guitar and so has a profound effect on the vibrational behaviour of the guitar, and consequently affects the sound of the guitar considerably." A stiff bridge will efficiently transfer string energy to the soundboard, while a flexible bridge will consume energy if it is allowed to bend, effectively acting as a spring-damper. For optimal sound production, the goal is to flex and vibrate the soundboard, not the bridge. Somogyi [2011a] offers, "(the bridge) is in a real way acting as a lever upon the top." Taken to an extreme, an infinitely flexible "lever" would be unable to move the soundboard at all.

However, by nature of requiring a substantial footprint for successful soundboard adhesion, traditional steel-string guitar bridges are likely over-engineered in terms of stiffness due to their large, bulky design [Gore and Gilet 2011a]. This contention suggests either an allowance for less stiff woods or an opportunity to re-think bridge design to utilize woods with extremely high stiffness-to-mass characteristics.

Moisture stability indicates the potential for dimensional changes in a wood sample due to changes in ambient humidity. Because wood is anisotropic, shrinkage/swelling due to changes in humidity will occur at different rates relative to grain direction. The tangential direction will typically demonstrate the highest dimensional change while the longitudinal direction exhibits the lowest, a mere 0.1%-0.2% from full saturation to oven-dry [Forest Products Laboratory 2010]. Because radial grain direction stability is always greater than the tangential, sometimes as much as a factor of 3x, it makes sense to utilize a radially cut surface (i.e., quarter-sawn) as the surface to adhere to the soundboard. This convention ensures the least amount of grain movement between the two surfaces reducing stress to the glue joint. In addition, a quarter-sawn bridge will have a lower tendency to exhibit surface distortions over time with changes to ambient humidity levels [Somogyi 2009a].

A less obvious consequence of dimensional stability due to ambient humidity is the effect it has on the dimensions of the slot that hold the saddle. Luthiers take great care to properly fit saddles snugly in the routed slot to ensure string vibrations are not damped by a loose saddle. Low humidity, exacerbated by a wood species with low moisture stability, would cause grain shrinkage that would enlarge the width of the saddle slot resulting in a loosely fitted saddle. Somogyi [2009a] asserts, "Significant energy can be lost at this coupling point…I guarantee you can hear a difference; it may be slight on the average guitar, but it'll be dramatic on responsive, sensitive ones." Because quarter-sawn wood is preferred for the application as a bridge, moisture stability only in the radial direction was examined [Haines 1979].

9.3 Candidates and Results

Published material properties data from *Wood: Identifying and Using Hundreds of Woods Worldwide* [Meier 2016] was utilized to select alternative species to compare with the traditional wood species used for guitar bridges. Specific alternative species selections were made based on achieving a benchmark in terms of mechanical properties, subjectively assessing commercial availability, and the rejection of any species currently listed in a CITES Appendix or on the *IUCN Red List of Threatened Species*. Due to the acoustical ramifications of mass, individual strength-to-weight ratios, or specific modulus (E/ρ), was used as a litmus test to qualify a specific species for further investigation. Alternative species were required to at least surpass East Indian rosewood in terms of E/ρ in order to be considered. Candidates were further eliminated if moisture stability was greater than 4%, Janka score was below 8,000 N, and *MOR* was less than 100 MPa. Table 9.1 compiles the mechanical properties of traditional bridge woods and alternative species that met the established benchmarks. Wood species traditionally used for guitar bridges are in bold.

Species	**Density (ρ) (kg/m^3)**	**Janka (N)**	**Modulus of Rupture (MPa)**	**Modulus of Elasticity (E) (GPa)**	**Specific Modulus (E/ρ)10^3 (GPa)**	**Moisture Stability (%)**
Katalox (*Swartzia cubensis*)	1,150	16,260	193.2	25.62	22.28	3.9
Machiche (*Lonchocarpus spp.*)	890	12,010	173.8	18.93	21.27	3.9
Granadillo (*Platymiscium spp.*)	950	12,030	148.6	19.56	20.59	2.8
W. African Ebony (*Diospyros crassiflora*)	**960**	**13,700**	**158.1**	**16.89**	**17.59**	**8.3**
Brazilian Rosewood (*Dalbergia nigra*)	**840**	**12,410**	**135.0**	**13.93**	**16.58**	**2.9**
African Padauk (*Pterocarpus soyauxii*)	750	8,760	116.0	11.72	15.62	3.3
Bocote (*Cordia spp.*)	850	8,950	114.4	12.19	14.34	4.0
E. Indian Rosewood (*Dalbergia latifolia*)	**830**	**10,870**	**114.4**	**11.5**	**13.86**	**2.7**

*Estimate based on related species.

Table 9.1: Mechanical properties of traditional and alternative woods for bridge use consideration.

9.4 Discussion

One of the more significant revelations of this analysis was the number of sustainable species that outperform on nearly every metric than the most commonly used species for guitar bridges, East Indian rosewood. Nevertheless, *D. latifolia* became the primary substitute for the superior *D. nigra* after its CITES Appendix I prohibition. Likely, utilizing a true rosewood substitute for Brazilian rosewood satisfied those with a traditional view that guitar bridges should be made of ebony or rosewood. In addition, when Brazilian rosewood became expensive and difficult to acquire in the early 1960s, East Indian rosewood was relatively cheap and supply abundant [Johnston, Boak, and Longwirth 1988]. However, in light of the long-term sustainability issues facing *D. latifolia*, the luthier community can be assured that there are many currently sustainable species that would be superior alternatives.

Another conspicuous observation in Table 9.1 is the deficiency of West African ebony in terms of moisture stability. In addition, *D. crassiflora* is characterized by very high density, second only to Katalox. Despite its susceptibility to dimensional changes and high density, guitar manufacturers, steel-string in particular, customarily utilize ebony on their high-end models [Gerken et al. 2003]. And much like East Indian rosewood, in terms of mechanical properties, there are a number of species in Table 9.1 that would outperform West African ebony as a bridge wood. Specific observations of the woods included in Table 9.1 are as follows:

East Indian Rosewood (EIR) became the standard rosewood used in guitars after Brazilian rosewood become effectively unavailable in the early 1960s [Gerken et al. 2003]. The acceptance of EIR was likely based on the similar genus, color, and density of the iconic Brazilian. While EIR succeeds as a bridge wood in terms of density and stability, its scores for modulus of rupture and modulus of elasticity are at the bottom for all the species listed in Table 9.1. Furthermore, its bottom-listed specific modulus indicates EIR would not benefit from bridge design alterations relative to the other listed species.

Bocote is a timber indigenous to Central and South America. Due to the relatively small trunk diameter of the *Cordia spp*., available boards are more conducive for use on smaller items, such as guitar bridges. While the listed mechanical properties indicate Bocote to be a reasonable alternative for EIR, its selection would most likely be for aesthetic reasons; Bocote often demonstrates a striking visual wood grain contrast of brown and black.

African padauk is widely available at a relatively low cost. With the lowest density of all the woods listed in Table 9.1, African padauk would be the leading choice when low-mass is a primary consideration. The bright orange coloration of fresh-cut wood eventually oxidizes towards a dark brown. However, its coloration in both fresh-cut and oxidized embodiments may deter consumers who are only comfortable with the brown and black wood hues with which they are accustomed.

Brazilian Rosewood was included in Table 9.1 as a reference due to its prevalent historical use. Once the leading choice for guitar back and sides, Brazilian was also commonly used for guitar fretboards and bridges. *D. nigra* supply became increasingly scarce starting in the 1960s when Brazil heavily restricted its export [Gerken et al. 2003]. A complete ban on harvest and trade was enacted in 1992 with *Dalbergia nigra's* listing in CITES Appendix I. Its characteristic density, surface hardness, strength, and stability once made Brazilian rosewood an ideal candidate for use as a guitar bridge. In particular, classical guitar makers preferred Brazilian rosewood over ebony due to its low density and resulting mass [Gerken et al. 2003].

West African ebony is typically the bridge wood of choice for high-end instruments. According to Gerken et al. [2003], "On early instruments, the material used was directly related to the price: cheap guitars had birch or maple bridges stained to look like ebony, while higher quality guitars used rosewood, with ebony reserved for the finer examples." In essence, guitar makers sought to elevate their instruments' perceived quality by the use of expensive woods. Ironically, the use of an ebony bridge may increase perceived quality while, in fact, hindering potential performance in use due to its relatively high density and low moisture stability.

Granadillo is the ambiguous name often applied to the various *Platymiscium spp.*, in addition to many other similar hardwoods indigenous to the tropical regions of Central and South America. To increase confusion, the *Platymiscium spp.* are also often referred to as Macacauba, Macawood, Orange Agate, and Hormigo [Meier 2016]. A relative newcomer to the art of luthiery, *Platymiscium spp.* have traditionally been widely used in South America for marimba bars [Savage Woods 2020]. Granadillo's mechanical properties compare very favorably to West African ebony with the added benefit of exceptional moisture stability, nearly matching the scores of the *Dalbergia spp.* The calculated E/ρ also indicates that mass could be reduced through bridge design modifications to enhance the aforementioned acoustical properties. The dark brown coloration of Granadillo also coincides within the paradigm established by the *Dalbergia spp*.

Machiche is a tropical New World timber often associated with the ignoble purpose of flooring planks [Meier 2016]. However, the superior mechanical properties of the *Lonchocarpus spp.* demonstrate a high suitability to purpose as a guitar bridge. Its penultimate *MOR* makes Machiche particularly well suited for applications under high stress, such as twelve-string guitars. In addition, its characteristic high E/ρ suggests the potential for bridge design mass reduction. Machiche also demonstrates a coloration within the rosewood paradigm.

Katalox is another relative newcomer to luthiery. With heartwood often approaching a near-black color, *S. cubensis* is often used as a substitute for the ebonies. Katalox is becoming more widely available as ebony prices and availability increasingly deter commercial consumption. Its class-leading surface hardness, *MOR*, E, and E/ρ make *S. cubensis* the optimal candidate for use as a bridge when design considerations can be employed to reduce overall mass. Within traditional bridge designs, however, this high-density species would have negative implications on acoustical properties.

9.5 Conclusions

For centuries luthiers have adhered to a limited scope of woods from which to select for guitar bridges. Originally, species selection was based on a limited number of material properties and an attempt to elevate quality perceptions through the use of species held in high cultural esteem. Five mechanical properties were used to compare potential alternative wood species to those used in accordance with tradition. Only species without an IUCN Red List designation or CITES Appendix listing were considered. Through this more comprehensive analysis of material properties, many currently sustainable alternative species were found to be superior to the traditional woods presently threatened with overexploitation. Furthermore, with many of the species demonstrating superior strength-to-weight properties, it was proposed that acoustic properties could be further enhanced through the re-design of traditionally shaped bridges to effectively reduce overall mass. Additionally, the wood coloration of the alternative species was evaluated in order to reconcile consumer prejudice in terms of visual aesthetics. Finally, a word on sustainability: the alternative species offered in this examination were subjectively deemed "sustainable" only by the fact that they are not currently threatened by overexploitation. The employment of alternative species should advance with caution; East Indian rosewood was once considered a sustainable replacement for Brazilian.

Chapter 10

Utilization of Static Modulus of Elasticity Testing to Estimate Final Soundboard Thickness

10.1 Background

There is a general consensus that the single most important component in terms of sound production for a chordophone is the instrument's soundboard [Campbell and Greated 1987; Haines 1979; Gore 2011; Sloane 1966; Sturgill 1974; Somogyi 2009a; Bennet 2016]. Because within species physical properties of wood can vary by as much as a factor of 2x or more, it becomes imperative to utilize a means to determine these physical properties in specific samples [Gore and Gilet 2011; Haines 1979]. Treatises on guitar building often refer to the necessity of having a "low mass" soundboard that is neither "too stiff nor too flexible" [Somogyi 2009a; Gore and Gilet 2011; Cumpiano and Natelson 1987]. However, many of these same treatises merely offer a singular suggested plate thickness when dealing with soundboard dimensioning [Siminoff 2006; Overholtzer 1974; Sloane 1966]. While this simple method is widely adhered to from hobby builders to large-scale manufacturers, it does not take into consideration the idiosyncrasies of specific wood samples. A more advanced method often used by some practicing luthiers involves judging plate stiffness using a hand-flexing technique during the dimensioning process to get a feel for when the wood seems "just right" [Young 1975; Somogyi 2009a]. Unfortunately, the hand-flexing method takes years of experience to develop a sense of stiffness and would be of little help to a new builder or a line-worker at a factory [Benedetto 1994].

According to Haines [1980], "ordinarily, nine stiffness moduli are required" to fully describe the physical characteristics of a wood plate. However, for the purposes needed for the specific application of a soundboard, the scope will be limited to the modulus of elasticity in the longitudinal (E_L) and radial (E_R) directions. This convention is based on the guidance of Dumond and Baddour [2015]. Additionally, these two grain stiffness directions are traditionally of greatest interest to luthiers in both material selection and dimensioning. To demonstrate both the anisotropy and within species disparity of stiffness characteristics of European Spruce (*Picea abies*), Figure 10.1 plots the modulus of elasticity in the longitudinal and radial directions of twenty samples that were acquired for use as soundboards.

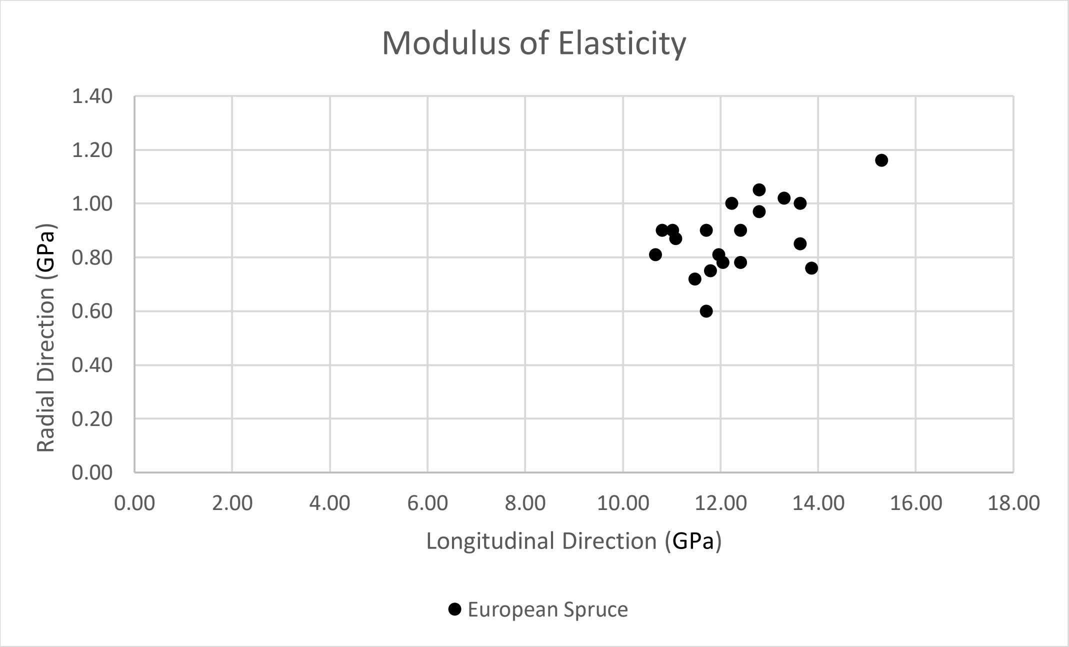


Figure 10.1: A plot of the measured modulus of elasticity for twenty European spruce samples in the longitudinal and radial directions.

The scatter plot of the modulus of elasticity calculations in Figure 10.1 demonstrates the disparity of stiffness properties. What is more, the European spruce samples depicted in Figure 10.1 were sourced from a relatively small region in Eastern Switzerland, possibly from a singular stand of trees. Also, the samples were processed in an identical manner specific for the end-use as instrument soundboards.

In addition to knowing how much to thin a particular soundboard plate to achieve optimal flexibility, the luthier's other objective is to produce a soundboard with the lowest mass possible. Gore and Gilet [2011a] maintain, “The lower the overall mass of the finished soundboard, the greater its potential acceleration from the vibratory energy transfer of the strings, therefore once the static criteria are satisfied, the most significant measure of a soundboard’s quality is its overall mass.” In terms of stiffness, the higher the relative initial stiffness of a prospective soundboard sample, the more mass may be eliminated through the thinning process. All other things being equal, a stiff wood sample will produce a lower mass soundboard. Very often, though, higher stiffness comes at the cost of additional mass. The consequence of including mass with stiffness is calculated by the relationship of modulus of elasticity to the specific gravity of a specific sample. Figure 10.2 adds the density variable into the modulus of elasticity calculation to illustrate this concept.

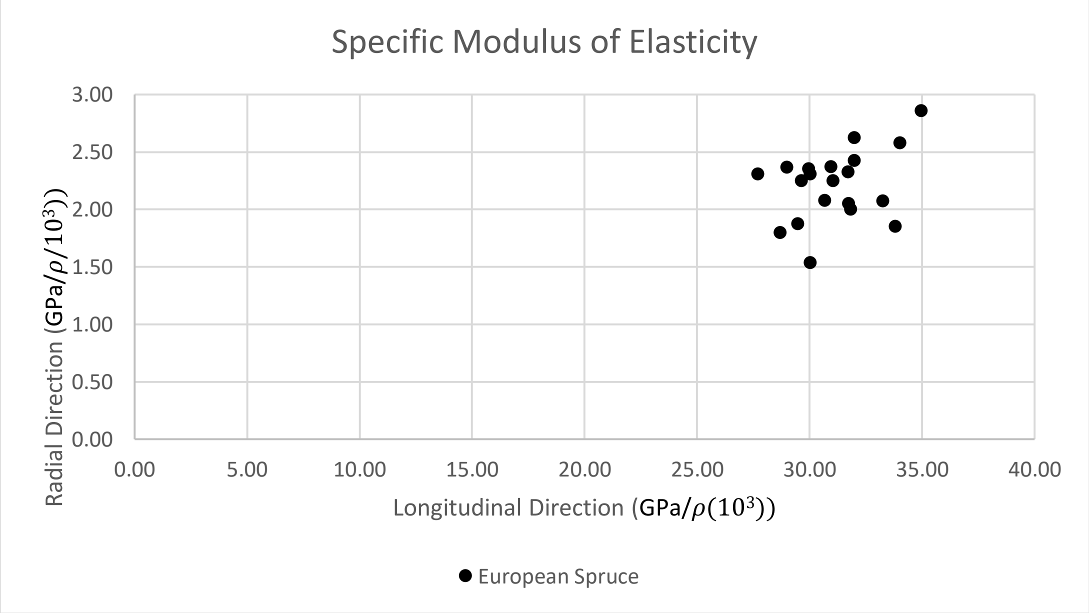


Figure 10.2: A plot of the measured specific modulus of elasticity for twenty European spruce samples.

Figure 10.2 shows that even within the consequence of admitting density into the stiffness calculation, there remains a significant disparity regarding the modulus of elasticity in both the longitudinal and radial directions. While the sample represented by the upper right corner point would be considered the most optimal wood sample based on the highest strength-to-weight ratio, it would likely not perform to its potential if thinned to a standardized average dimensional thickness; the soundboard would be too stiff in service. In order to maximize the performance in service of each of these samples, it would require a manufacturing process that responds to their individual inherent characteristics. Gore and Gilet [2011] offer a method to estimate plate thickness based on the dynamic testing for modulus of elasticity mentioned in Chapter 2 and illustrated by equations 2.4 and 2.5. This research utilizes the static method to determine modulus of elasticity and predict finished soundboard (or backplate) thickness and mass.

10.2 Assumptions

The methods offered below rely on assumptions to provide an example and are listed as follows:

- Steel-string guitar based on the common Dreadnaught shape
- Typical X -style bracing pattern of moderate stiffness
- European spruce soundboard
- 2.8 mm soundboard thickness for the “average” soundboard.
- Intended instrument longevity of 30+ years

Modifications to the previous assumptions would likely be due to the following:

- Guitar size and type different from the steel-string Dreadnaught
- Different bracing pattern
- Specific goals of the luthier that would require a heavier or lighter build (i.e., longevity, playing style, assumption of abuse, or other).

As guitar shape and bracing designs can differ dramatically between manufacturers, the assumption of a 2.8 mm soundboard thickness is drawn from convention but could be modified by the individual luthier based on their own experience as to an ideal average for their own design.

10.3 Data Acquisition

The modulus of elasticity data was calculated using a rig that measured the deflection of the wood sample under a static load, as shown previously in Figure 2.9.

Wood plates were dimensioned to 3.8 mm x 200 mm x 546 mm. The end supports were spaced at 457 mm for the longitudinal direction and 178 mm for the radial direction. The plates were biased against the end supports with a 1 kg beam. A 1 kg weight was used as the static load to initiate deflection. A digital micrometer was used to measure deflection after being zeroed-out after biasing. The measured deflection data was then used to determine the modulus of elasticity using equations 2.2 and 2.3. Table 10.1 displays the data collected for the twenty samples.

Sample	Mass (grams)	Density (kg/m^3) (ρ)	E_L (GPa)	$E_L/\rho(10^3)$	E_R (GPa)	$E_R/\rho(10^3)$
1	157	380	12.06	31.74	0.78	2.05
2	169	410	13.87	33.83	0.76	1.85
3	165	400	12.80	32.00	0.97	2.43
4	164	390	11.72	30.05	0.60	1.54
5	168	400	12.80	32.00	1.05	2.63
6	155	370	11.09	29.97	0.87	2.35
7	162	390	11.72	30.05	0.90	2.31
8	180	430	13.64	31.72	1.00	2.33
9	147	350	12.24	34.97	1.00	2.86
10	148	360	10.67	29.64	0.81	2.25
11	157	380	11.02	29.00	0.90	2.37
12	188	450	15.31	34.02	1.16	2.58
13	162	390	12.42	31.85	0.78	2.00
14	166	400	11.48	28.70	0.72	1.80
15	165	400	11.80	29.50	0.75	1.88
16	171	410	13.64	33.27	0.85	2.07
17	166	400	12.42	31.05	0.90	2.25
18	177	430	13.31	30.95	1.02	2.37
19	163	390	10.81	27.72	0.90	2.31
20	164	390	11.97	30.69	0.81	2.08
Mean (M)	164	400	12.34	31.14	0.88	2.21
Standard Deviation (SD)	9.80	20	1.18	1.90	0.13	0.31
Coefficient of Variation (CV=SD/M)	5.9%	5.9%	9.5%	6.1%	15.1%	14.1%

Table 10.1: Mass and stiffness data for twenty European spruce samples.

In terms of material selection, sample 12 appears to be superior based on modulus of elasticity in both the E_R and E_L directions. However, when mass is also considered, the relatively average sample 9 becomes the highest-scoring sample of the group. To simplify, if sample 12 and 9 were to be dimensioned so that they demonstrated similar deflection under a static load, sample 9 would end up being the lower mass specimen. Going forward, the modulus of elasticity (E) will enable the determination of final thickness dimensions while the specific modulus (E/ρ) will determine material superiority should all samples be reduced to a standard deflection. Also, because the coefficient of variation is greater in the E_R (15.1%) direction versus the E_L direction (9.5%), E_R will be used for this illustration. Using the mean E_R value of .88 mm and the assumption of average finished plate thickness of 2.8 mm, equation (2.3) was modified to solve for target deflection ($\boldsymbol{\Delta}$):

$$\Delta = \frac{PL^3}{48(E_R)(I)} \tag{10.1}$$

where P is 1 kg, L is the span of the supports (177.8 mm). Solving for target deflection results in:

$$\Delta = 1.31\ mm \tag{10.2}$$

Using $\boldsymbol{\Delta}$=1.31 mm and the specific E_R of each sample allows for the determination of the Second Moment of Area for each sample by modifying equation (10.1) as follows:

$$I = \frac{PL^3}{48(\Delta)(E_R)} \tag{10.3}$$

Finally, modifying equation (2.2) to solve for h calculates the final thickness for each individual wood plate:

$$h = \sqrt[3]{\frac{12(I)}{b}} \tag{10.4}$$

Table 10.2 displays the calculated final plate thicknesses and resulting mass for the twenty spruce samples dimensioned so that they each would demonstrate 1.31 mm deflection in the radial direction under a 1 kg load. The calculated mass considers the final dimensions of the plate based on the calculated thickness. The rank column assigns a score based on the resulting mass.

Sample	Original Mass	Rank	E_R (GPa)	Calculated Thickness	Calculated Mass	Rank
1	157	4	0.78	2.91	120	9
2	169	16	0.76	2.93	130	18t
3	165	11t	0.97	2.71	117	6
4	164	9t	0.60	3.18	137	20
5	168	15	1.05	2.64	116	5
6	155	3	0.87	2.81	114	3t
7	162	6t	0.90	2.77	118	7
8	180	19	1.00	2.68	127	15t
9	147	1	1.00	2.68	103	1
10	148	2	0.81	2.87	112	2
11	157	4t	0.90	2.77	114	3t
12	188	20	1.16	2.55	126	14
13	162	6t	0.78	2.91	124	11t
14	166	13t	0.72	2.99	130	18t
15	165	11t	0.75	2.95	128	17
16	171	17	0.85	2.83	127	15t
17	166	13t	0.90	2.77	121	9
18	177	18	1.02	2.66	124	11t
19	163	8	0.90	2.77	119	10
20	164	9t	0.81	2.87	124	11t
Mean (M)	164		0.88	2.81	121	
Standard Deviation (SD)	9.80		0.13	0.15	7.65	
Coefficient of Variation (CV=SD/M)	5.9%		15.1%	5.2%	6.3%	

Table 10.2: Calculated thickness and mass after thinning plates to a standard deflection.

10.4 Discussion

Table 10.2 illustrates the argument that initial density or initial stiffness in and of themselves do not give a complete indication of sample superiority. Only after the sample is considered at its final thickness can mass be accurately compared to offer the most conclusive insight into soundboard inertia as a function of mass. This concept is evidenced by the change in mass rankings from the wood plates dimensioned at a standard thickness of 3.8 mm to a finished thickness based on the calculated modulus of elasticity for each individual sample. Because the soundboard requires a level of structural integrity to withstand the constant stress of tensioned strings, there is a lower limit of strength required to ensure the longevity of the instrument [Gore 2011]. However, since the physical properties of wood demonstrate disparity, there can be no single thickness that balances strength with optimal performance as a vibrating plate [Buksnowitz et al. 2007; Siminoff 2006]. To further illustrate, Master luthier Ervin Somogyi [2009b] contends:

> While there is a logic to giving firm numbers for thickness measurements in a method book such as this, it needs to be recognized that this represents an essentially mechanical approach to guitar building. Once one has made two or three guitars, such a mechanical/recipe method begins to show its limitations: it leads to guitars that sound different in spite of the fact measurements are identical. It begins to make more sense to think in terms of stiffness…One eventually begins to appreciate that thickness measurements might not be all that meaningful by themselves.

The axiom that the lowest mass soundboard will be the most responsive to string vibration confirms the importance of thinning a soundboard to its lowest limit of structural integrity to minimize inertia [Gore and Gilet 2011]. Calculating final soundboard thickness based on modulus of elasticity allows the soundboard to be taken down its lowest workable mass based on the luthier's stiffness standards. The prediction of final mass based on the modulus of elasticity is also a means by which luthiers can grade prospective wood sets during the selection process.

10.5 Conclusion

This chapter's goal was to provide a method by which luthiers could calculate final soundboard thickness based on the inherent properties of a specific wood sample. A process to determine the modulus of elasticity was illustrated using a static testing rig and mathematical equations founded in elementary beam theory. Using a material deflection standard based on typical soundboards, final plate thickness was calculated for twenty European spruce samples based on their individual modulus of elasticity metric in the radial direction. Plate mass was subsequently calculated based on final plate dimensions. Samples were then scored in terms of their predicted final mass.

The test results demonstrated the disparity of physical properties within the sample set despite being the same species and processed to optimize stiffness characteristics. The test indicated a range of plate thickness from 2.55 mm to 3.18 mm – a thickness difference of 24.7%. What makes this difference more remarkable is the homogeneity of the samples sourced from a single geographic location and processed specifically for instrument soundboards. This disparity enforced the importance of treating each sample on an individual basis rather than a strict specification. It is imperative to recognize the inherent physical properties of a wood specimen so that it can be dimensioned in a way to maximize its performance in service. The methods described herein provide a means to determine tonewood's stiffness properties and calculate final thickness dimensions based on their individual characteristics. Additionally, final mass could be predicted based on calculated thickness to score the samples in terms of inertia. While the soundboard is the primary sound producer of a chordophone and the focus of this chapter, the methods devised here could also be used for analyzing and predicting the quality of guitar backs and braces as well.

Chapter 10 - Utilization of Static Modulus of Elasticity Testing to Estimate Final Soundboard Thickness

Chapter 11

Vibration and Elastic Characterization of Traditional and Alternative Tonewoods

11.1 Background

Brazilian rosewood became the premier de facto guitar-body tonewood concurrent with the inception of the modern classical guitar by Antonio de Torres in the late nineteenth century [Romanillos 1987]. Brazilian rosewood (*Dalbergia nigra*) has since attained legendary status for its use as a tonewood in guitar luthiery. Often referred to as the “Holy Grail” of woods used for guitar backs and sides, available Brazilian rosewood guitar sets command premium prices due to the woods protected status under international treaty [Bennett 2016; Carcagno et al. 2018]. Subsequently, Brazilian rosewood has been the most regarded tonewood throughout the twentieth century with both classical and steel-string builders [Pedgley and Norman 2012].

While Brazilian was often reserved for luthiers’ top-of-the-line models, Honduran mahogany was often featured for more moderately priced product lines [Gruhn and Carter 1993]. Even so, there were some advocates, such as the famed Doc Watson (1923-2012), that preferred the “mahogany” sound and employed such an instrument in his professional recording and touring career [Miller 1998]. Even before Brazilian rosewood’s eventual harvest ban in 1992, larger guitar manufacturing companies began substituting East Indian rosewood due to supply and quality issues resulting from the lack of timber available for harvest [Whitford, Vinopal, and Erlewine 1994]. By the mid-1960s, the heir apparent East Indian rosewood became the new standard for high-end factory guitars [Johnston, Boak, and Longworth 2009]. And just as Brazilian rosewood attained a “Holy Grail” status concurrent with its loss of availability, East Indian rosewood and Honduran mahogany are trending towards similar prestige as their future becomes less certain.

Brazilian rosewood found its way to Europe's lumber markets soon after the first exploitation of forest resources began at the outset of the sixteenth century. While the woods used for making textile dyes were of primary commercial importance to trans-Atlantic traders, other hardwoods such as mahogany (*Swietenia spp*.), Snakewood (*Brosimum guianense*), and various rosewoods (*Dalbergia spp*.) filled out vessels bound from the New World to Europe [Dean 1995]. Initially, these exotic tropical hardwoods were primarily destined for the larger manufacturing enterprises of shipyards, high-end furniture, and cabinetry [Cross 1994; Romanillos 1987]. Only gradually over the next 350 years did New World tropical hardwoods enter the luthier trades as guitar components. As previously theorized herein, Brazilian rosewood’s initial inclusion in guitar manufacturing was due more to its visual aesthetic than in any consideration for its contribution as a tonewood. In fact, its early use as a wood species for backs and sides was often as a veneer applied over a less expensive base wood [Usher 1956]. Master luthier and historian José Romanillos [1987] explains:

> The veneering of rosewood onto other woods was common practice in the seventeenth century and continued well into the nineteenth century. Pagés in Spain, Lacóte in France, and Panormo in England all made guitars with veneered backs, a technique that indicates rosewood was used not so much for its acoustic properties as for the attractiveness of its figuration and color. By the mid-nineteenth century, when the supply of rosewood became much improved, (at least in England, as the import tax was removed on rosewood in 1845), the best guitars had both back and ribs made out of solid rosewood.

The sentiment that the “best” guitars are made with Brazilian rosewood has been further echoed through the years by other authors reinforcing its predilection over other tonewoods [Johnston, Boak, and Longwirth 2009; Huber

1994; Whitford, Vinopal, and Erlewine 1994; Somogyi 2009a; Gerken et al. 2003]. The penchant for Brazilian rosewood might be best summed up by master luthier Manuel Rodriguez [2003] in his treatise *The Art and Craft of Making Classical Guitars*:

> Without any doubt at all, this is the most beautiful wood ever created by Nature. And our guitar-making industry, with the artistic spirit that this wood can evoke in us, is obliged to create a musical instrument into which we pour all our stylistic veins. With this wood, plus our taste in decorative craftsmanship, producing a work that gives satisfaction to the senses of hearing and sight is not such a difficult task. Thanks to its affable and steady sounds and very distinct intonation, the ear delights; and the combination of the wood's beauty and our taste in decoration let the eyes feast on its exquisiteness.

However, the easy access to Brazilian rosewood lasted only into the mid-twentieth century before overutilization created supply disruptions causing larger manufacturers to look to alternative rosewood and non-rosewood substitutes. By the late 1930s, the Gibson Guitar Co. phased out most of its Brazilian rosewood models due to the difficulty obtaining a consistent supply of rosewood logs [Whitford, Vinopal, and Erlewine 1994]. Similarly, C.F. Martin & Co. began switching from their exclusive use of *Dalbergia nigra* on rosewood models to primarily Indian rosewood (*Dalbergia latifolia*) beginning in the early 1960s [Johnston, Boak, and Longwirth 2009]. Finally, the Convention on International Trade of Endangered Species (CITES) effectively eliminated Brazilian rosewood harvest and trade with its inclusion in Appendix I on June 11, 1992. According to CITES, "Appendix I includes species threatened with extinction. Commercial trade in specimens of these species is permitted only in exceptional circumstances (CITES 2020)." Except for the fortunate few who had Brazilian rosewood inventories sourced prior to the CITES Appendix I listing, guitar makers could no longer procure this quintessential species.

While recent research by Carcagno et al. [2018] and Yano, Furuta, and Nakagawa [1997] contend the guitar's backplate has a limited effect on sound, subjective testimony by Gore [2011a] and Somogyi [2009a] argues for the importance of backplate tonal contribution, particularly when the instrument is constructed with a back intended to function as a coupled “harmonic oscillator” rather than a high-mass “sound reflector”. While there is a relatively large body of research concerning the musical instrument soundboards, very little attention has been paid to the other tonewoods used in lutherie. And yet, conventional wisdom maintains that a superior instrument is defined by the sum of its parts, the guitar backplate being secondary only to the soundboard [Somogyi 2009; Gore and Gilet 2011].

This chapter aims to quantify the physical and vibrational properties of the iconic Brazilian rosewood to provide a benchmark by which alternative tonewoods can be objectively compared. As established in Chapter 2, the metrics of particular interest are density (ρ), modulus of elasticity (*MOE*), and damping (Q). Using these metrics, the current popular tonewoods of Hard maple, Honduran mahogany, and Indian Rosewood were similarly characterized and compared against the Brazilian rosewood samples. Finally, lesser known alternative species were measured against the two rosewood species. Their potential performance in service was evaluated by objectively measuring these metrics for traditional tonewoods and potential substitutions. The alternative tonewoods for the test were selected from a list of woods commonly offered by commercial luthier suppliers [LMII 2020]. The list was reduced to Chakte Viga (*Cæsalpinia platyloba*), Ziricote (*Cordia dodecandra*), Granadillo (*Platymiscium spp*.), and African padauk (*Pterocarpus soyauxii*) based on favorable testimony within the luthier industry. In addition, the alternative tonewood species are not listed by CITES in any of their Appendixes. As a final note, since visual aesthetic is not easily objectified, it will be left out of the scope of this analysis other than to concede that all other characteristics being equal, the beauty of the wood matters.

11.2 Testing Protocol

The woods used for testing was acquired as typical luthier-grade stock. The materials had been seasoned for at least five years and were kept in a controlled humidity environment between 40%-50%. Actual testing took place at a relative humidity of 45%. Wood samples were precisely dimensioned to 483mm X 63.5mm X 6.35mm. The modulus of elasticity calculation was conducted using the static testing rig shown previously in Figure 2.9. End supports were spaced at 460mm. A 2 kg weight was used to bias the wood samples against the end supports to account for any twist or bow in the tested sample. A 1 kg weight was used to create the deflection, which was, in turn, measured by a digital indicator with a tolerance of .001mm. Recorded data was the average of measurements from each side. Damping data was acquired using the rig shown in Figure 2.11. Wood samples were hung from the rig by a nylon filament via alligator clips. The location of the attachment was at the nodal points of the first longitudinal mode. This location was established at 22.4% of the total length from each end. A PCB model 352C22 miniature accelerometer was used to measure the vibration signal generated by a miniature impulse hammer [PCB 086C01]. FFT analysis was computed using SpectraPLUS software.

11.3 Results and Analysis

Figure 11.1 shows the relationship of specific modulus to the Q factor for twenty samples of Brazilian rosewood. Note, a high Q represents low damping.

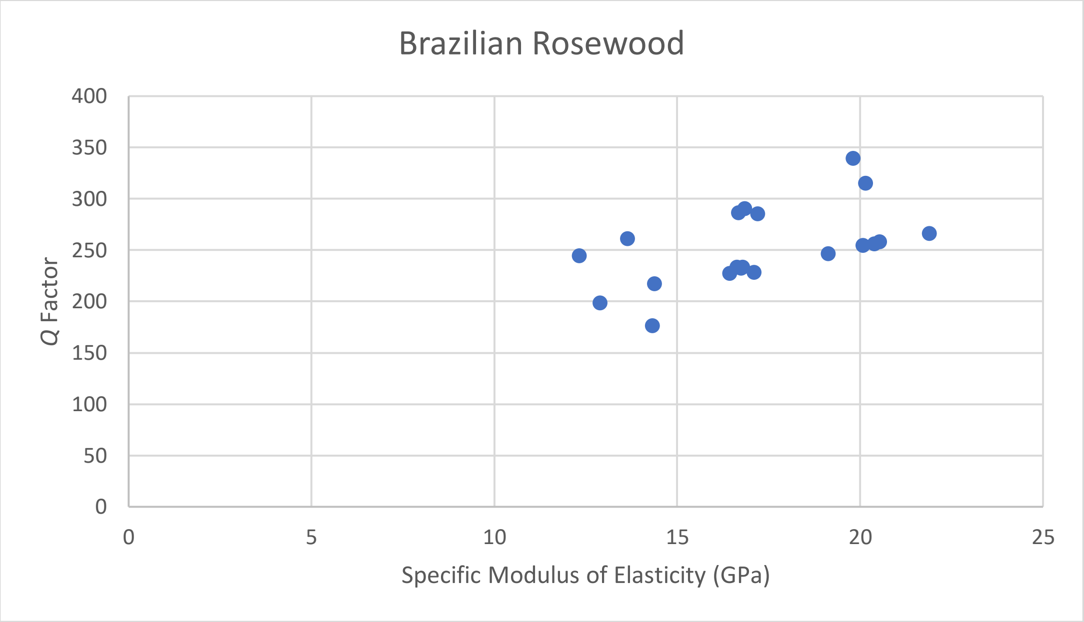


Figure 11.1: A plot of the specific modulus of elasticity and damping test results for Brazilian rosewood.

Immediately evident in Figure 11.4 is the disparity between samples relative to specific modulus and damping. This disparity concurs with the findings of Brémaud, Minato, and Thibaut [2009], Fouilhe, Houssay, and Brémaud [2012], and Wegst [2006]. The variation of these results demonstrates the importance of material testing illustrated by the 2x difference in both damping and specific modulus. The other characteristic worth noting in Figure 11.4 is the general trend of increasing Q with increasing material stiffness. This relationship also concurs with the findings of Brémaud, Minato, and Thibaut [2009]. Without access to damping data, one can at least infer that vibration damping tends to decrease as specific modulus increases. However, of more central importance to this analysis is how Brazilian rosewood compares to other tonewoods regarding stiffness and damping. Figure 11.2 shows Brazilian rosewood compared to the other most popular traditional tonewoods used for back and sides – Hard maple and Honduran mahogany.

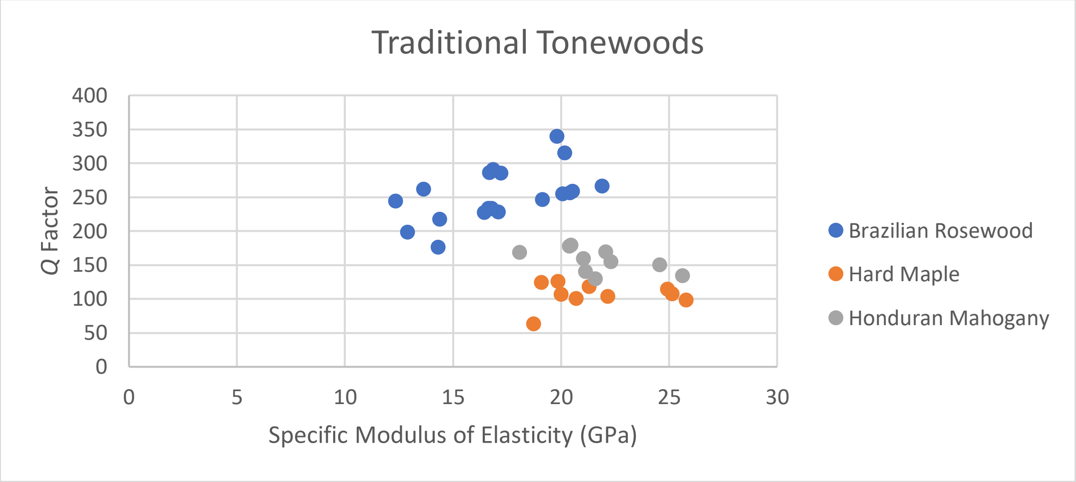


Figure 11.2: A plot of the specific modulus of elasticity and damping comparison of popular tonewoods.

Interestingly, even though Brazilian rosewood scores higher in modulus of elasticity (13.93 GPa) according to published data versus Hard maple (12.62) and Honduran mahogany (10.06 GPA), it does so at the expense of much higher mass. On a specific modulus basis, maple and mahogany are often superior to Brazilian rosewood, as shown in Figure 11.5. However, neither maple nor mahogany score as well as Brazilian rosewood in terms of damping. In fact, this characteristic is what gives Brazilian rosewood its reputation as having a superior “tap tone”. The tap tone exhibited by Brazilian rosewood is often described within luthier circles as “bell-like” due to its clear fundamental frequency and sustain [Somogyi 2009; Blumenou 2004]. The next consideration is the comparison of Brazilian rosewood to Indian rosewood. Indian rosewood became the de facto rosewood species for luthiers once Brazilian became unattainable after its CITES listing in 1992. Figure 11.3 shows the specific modulus to damping comparisons of these two rosewood species.

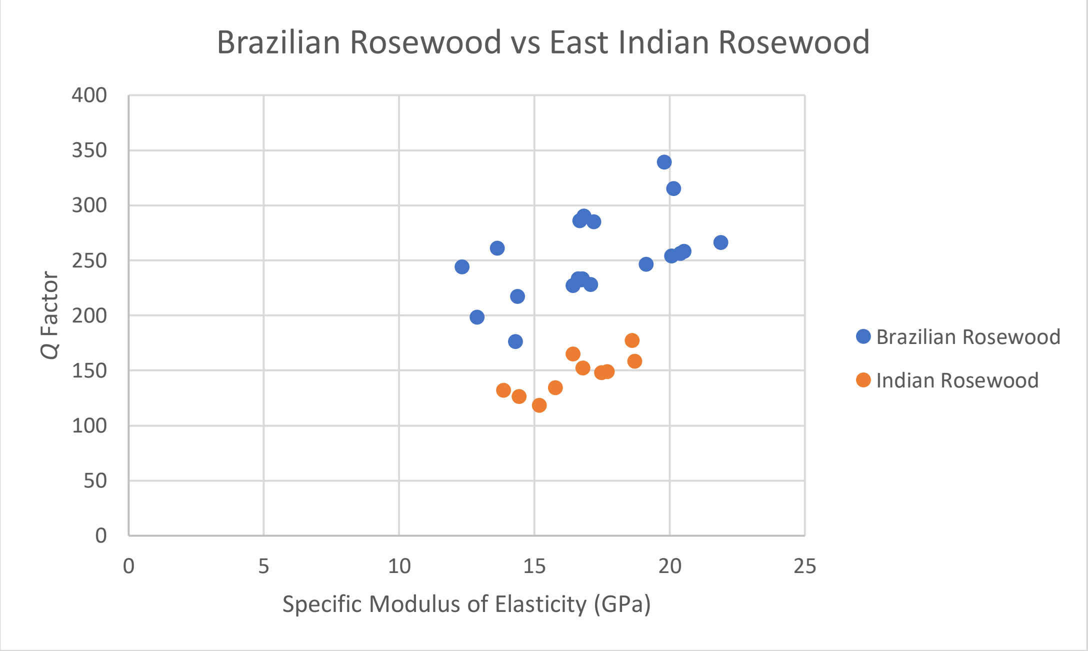


Figure 11.3: Plot of specific modulus of elasticity and damping characteristics of Brazilian rosewood and East Indian rosewood samples.

Once again, while specific modulus characteristics are fairly similar, East Indian rosewood does not match the superior Q factor of Brazilian rosewood. To emphasize the importance of damping consider Daniel Haines [1979] following analysis regarding the importance of low damping woods in guitar construction:

> The “sustain” in guitars is valued highly. Sustain refers to the ability of a guitar to prolong a sounded tone. Low damping certainly contributes to sustain. Also, by its nature as a plucked instrument, the guitar has low volume of sound, a distinct handicap in many contexts. For this reason, a great premium is placed on wood for guitars possessing low damping.

Figure 11.4 shows the comparison of alternative tonewoods to the rosewood benchmarks.

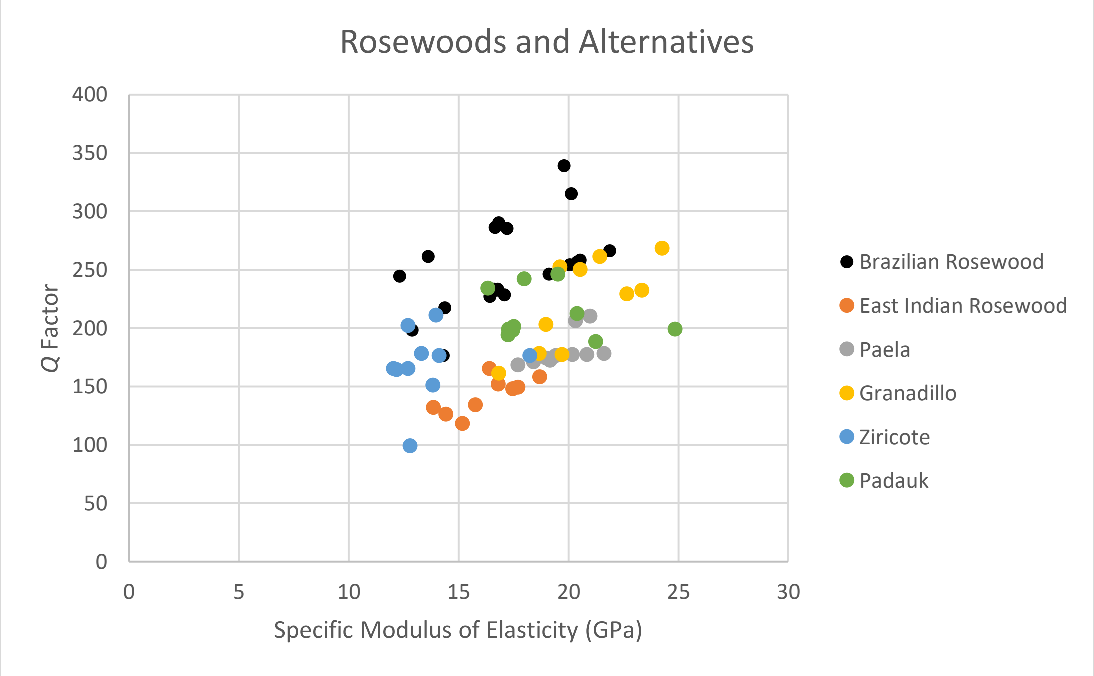


Figure 11.4: Plot showing the comparison of specific modulus of elasticity and *Q* factor for various tonewoods.

The most revealing aspect of Figure 11.4 was that most of the alternative tonewoods score better in *Q* factor than East Indian rosewood and, in some cases, exceed even Brazilian rosewood. Furthermore, except for Ziricote, all of the alternatives scored well in terms of specific modulus, indicating suitable strength to weight ratios. Specific scores for each tested sample can be found in Appendix II. Individual analysis for each species is offered as follows:

Ziricote scored towards the average in terms of *Q* factor. However, except for a single sample, Ziricote tended towards the low end as far as Specific Modulus. The consequence of a lower strength-to-weight ratio indicates the use of Ziricote will generally necessitate higher mass in order to attain equal stiffness relative to the other tonewoods.

Paela scored better than East Indian rosewood in terms of Specific Modulus and *Q* factor. The consistent performance of Paela suggests it would be a very viable tonewood alternative.

African padauk performed superior to East Indian rosewood in both Specific Modulus and *Q* factor. In some cases, African padauk demonstrated a *Q* factor on par with some of the Brazilian samples and produced the highest single score of all the samples for Specific Modulus.

Granadillo showed a wide disparity in both its *Q* factor and Specific Modulus. On each metric, Granadillo demonstrated a range from the high end of East Indian rosewood to the low end of Brazilian rosewood. One sample, in particular, demonstrated the second-highest specific modulus and a *Q* factor well within the range of Brazilian rosewood. It was suspected that this particular sample was of the sub-species *Platymiscium pleiostachyum* based on visual indicators. This particular *Platymiscium spp.* is often referred to in Central America as "La Madera Que Canta", the wood that sings. Unfortunately, *P. pleiostachyum* is the only *Platymiscium* sub-species on the IUCN CRITICALLY ENDANGERED list [Meier 2016; Barstow, Jiménez, and Klitgård 2018].

11.6 Conclusions

By means of its visual appeal, Brazilian rosewood may have found its initial inclusion in luthiery more for its beauty than any consideration for tonal contribution. However, its long-standing dominance as the tonewood of choice for the last 250 years suggests Brazilian rosewood is more than just a pretty face. Subjective testimony has long professed the superiority of Brazilian rosewood, elevating it to an iconic status. Yet, objective quantification of Brazilian rosewood's attributes has not been the focus of much scientific research, especially compared to the attention given to violin and guitar soundboards. Given the premium monetary value of the remaining Brazilian rosewood stock, it is even more critical to understand whether that value should be attributed to its visual appeal or its superiority as a sound-enhancing tonewood. The first conclusion is that there exists within species disparity by a factor of 2x for the properties of specific modulus and damping. The sample to sample variability of Brazilian rosewood properties is a compelling argument for objective testing prior to material selection. Secondly, while common alternative species demonstrate sufficient strength to weight characteristics, none of the tested species included in this research compared well, systematically, to Brazilian rosewood in terms of vibration damping. These findings coincide with the long-held belief by those in the luthier community that Brazilian rosewood possesses a superior "tap tone" in terms of sustain. Concurrent with conventional wisdom, Brazilian rosewood proved to warrant its reputation as a superior tonewood over East Indian rosewood based on these metrics. Surprisingly, though, three of the four tested alternative tonewood species demonstrated scores consistently higher than East Indian rosewood, and, in some specific samples, within the range of metrics established by Brazilian rosewood. Even though East Indian rosewood might have been a logical replacement for Brazilian rosewood, non-rosewood species may, in fact, perform better in the role of a guitar tonewood. While consumer reluctance and prejudice might impede full acceptance of non-rosewood alternatives, this objective testing makes a case for the superior performance metrics of African padauk, Chakte Viga, and Granadillo versus East Indian rosewood. With further testing of more species, it is conceivable that there may one day be a wood proven the equal of Brazilian rosewood.

Chapter 12

Indistinguishability of Tonewood Substitution: A Blind Test of Guitars made from African Padauk and East Indian Rosewood

12.1 Background

The current Golden Age of guitar lutherie's era is threatened by the potential loss of the tonewoods on which guitar making has depended since the time of Torres [Carcagno et al. 2018]. Throughout the last two centuries, wood selections for the guitar back and sides in its idealized form have been fairly fixed as Brazilian rosewood (*Dalbergia nigra*). While other woods can and have been used successfully to produce exceptional instruments, Brazilian rosewood has achieved iconic status within the lore of the guitar community, luthiers and players alike [Haines 1980; Wegst 2006; Usher 1956; Bennet 2016; Pedgley and Norman 2012]. With the prohibition of any future Brazilian rosewood harvest by CITES, Indian rosewood (*Dalbergia latifolia*) became the *de facto* substitute used by large manufacturers and individual luthiers for typical instruments. To a lesser extent, in addition to Indian rosewood, luthiers employed other rare rosewood species to replace the highly coveted Brazilian. In order to add some aesthetic allure, luthiers have utilized Cocobolo (*Dalbergia retusa*), African blackwood (*Dalbergia melanoxylon*), Madagascar rosewood (*Dalbergia baronii*), and Amazon rosewood (*Dalbergia spruceana*). Yet, as the guitar community looked to replace Brazilian rosewood, so did the other industries that once depended on this natural resource. Veneer mills and furniture manufacturers turned to the luthier community's same substitutes, effectively transferring the demand strain from Brazilian to these other rosewoods [Zhu 2020]. This consumption led to the entire genus of rosewood to be listed in CITES Appendix II on January 2, 2017.

CITES defines Appendix II as "…species not necessarily threatened with extinction, but in which trade must be controlled in order to avoid utilization incompatible with their survival [CITES 2020]." While harvest and trade are still allowed under Appendix II, the listing indicates a dim outlook for all the rosewoods without a reduction in consumption and an expansion of tree populations. Yet, even with an effort to plant additional trees, it generally takes upwards of 150 years to produce high-grade timber [PFAF 2020]. In other words, trees lost to harvest cannot be quickly replaced.

The fundamental consequence of tonewood overutilization is the necessity to consider alternative species to replace the iconic wood species that either are or will be unavailable for future use in the construction of concert quality guitars. The single most challenging aspect of gaining the acceptance of potential substitutes will be convincing luthiers and players that instrument quality is based on the physical and vibrational qualities of the wood used, not necessarily by the name of the specific species itself. This task will likely require a number of objective scientific studies to make this case. The guitar community has deep-seeded prejudices regarding tonewoods that have been reinforced by centuries of tradition, lore, and possibly the marketing efforts by guitar companies to generate veneration for their high-end models; mere subjective testimony would likely fail to overcome the predilection for rosewood, or any other threatened tonewood species for that matter [Carcagno et al. 2018].

This chapter endeavors to join a growing body of research aimed at quantifying the impact different wood species have on the perception of guitar sound. The ultimate aim is to maintain luthiery at the quality standards established within the current "Golden Age of Lutherie" while existing within the moral and legal ramifications of flora conservation. This condition will become of even greater importance should the remaining traditional tonewoods go the way of Brazilian rosewood and end up with a CITES Appendix I listing, effectively prohibiting further harvest and trade. If the guitar community can be convinced that alternative wood species are equivalent and possibly superior to traditional tonewoods, it will alleviate some of the demand pressure causing overexploitation. The following experiment concentrates specifically on the woods used for guitar backs and sides. The aim is to discover whether guitars are indistinguishable despite using different woods for the backs and sides. Specifically, this experiment will examine the equivalence of East Indian rosewood and African padauk (*Pterocarpus soyauxii*).

12.2 Materials and Testing Methods

Four guitars were constructed with identical wood components, except two of the instruments had East Indian rosewood back and sides while the other two guitars used African padauk. See Figure 12.1.

Figure 12.1: Photo of the two African padauk (Left) and two East Indian rosewood (Right) guitars to be used in the blind test. Other than the backs and sides, the remaining wood components were matched as closely as possible in all four instruments. Photo by author.

To further ensure the equivalence of the instruments, the four soundboards used on the guitars were cut from a single billet of Sitka spruce (*Picea stichensis*). As the soundboard is the primary vibratory plate of the guitar, it was essential to limit any impact these would have had on differentiating the sound produced by the instruments [Haines 1980; Richardson 1994]. For similar reasons, the ebony (*Diospyros crassiflora*) bridge, ebony fretboard, and Honduran mahogany (*Swietenia macrophylla*) neck woods were all matched as practically as possible in terms of species, density, and modulus of elasticity in the longitudinal direction. The components of specific interest, the backplates, were chosen from the luthier's stock and matched as closely as possible regarding their density, "tap tone", and modulus of elasticity in the longitudinal and radial directions. All wood components were well seasoned and conditioned to a building environment of 45% relative humidity. African padauk was selected as the preferred candidate to match East Indian rosewood due to the seeming similarity of mechanical properties in published resources. In addition, African padauk is not listed as threatened by the IUCN, and quarter-sawn lumber is readily available in sizes appropriate for luthiery. Table 12.1 shows the comparison of mechanical and damping properties of East Indian rosewood and African padauk.

Species	**Density (ρ) (kg/m^3)**	**E_L (GPa)**	**Volumetric Shrinkage %**	**Damping Coefficient (tanδ)**
East Indian Rosewood	830	11.50	8.5	7.3
African Padauk	750	11.72	7.6	5.2

Table 12.1: Mechanical properties of East Indian rosewood and African padauk [Meier 2016; Brémaud et al. 2011].

It should be noted that the density, modulus of elasticity (E_L), volumetric shrinkage and damping coefficients provided by Meier [2016] and Brémaud et al. [2011] are indicative of an average of tested samples. As demonstrated in previous chapters, individual samples can differ significantly from these averages [Dumond and Baddour 2015]. Nonetheless, the published figures provide some indication of similarity between species.

To determine the specific properties of potential samples, testing rigs were utilized to carry out non-destructive testing. The center-point loading test rig shown previously in Figure 2.9 was utilized to determine the modulus of elasticity of the wood plates. Equations 2.2 and 2.3 were used to calculate the modulus of elasticity for the specific samples.

The earlier referred to “tap tone” is a traditional method used by those in the luthier community to estimate the quality of a wood sample based on a judgment of the sound produced by tapping the sample while holding the wood at a specific location. Specifically, the tester holds the wood at a distance of 22.4%, illustrated previously in Figure 2.11, of the sample’s total length from one end and subjectively judges the sound produced by a finger tap. This sound is evaluated for the note produced and the duration of the vibration. The pitch of the sound produced suggests a relationship between mass and stiffness, while the duration of the vibration suggests the internal damping mechanisms of the wood, indicating a quality of sustain [Haines 1979]. Besides being purely subjective, this method does not allow for documentable data to be compiled and referenced after the sample has been put into service. However, the intent of the “tap tone” can, in fact, be verified using the dynamic testing rig, as shown in Figure 2.11.

Rather than using human judgment to analyze the sound produced by a fingertip tap, the sound produced by an impulse hammer strike at the antinode, ½ the sample’s length, is recorded and saved in a computer file to be further analyzed. Figure 12.2 demonstrates a visual representation of the frequencies produced on a rectangular East Indian rosewood plate.

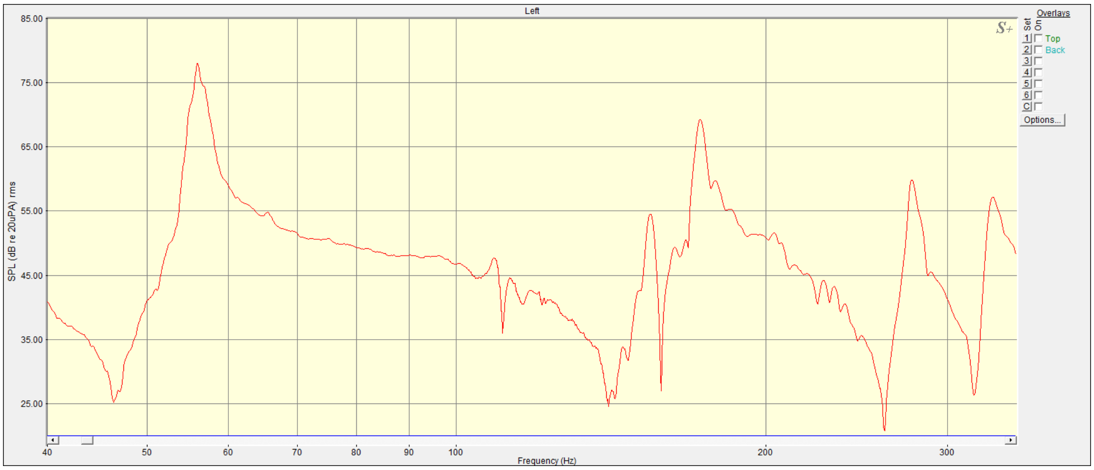


Figure 12.2: Plot of the frequency peaks generated by an impulse hammer on a rectangular East Indian rosewood plate.

Even though a general idea regarding the fundamental frequency can be gleaned from merely locating the dominant peak's apex, many relatively inexpensive audio-analyzing software products offer specific analysis functions to assist in documenting vibrational characteristics. The first characteristic of interest to the luthier is defining the fundamental frequency of the vibrating mode, in this case, the first longitudinal mode. Visually it can be estimated at just over 55 Hz and can be verified using an available software function at precisely 55.91 Hz. The second characteristic of importance to the luthier is the damping of that fundamental frequency to indicate the wood sample's ability to sustain vibration. The simplest way to measure the inherent damping of the fundamental frequency is to use the half-power bandwidth method, as illustrated previously in Figure 2.13.

To further illustrate the implications of this damping measurement, a long ringing tap tone would measure a high *Q* with a corresponding low damping rate [Campbell and Greated 1987]. However, according to Gore and Gilet [2011a], in order to achieve results that are comparable between samples, certain conditions are critical. To ensure accurate comparisons, samples must be:

1. Flat
2. Exactly the same dimensions
3. Of exactly the same surface finish
4. Of the same moisture content
5. Supported in the exact same way
6. Excited in the same way, and
7. Have their vibrations measured in precisely the same manner

Because these conditions could be sufficiently managed during testing, the results should be adequately reliable to draw conclusions. In addition, the audio software being utilized has a built-in function to calculate *Q* automatically and will be utilized for the tests.

Wood is highly anisotropic, having differing mechanical properties depending on grain direction. It is not unusual to have the modulus of elasticity 10x stiffer or more in the longitudinal direction (E_L) than in the radial direction (E_R) depending on the species [Haines 1980; Kretschmann 2010]. Furthermore, the modulus of elasticity and the *Q* factor can differ by 2x or more within species depending on the age of the tree, its growing environment, and location in the tree where the sample was taken [Gore and Gilet 2011a; Gore 2011; Brémaud et al. 2011]. Typically, luthiers estimate plate stiffness and damping by merely flexing wood plates across the radial (i.e., quarter-sawn face) and sometimes longitudinal (i.e., lengthwise) direction and tapping the wood to judge vibration decay. In order to ensure the Sitka spruce plates intended for the soundboards on the test guitars are homogenous to each other, the testing methods outlined above were used to measure and compare E_L, E_R, and Q_L. In addition, mass and the fundamental frequency of the first mode of vibration were also calculated. The results are shown in Table 12.2.

Sample	**Mass (g)**	E_L **(GPa)**	E_R **(GPa)**	**Fundamental Frequency (Hz)**	Q_L
Sitka A	152.4	13.53	.94	58.83	88.8
Sitka B	151.3	13.48	.91	58.09	86.3
Sitka C	152.7	13.56	.97	61.61	90.1
Sitka D	152.9	13.54	.94	60.09	91.3
Mean (M)	152.3	13.53	.94	59.66	89.1
Standard Deviation (SD)	.62	.03	.02	1.34	1.86
Coefficient of Variation % (CV=SD/M)	.41	.22	2.13	2.24	2.09

Table 12.2: Calculated elastic and vibrational measurements of the Sitka soundboard plates.

The results in Table 12.2 confirm the fairly homogenous aspects of the four Sitka spruce sets. Since these sets were consecutively cut from a single billet, the results are what might be expected. These results indicate that, notwithstanding small variations in final assembly and finishing, the soundboards themselves should have relatively little, or even no, differentiation impact on the vibroacoustics of the finished guitar [Gore 2011].

Because the wood sets being selected for the backplates are not from a single tree, much less a single species, it would be reasonable to expect more difficulty in achieving a low *CV* percentage. The selection process started with two sets of African padauk that indicated promise using the subjective “tap tone” method described above. Fifty-four sets of East Indian rosewood were similarly tested with only two sets that showed subjective similarity. The two sets of African padauk and two sets of East Indian rosewood were then objectively tested with results shown in Table 12.3.

Sample	**Mass (g)**	**E_L (GPa)**	**E_R (GPa)**	**Fundamental Frequency (Hz)**	**Q Factor**
East Indian Rosewood A	302.5	15.7	2.1	58.83	74.8
East Indian Rosewood B	325.8	16.0	2.2	58.09	79.2
African Padauk A	277.3	15.9	1.9	61.61	84.1
African Padauk B	279.9	15.9	2.0	60.09	82.3
Mean (M)	296.4	15.9	2.1	59.66	80.1
Standard Deviation (SD)	22.65	.13	.13	1.54	4.07
Coefficient of Variation % (CV=SD/M)	7.6	.8	6.2	2.6	5.1

Table 12.3: Elastic and vibrational measurements of prospective backplate candidates.

With the top and backplates selected, four guitars were manufactured according to common luthier processes and techniques. Special attention was given to matching billets of brace wood for specific braces in each guitar (i.e., cross braces for each of the guitars were taken from a single billet). In addition, all dimensionally critical components were machined using a CNC router to produce precise and indistinguishable components. The use of CNC manufactured bridges, fretboards, and necks ensured that each guitar would intonate correctly and feel the same while being played. After completion, string heights were adjusted to a standard clearance at the twelfth fret of 2mm for the low E string and 1.6mm for the high E string. After allowing the guitars to become accustomed to string tension for seven days, string clearances were checked and adjusted, as necessary.

Before commencing the blind test, the final adjustment was to match the fundamental frequencies of the three primary modes of the guitar: the air cavity, soundboard, and backplate [Gore 2011]. When a guitar note is played, the fundamental frequency of these modes contributes a sympathetic resonance to the tone of the note. Having the modes on these guitars tuned to different frequencies would, in effect, add distinguishing characteristics to their sound output [Richardson 1992; Carcagno et al. 2018]. Since the air cavity mode is fixed by the internal dimensions of the instrument body and size of the soundhole, very little can be done after construction to alter this frequency. However, the top and backplates are relatively easy to tune by removing material from the primary structural braces for these plates. The removal of wood on the top's "X" brace and the back's cross braces effectively lowers that component's fundamental frequency by reducing plate stiffness, akin to lowering the tension on a guitar string to reduce its pitch. This process effectively equates any differences due to plate and brace stiffness variability. Figure 12.3 shows the resonant peaks of the three modes after tuning. The modes were generated by an impulse hammer tap to the bridge.

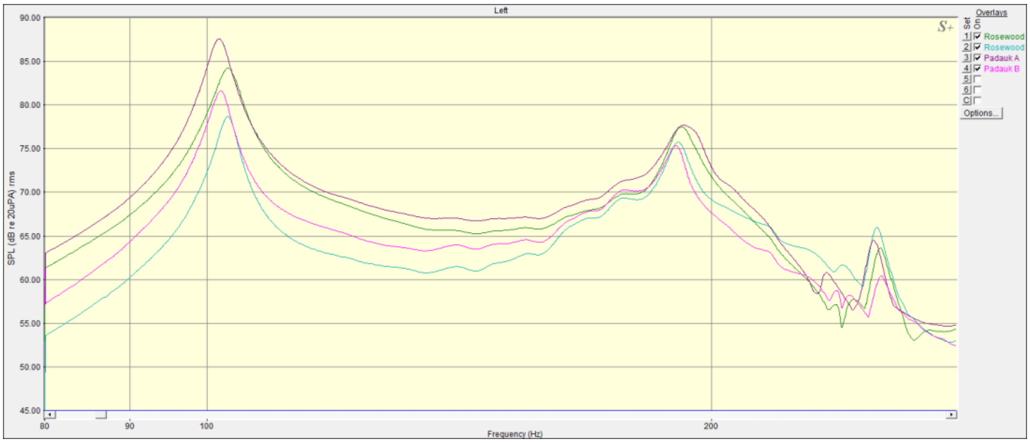


Figure 12.3: The resonant peaks of the air cavity, soundboard, and backplate for the four test guitars.

To further illustrate the similarity of the peaks, Table 13.4 lists them individually.

Guitar	Air Cavity (Hz)	Soundboard (Hz)	Backplate (Hz)
East Indian Rosewood A	102.85	191.80	252.11
East Indian Rosewood B	102.94	191.28	251.18
African Padauk A	101.63	192.69	250.03
African Padauk B	101.92	190.75	252.57
Mean (M)	102.34	191.63	251.47
Standard Deviation (SD)	.66	.83	1.12
Coefficient of Variation % (CV=SD/M)	.64	.43	.45

Table 12.4: Fundamental frequency response of the primary guitar modes.

Based on the low coefficient variations, there is reassurance that the four guitars should impart a body-induced overtone contribution in a nearly identical manner.

12.3 Test Specifics

Two playing tests were carried out with each subject to determine whether or not players could effectively distinguish between guitars made with different wood species for their back and sides.

1. The first test used a “forced-choice AAB/ABB format” requiring the participant to play three of the four guitars with the objective to estimate which of the three was made of a differing species. The

specific combination of guitars presented for evaluation was pre-determined by the observer to ensure each potential combination was used equally over all test repetitions and all players.

2. The second test entailed having all test participants play each of the four guitars in a random order with the instruction of determining the preferred guitar in terms of overall tone. Again, this was a forced choice scenario. Test subjects were allowed full latitude in determining their tonal preference without instruction or constraint. Before the initiation of the test, participants were shown the instruments that would be used. Participants were given a full explanation of how they were similar in terms of physical and vibrational characteristics and how they differed in terms of wood species used for the backs and sides.

The blind playing tests were conducted with sixty-one experienced guitar players of varying proficiency. The pool was drawn from the customers and acquaintances of Applegate Guitar Co. Blackout goggles were fitted so that no visual clues could be discerned to help distinguish between the East Indian rosewood and African padauk guitars. A single room with dimensions of 6 meters by 11 meters was utilized for each performance. The instruments were tuned immediately before each test using a digital tuning device to ensure the test guitars' proper intonation. Players were seated on a stool that accommodated typical playing styles and ergonomics. Players were encouraged to play pieces of low technical demand so that they could adequately judge the tone of the guitars being tested rather than focus on the intricacies of a difficult piece. The test participants were allowed to play any piece they felt would provide the greatest success at determining any differentiation between test instruments. Subjects were also permitted to play instruments more than once if they felt it would increase their success. Participants also had full discretion on when to switch instruments.

12.4 Results and Analysis

Of the sixty-one sets of tests conducted in the_forced AAB/ABB playing test, eighteen of players successfully (29.8% of the total of 61 players) selected the odd-one-out. The success rate is very close to what would be expected by a random guess (33.33%). The slightly less than guess-rate of success indicates that the sound of the guitars, with matched physical and vibrational properties, were essentially indistinguishable despite using different species for the back and sides. Table 12.5 illustrates the specific data available from the two tests.

Guitar	Odd-One Out Incidence	Preferred by a Player Incidence
East Indian Rosewood A	6	11
East Indian Rosewood B	5	16
African Padauk A	3	18
African Padauk B	4	16
Total	18	61

Table 12.5: Total individual selections for the blind performance tests.

While test subjects could not distinguish between the guitars based on the wood used for the back and sides above the rate of a random guess, one notable inference can be made using the data in Table 12.5; the African padauk guitars were preferred by 55.8% of the test participants. While this rate of preference in no way demonstrates any large margin of superiority, it further argues for the successful substitution of threatened iconic species without any negative consequence in the guitar’s tonal quality. Indeed, according to this test group, instruments using African padauk for the back and sides were slightly preferred over those made with East Indian rosewood. However, a more extensive study with more than two samples of each type of guitar would be helpful in further validating this assertion.

12.5 Conclusions

The expectation of rosewood for guitar back and sides have been established by the luthier community due to its predominant use over the last two centuries on high-end instruments. As such, there is a cynical view amongst musicians and luthiers that any substitution would adversely affect the quality of the guitar and its inherent value [Carcagno et al. 2018]. For many, the idea of owning something rare, or in some cases forbidden, has an intrinsic value that may, in fact, supersede the quality aspects of a specific guitar. Also, this test did not account for the visual appeal of East Indian rosewood versus African padauk. Anecdotally, a large number of test subjects found the brick-orange coloration of the African padauk guitars appealing despite an initial prejudice towards the traditional rosewood paradigm. While African padauk tonewood is currently easily sourced at luthier supply stores, it is still considered a “novelty” wood rather than a stalwart species. Its low cost may additionally hinder its acceptance due to the psychological predisposition of high quality being related to high cost. In total, there are many barriers to the acceptance of rosewood substitutes: tradition, lore, expectation, visual appeal, and intrinsic value. However, the test results in this study add to a growing body of work that confirms the specific physical and vibrational qualities of a wood sample will determine its performance in use. While a particular species may have endemic characteristics, it does not preclude a very different species from having those same characteristics. Moreover, in the end, it is the vibrational and physical properties of a specific piece of wood that is of the greatest importance, not the identity of its species.

Chapter 12 – Indistinguishability of Tonewood Substitution: A Blind Test of Guitars made from African Padauk and East Indian Rosewood

Chapter 13

Thesis Summary

13.1 Review of Key Components

This thesis set out to explore the wood materials used in the construction of concert quality acoustic guitars. This macro-level objective was broken down to specifically research: (1) the evolution of material selection throughout the instrument’s roughly 600-year history, (2) the initiation of tropical hardwoods into the art of lutherie, (3) the physical properties that determine optimal functionality, and (4) the wood species that demonstrate these characteristics.

Chapter 2 introduced the vibroacoustic concepts that would be referred to throughout the entire thesis. Chapters 3, 4, and 5 developed the foundation with which the guitar evolved in terms of the prominent woods that were used historically. The evolution of material selection was determined primarily through the review of historical guitars preserved in private and museum collections. While this method provided a reasonable overview of surviving instruments, it does not account for the greater number of guitars lost through the ages. It was theorized that while exemplary guitars were collected for posterity, common instruments were more likely to be discarded rather than repaired and preserved. Therefore, the is a resulting gap in fully accounting for guitar material selection based on preserved specimens. The underlying question of interest to this research is, why did certain tropical hardwoods become the archetypal wood selections for the guitar’s other components? Based on the historical records that exist, it is clear that the use of tropical hardwoods in luthiery reached back to the earliest guitar example, the Kingwood (*Dalbergia cearensis*) darts and panels incorporated into the fifteenth-century “Guadalupe” vihuela. Rosewood and ebony also appeared early in the guitar’s development, while Spanish cedar and mahogany’s inclusion shows nearly no documented use prior to the nineteenth century. However, further research into historic guitar necks might prove otherwise as collection descriptions often fail to remark upon the material used for this component.

The proliferation of tropical hardwood use was theorized to be the result of superior visual aesthetic, cultural reverence for esteemed exotic species, and outstanding suitability to purpose. While the visual aesthetic is subjective, the penchant for rosewood, ebony, Spanish cedar, and mahogany was demonstrated through their utilization for fine cabinetry and furniture in parallel with the guitar's history. The use of these woods in an instrument elevated the quality perception based on their mere inclusion, a practice that continues with modern luthiers. In addition to their extrinsic value, these tropical hardwoods demonstrated optimal suitability to purpose. The strength and stiffness of ebony and rosewood made them excellent candidates for fingerboards, bridges, and backs & sides, while Spanish cedar and mahogany's density and stiffness proved to be optimally suited for guitar necks. Beauty, esteem, and excellent functionality eventually led to a wood-material expectation paradigm for concert quality guitars around the time Antonio de Torres established the modern design in the mid-nineteenth century. Consistently over the following 100 years, the guitar in its highest form consisted of a spruce soundboard, Brazilian rosewood back and sides, ebony fretboard, a bridge made from ebony or rosewood, and a neck made from Spanish cedar or Honduran mahogany. This paradigm would have likely continued indefinitely if not for the impact of widespread industrial overutilization and poor timber management practices. Instead, luthiers need to consider alternative species to replace the woods that have achieved iconic status within the guitar community.

In order to achieve acceptance for alternative wood species, it was determined that potential candidates had to be objectively analyzed to ensure at least an equal substitution in terms of mechanical property metrics. The first step was to establish material selection criteria based on the function of the component being considered. Traditional wood selections were then analyzed against these criteria to establish a baseline understanding of their workability and suitability characteristics. This exercise, covered in Chapter 6, more or less confirmed the suitability of traditional tonewoods in their specific application in use.

The analysis and experiments detailed in Chapters 7-12 focused on objective methods to quantify alternative wood species' suitability for the guitar bridge, fretboard, neck, and back and sides. Also, the resulting test methods offered strategies to not only compare between different species but also enhance within species material selection. Using the published mechanical property data for traditional tonewoods as a benchmark, non-threatened alternative species were compared based on defined characteristics of importance for a particular component. Overall, it was determined that there are many suitable alternatives to the threatened traditional tropical hardwoods. Furthermore, it was determined in several cases that alternative candidates were, in fact, superior to traditional species. The most notable incidence for each is as follows:

- **Necks** – Port Orford cedar demonstrated lower density and higher stiffness than Honduran mahogany and Spanish cedar. Additionally, Port Orford cedar's low surface hardness indicates a wood conducive to shaping with hand tools.
- **Fingerboards** – Katalox exhibited the highest published scores regarding surface durability, stiffness, and compression strength. While moisture stability was slightly lower than East Indian rosewood, it compared substantially better than the perennial favorite West African Ebony.
- **Bridges** – Brazilian rosewood exhibited the best combination of density, surface hardness, stiffness, and stability. Other candidates were suitable alternatives but did not demonstrate overall superiority.

- **Backplates** – While Brazilian rosewood demonstrated overall superiority, Chakte Viga and Granadillo generally scored higher than East Indian rosewood in terms of strength-to-weight characteristics and superior in terms of internal damping.

Chapter 12 set out to prove that measurable mechanical and material properties will more accurately define a wood sample in service than the name of the species alone. Specifically, a blind test was designed to determine whether participants could distinguish between instruments made from different woods for the back and sides, which had been specifically selected and crafted so as to possess nearly identical mechanical properties. The results showed a rate of success for participants to identify the odd guitar from a forced AAB/ABB trial as just below what would be expected from a random guess (in other words, comparable with random chance). The outcome demonstrates the viability of material substitution for guitar backs and sides based on characterization of measurable mechanical properties. This implication further substantiates the contention for successful wood species substitutions for guitar necks, fingerboards, and bridges.

There is an existential threat to the future availability of tropical hardwoods traditionally utilized in guitar luthiery. Already, the highly revered Brazilian rosewood has been eliminated for future use. The current commercial overutilization of East Indian Rosewood, West African ebony, Spanish cedar, and Honduran mahogany indicate a potentially similar fate. Many fear the quality of instruments made with alternative species will never match those made with the familiar traditional tropical hardwoods. Overcoming this prejudice is the greatest obstacle in the acceptance of alternative woods by the guitar community. Success will require an overwhelming body of objective research providing unequivocal proof of successful material substitution, of which this research endeavors to be a part.

Appendix I

Guitar Catalog

Year	Luthier	Sound-board	Back and Sides	Neck	Fretboard	Bridge	Decoration	Source
15th Century	Guadalupe	Spruce or Pine	Boxwood, Kingwood	Boxwood, Kingwood			Ornate	2
16th Century	Anonymous "Chambure"	Spruce or Fir	Boxwood and Cypress					7
16th Century	Anonymous "Quito"	Pine	Pine	Maple or Alder				8
1581	Dias, Belchior	Spruce	African Blackwood	African Blackwood			Ornate	2
1590	Dias, Belchior		African Blackwood	Ivory Veneer	Spruce		Ornate	2
1602	Cocko, Christopher	Spruce or Pine	Ivory	Ivory			Ornate	2
1620 ca.	Tessler, Giovanni	Spruce	Wood, Ivory	Ivory, wood	Mop, Iv, Eb		Very Ornate	2
1620 ca.	Anonymous		Ebony, Bone	Ebony, Bone	Ebony, Bone		Very Ornate	2
1620 ca.	Stadler, Jacob		Dark Wood, Ivory	Dark Wood, Ivory	Ivory		Ornate	2
1623	Sellas, Matteo		Ebony, Ivory	Ebony, Ivory	Ebony, Ivory		Very Ornate	2
1627	Sellas, Matteo	Spruce or Pine	Ebony, Ivory	Ebony, Ivory	Ebony, Ivory		Very Ornate	2
1630	Sellas, Matteo	Spruce	Snakewood		Ivory		Ornate	3
1640 ca.	Sellas, Matteo	Spruce	Ebony	Ivory Ebony	Inlay	Ebony	Ornate	4
1641	Voboam, Rene	Spruce or Pine	Tortoise, Ebony, Ivory	Tortoise	Ebony, Ivory		Very Ornate	2
1646	Smit, Giovanni		Dark Wood, Ivory	Dark Wood, Ivory	Ivory		Ornate	2
1648	Du Mesnel		Dark Wood, Ebony, Ivory				Ornate	2
1650	Santos Vievra	Spruce or Pine	Brazilian Rosewood				Very Ornate	2
1650 ca.	Anonymous	Spruce	Brazilian	Ebony Veneer	Inlay		Ornate	4
1652	Sellas, G. & M.		Ebony, Ivory	Ebony, Ivory	Ebony, Ivory		Very Ornate	2
1670	Voboam, Alexander	Spruce	Juniper, Ebony	Ebony Veneer	Ebony	Ebony	Ornate	4
1670 ca.	Sellas, Dominico	Spruce	Brazilian Rosewood	Ebony Veneer	Inlay		Ornate	4
1676	Voboam, Alexander		Dark Wood, Ivory	Dark Wood, Ivory	Dark Wood, Ivory		Ornate	2
1684	Fleischer, Hans Christian		Tortoise, Ivory	Tortoise, Ivory	Mother of Pearl		Very Ornate	2
1687	Voboam, Jean	Spruce	Tortoise, Ivory	Tortoise, Ivory			Very Ornate	2
1688	Stradivari, Antonio	Spruce or Pine	Maple	Maple	Ebony		Austere	2
1690	Ertel, Giacomo	Spruce	Mosaic	Mosaic	Mosaic	Ebony	Ornate	3

1693	Tielke, Joachim		Tortoise, Ivory	Tortoise, Ivory			Very Ornate	2
1694	Cheron, Robert	Spruce	Yew	Ebonized Wood	Ebony		Ornate	3
1695	Tielke, Joachim	Spruce	Ebony, Ivory	Ebony, Ivory	Pine, Tortoise	Ebony	Ornate	3
1697	Voboam, Jean-Babtiste	Spruce	Tortoise Veneer			Ebony	Ornate	3
1700 ca.	Tielke, Joachim		Ebony, Ivory	Ebony, Ivory	Ebony, Ivory		Ornate	2
1700	Stradivari, Antonio	Spruce	Maple	Maple Ebony	Ebony	Maple	Austere	4
1715	Costa, Diego	Spruce	Maple	Maple	Maple		Austere	2
1720 ca.	Anonymous	Spruce	Maple	Maple	Ebony		Austere	2
1730 ca.	Anonymous	Spruce	Fruitwood	Fruitwood	Fruitwood	Rosewood	Ornate	4
1749	Boivin, Claude	Spruce or Pine	Tortoise, Ivory	Pine with Marquetry	Pine with Marquetry		Very Ornate	2
1755	Massague, Jose	Spruce	Maple				Ornate	3
1760 ca.	Preston	Spruce	Maple	Maple	Ebony		Austere	2
1763	Perez, Francisco		M. Cypress		Ebony		Austere	2
1770 ca.	Cousineau, George	Spruce	Maple		Ebony		Austere	1
1770 ca.	Colin		Maple				Ornate	2
1770 ca.	Lekeu, Guilaume Joseph	Spruce	Mosaic				Ornate	3
1773	Lupot, Francois	Spruce	Ash or Elm				Austere	2
1779	Aubry, Antoine	Spruce	Mosaic	Mosaic	Inlayed	Ebony	Ornate	4
1780 ca.	Sanguino, Francisco						Austere	2
1780 ca.	de Frias, Joseph	Spruce					Ornate	3
1783	Benedit, Josef	Spruce	Rosewood				Austere	2
1784	Guerra, Dionisio	Spruce or Pine	M. Cypress				Ornate	2
1785	Fabricatore, Giovanni	Spruce	Maple		Ebony	Ebony	Austere	1
1787	Benedid, Joseph	Spruce	Maple				Ornate	3
1790 ca.	Villaume and Giron	Spruce	Maple				Austere	1
1790 ca.	Oliveira, Pedro Ferreira						Ornate	2
1790	Vinaccia, Antonia		Fruitwood				Austere	2
1792	Pages, Juan		Rosewood				Ornate	2
1792	Trotto, Gioacchino				Tortoise		Austere	2
1796	De Los Santos, Ignacio						Austere	2
1797	Sanchez de Aguilere, Benito	Spruce	M. Cypress				Austere	3
1798	Pages, Jose		M. Cypress				Austere	2
1800	Anonymous	Spruce	Ebony		Tortoise		Ornate	3
1802	Pages, Juan	Spruce	Rosewood		Ebony		Ornate	3
1804	Alcaniz, Josef		M. Cypress				Ornate	2

1820	Grobert		Brazilian Rosewood				Austere	2
1820	Morlot, Nicholas						Austere	2
1822	Panormo, Louis	Spruce	Brazilian Rosewood	Maple, Mahogany	Ebony		Austere	2
1824	Lacôte, René		Pine, Rosewood		Ebony		Austere	2
1825	Staufer, Johann	Spruce	European Maple				Austere	2
1829	Panormo, Louis	Spruce	Brazilian Rosewood			Ebony, Ivory	Austere	2
1830	Fabricatore, Gennaro	Spruce	Ebony		Ebony	Ebony	Ornate	1
1830 ca.	Stauffer, Johann-Anton	Spruce	European Maple		Ebony		Austere	1
1830	Lacôte, René	Spruce	Satinwood		Ebony		Austere	1
1830 ca.	Coffe-Goguette						Ornate	2
1831	Recio, Jose	Spruce	Rosewood				Austere	2
1834	Martin, C.F.	Spruce	European Maple		Ebony		Ornate	1
1835	Stauffer, Johann-Anton	Spruce	European Maple	Ebony Veneer	Ebony	Ebony	Austere	3
1836	Martin, C.F.		Brazilian Rosewood				Austere	2
1837	Martin, C.F.	Spruce	Brazilian Rosewood	Spanish Cedar	Ivory	Ivory	Ornate	3
1838	Martin, C.F.	Spruce	Maple	Ebony Veneer	Ebony	Ebony	Austere	3
1840	Beau						Austere	2
1840 ca.	Altimira, Agustin	Spruce	E. Maple over pine				Very Ornate	2
1840 ca.	Altimira, Agustin	Spruce	Walnut		Mother of Pearl		Ornate	1
1840 ca.	Roudloff, Dominic and Arnould	Spruce	Rosewood		Ebony		Austere	1
1840 ca.	Panormo, Louis	Spruce	Rosewood	Spanish Cedar and Maple	Ebony	Ebony	Austere	5
1843	Panormo, Louis	Spruce	European Maple		Ebony		Austere	2
1845	Lacote, Rene	Spruce	Brazilian Rosewood		Ebony		Austere	3
1850	Martin, C.F.	Spruce	Brazilian Rosewood		Ebony	Ivory	Austere	1
1850 ca.	Anonymous	Spruce	Rosewood, Pine		Ebony		Austere	2
1852	Lacote, Rene						Austere	2
1852	Serrano, Jose	Spruce	Rosewood				Austere	2
1854	de Torres, Antonio						Austere	2
1855	Ashborn, James	Spruce	Rosewood		Ebony		Austere	1
1858	Fuentes, Pedro	Spruce	Maple and Walnut		Ebony		Ornate	3
1859	de Torres, Antonio	Spruce	Brazilian Rosewood				Austere	2
1862	de Torres, Antonio	Spruce	Papier Mache		Rosewood		Austere	2

Appendix I

1864	de Torres, Antonio	Spruce	European Maple		Ebony		Austere	1
1867	Martin, C.F.						Austere	2
1867	Torres	Spruce	European Maple	Spanish Cedar	Ebony	Brazilian Rosewood		6
1867	Martin, C.F.	Spruce	Brazilian Rosewood	Ebony Veneer	Ebony		Austere	3
1867	Martin, C.F.	Spruce	Brazilian Rosewood		Ebony		Austere	3
1869	Gonzalez, Francisco	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1870	Glasel, Mortz	Spruce	Walnut		Inlay	Inlay	Ornate	1
1870	Gonzalez, Francisco		Rosewood, Maple				Ornate	2
1870	Bini, Joseph	Spruce	Brazilian Rosewood		Ebony		Austere	3
1870	Haynes, John	Spruce	Brazilian Rosewood		Ebony		Austere	1
1874	Farfan, Miguel						Ornate	2
1874	Arias, Vicente		Rosewood		Rosewood		Austere	2
1880	Anonymous	Spruce	Rosewood		Ebony		Ornate	1
1880	Fernandez, Mariano	Spruce	Brazilian Rosewood	Spanish Cedar			Ornate	3
1882	de Torres, Antonio	Spruce	Brazilian Rosewood		Ebony		Austere	1
1883	de Torres, Antonio	Spruce	European Maple				Austere	2
1883	Torres	Spruce	M. Cypress		Rosewood	Rosewood	Austere	6
1889	Torres	Spruce	European Maple	M. Cypress	Ebony	Rosewood	Austere	6
1889	Arias, Vicente	Spruce	Brazilian Rosewood		Ebony		Austere	1
1889	de Torres, Antonio	Spruce	Mahogany		Ebony		Austere	1
1898	Arias, Vicente	Spruce	European Maple	Spanish Cedar	Ebony	Rosewood	Austere	6
1898	Ferer, Benito	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1900	Marin, Andres	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Rosewood	Austere	6
1890	de Torres, Antonio	Spruce	M. Cypress		Ebony		Austere	1
1900 ca.	Anonymous	Spruce	Brazilian Rosewood	Mahogany	Ebony	Ebony	Austere	4
1900 ca.	Anonymous	Spruce	Brazilian Rosewood	Spanish Cedar	Maple	Ebony	Austere	4
1901	Garcia, Enrique	Spruce	M. Cypress		Ebony		Austere	1
1902	Ramirez I, Jose	Spruce	Brazilian Rosewood		Ebony		Austere	1
1907	Ramirez I, Jose	Spruce	Mahogany	Spanish Cedar	Rosewood	Brazilian	Austere	6
1911	Ramirez, Manuel	Spruce	Rosewood				Austere	2
1912	Ramirez, Manuel	Spruce	Maple	Spanish Cedar	Ebony	Brazilian	Austere	6
1912	Rojas, Saturnino	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian	Austere	6
1912	Ramirez, Manuel	Spruce	Brazilian	Spanish Cedar	Ebony	Brazilian	Austere	3
1913	Ramirez, Manuel	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian	Austere	6

1917	Ramirez, Julian Gomez	Spruce	M. Cypress	Spanish Cedar	Rosewood	Brazilian	Austere	6
1917	Larson Brothers	Spruce	Mahogany	Mahogany	Rosewood	Brazilian	Austere	6
1920	Julve, Telesforo	Spruce	Walnut	Spanish Cedar	Rosewood	Brazilian	Austere	6
1922	Garcia, Enrique	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian	Austere+	6
1922	Esteso, Domingo	Spruce	Cypress	Spanish Cedar	Rosewood	Brazilian	Austere	6
1923	Hernandez, Santos	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian	Austere	6
1923	Borreguero, Modesto	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian	Austere	6
1924	Hernandez, Santos	Spruce	Brazilian Rosewood			Brazilian	Austere	2
1924	Hernandez, Santos	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian	Austere	3
1925	Sanfeliu, Enrique	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian	Austere	6
1926	Esteso, Domingo	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian	Austere	6
1926	Borreguero, Modesto	Spruce	East Indian Rosewood	Spanish Cedar	Ebony	Brazilian	Austere	6
1926	Viudes, Antonia Emilio	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian	Austere	6
1929	Simplicio, Francisco	Spruce	Brazilian Rosewood		Ebony	Brazilian	Austere	1
1929	Simplicio, Francisco	Spruce	Satinwood	Spanish Cedar	Ebony	Brazilian	Austere	6
1929	Rodriguez, Miguel	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian	Austere	6
1930	Esteso, Domingo	Spruce	East Indian Rosewood	Spanish Cedar	Ebony	Brazilian	Austere	6
1930	Hernandez, Santos	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian	Austere	6
1930	Hernandez, Santos	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian	Austere	6
1930 ca.	Regal Musical Inst.	Spruce	Maple	Maple	Ebony	Brazilian	Austere	4
1931	Simplicio, Francisco	Spruce	Brazilian Rosewood			Brazilian	Austere	2
1931	Galan, Juan	Spruce	Mahogany	Spanish Cedar	Ebony	Brazilian	Austere	6
1934	Esteso, Domingo	Spruce	M. Cypress		Ebony	Brazilian	Austere	1
1932	Gonzalez, Casa	Spruce	Walnut	Spanish Cedar	Rosewood	Walnut	Austere	6
1932	Hauser, Hermann	Spruce	European Maple	Mahogany	Ebony	Brazilian Rosewood	Austere	6
1934	Hauser, Hermann	Spruce	Brazilian Rosewood	Mahogany	Ebony	Brazilian Rosewood	Austere	6
1934	Barbero, Marcelo	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1935	Hauser, Hermann	Spruce				Brazilian Rosewood	Austere	2
1936	Galan, Rafael	Spruce	E. Indian Rosewood	Spanish Cedar	Ebony	Dark Wood	Austere	6
1937	Hauser, Hermann	Spruce	Brazilian Rosewood	Mahogany	Ebony	Brazilian Rosewood	Austere	3
1939	Ramirez, Julian Gomez	Spruce	Brazilian Rosewood		Ebony	Brazilian Rosewood	Austere	1

Appendix I

1940	Hauser, Hermann	Spruce	Brazilian Rosewood	Mahogany	Ebony	Brazilian Rosewood	Austere	3
1942	Esteso, V. y S.	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1946	Ramirez II, Jose	Spruce	Maple		Ebony	Brazilian Rosewood	Austere	1
1948	Barbero, Marcelo	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1952	Monch, Edgar	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1953	Fleta, Ignacio	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	3
1954	Bouchet, Robert	Spruce		Spanish Cedar		Brazilian Rosewood	Austere	2
1954	Ramirez II, Jose	Spruce	M. Cypress	Spanish Cedar	Rosewood	Brazilian Rosewood	Austere	6
1954	Lopez, Marcelino	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1957	Barbero, Marcelo	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1958	Lopez, Marcelino	Spruce	M. Cypress	M. Cypress	Ebony	Brazilian Rosewood	Austere	6
1958	Fernandez, Arcangel	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1960	Ramirez III, Jose	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1960	Fleta, Ignacio	Spruce	East Indian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1960	Rodriguez, Miguel	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1961	Fleta, Ignacio	Spruce		Spanish Cedar		Brazilian Rosewood	Austere	2
1961	Hernandez y Aguado	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1962	Ramirez III, Jose	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1962	Bouchet, Robert	Spruce	Brazilian Rosewood		Eb	Brazilian Rosewood	Austere	1
1962	Hauser II, Hermann	Spruce	East Indian Rosewood	Honduran Mahogany	Ebony	Brazilian Rosewood	Austere	6
1963	Hernandez y Aguado	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1963	Kono, Masuru	Spruce	East Indian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1964	Fernandez, Arcangel	Spruce				Brazilian Rosewood	Austere	2
1966	Hernandez Y Aguado	Spruce				Brazilian Rosewood	Austere	2
1966	Velazquez, Manuel	Spruce	East Indian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1967	Barbero II, Marcelo	Spruce	M. Cypress	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1967	Friedrich, Daniel	Spruce	Rosewood		Ebony	Brazilian Rosewood	Austere	1
1967	Bouchet, Robert	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1967	Ramirez III, Jose	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	3
1969	Friedrich, Daniel	Spruce	East Indian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1971	Bernabe, Paulino	W. Red Cedar	M. Cypress	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1974	Raponi, O.	W. Red Cedar	East Indian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6

1975	Fernandez, Gerundino	Spruce	E. Indian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1976	Rodriguez II, Miguel	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1980	Romanillos, Jose	Spruce	Indian	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1981	Rubio, David	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1981	Fleeson, Martin	Spruce	Indian	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1981	Ruck, Robert	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1983	Holroyd, Robert	Spruce	Indian	Mahogany	Ebony	Ebony	Austere	6
1985	Gilbert, John	Sitka Spruce	Indian	Spanish Cedar	Ebony	Teak	Austere	6
1986	Brune, Richard	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1987	Smallman, Greg	W. Red Cedar	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1988	Reyes, Manuel	Spruce	Cypress	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1989	Hauser III, Hermann	Spruce	Peruvian Rosewood	Mahogany	Ebony	Brazilian Rosewood	Austere	6
1990	Humphrey, Thomas	Spruce	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1994	Bernabe, Paulino	W. Red Cedar	Brazilian Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	6
1998	Field, Dominique	Spruce	Rosewood	Spanish Cedar	Ebony	Brazilian Rosewood	Austere	1
1911	Hauser, Hermann	Spruce	Maple		Ebony		Austere	1
1958	Hauser II, Hermann	Spruce	Brazilian Rosewood		Ebony		Austere	1
1988	Hauser III, Hermann	W. Red Cedar	Brazilian Rosewood		Ebony		Austere	1
1963	Hernandez y Aguado	Spruce	Brazilian Rosewood		Ebony	Brazilian Rosewood	Austere	1
1974	Fleta, Ignacio	W. Red Cedar	Brazilian Rosewood		Ebony	Brazilian Rosewood	Austere	1
1978	Romanillos, Jose	Spruce	Rosewood		Ebony	Rosewood	Austere	1
1974	Kohno, Masaru	Spruce	Rosewood		Ebony	Rosewood	Austere	1
1958	Fernandez, Arcangel	Spruce	Cypress		Ebony	Brazilian Rosewood	Austere	1
1969	Reyes, Manuel	Spruce	Cypress		Ebony	Brazilian Rosewood	Austere	1
Steel-String								
1935	Gibson	Spruce	Mahogany		Rosewood	Rosewood	Sunburst	1
1944	Gibson	Spruce	Rosewood		Rosewood	Rosewood	Sunburst	1
1952	Gibson	Spruce	Maple		Rosewood		Austere	1
1902	Martin, C.F.	Spruce	Brazilian Rosewood	Honduran Mahogany	Ebony	Ivory	Austere	1
1915	Martin, C.F.	Spruce	Brazilian Rosewood	Honduran Mahogany	Ebony	Ebony	Austere	1
1930	Martin, C.F.	Spruce	Brazilian Rosewood	Honduran Mahogany	Ebony	Ebony	Austere	1
1942	Martin, C.F.	Spruce	Mahogany	Honduran Mahogany	Ebony	Ebony	Austere	1
1906	Martin, C.F.	Spruce	Brazilian Rosewood	Honduran Mahogany	Ebony	Ebony	Austere	1

1968	Martin, C.F.	Spruce	Brazilian Rosewood	Honduran Mahogany	Ebony	Ebony	Austere	1
1928	Washburn	Spruce	Rosewood		Ebony	Ebony	Ornate	1
1973	Guild	Spruce	Mahogany		Ebony	Rosewood	Ornate	1

Sources:

(1) Westbrook 2015

(2) Evan and Evans 1977

(3) Metropolitan Museum of Art 2020

(4) Musical Instrument Museum 2020

(5) St. Cecilia’s Museum 2020

(6) Urlik 1997

(7) Schreiner 2020

(8) Bermudez 1991

Appendix II: Vibration and Elastic Characterization Test Scores for Traditional and Alternative Tonewoods

Sample	**Mass (g)**	**Specific Gravity (ρ) (g/cm^3)**	**Modulus of Elasticity (E) (GPa)**	**Specific Modulus (E/ρ)**	**Fund. Freq. (Hz)**	***Q* Factor**
Brazilian Rosewood						
1	176	0.91	13.81	14.38	108.8	217
2	162	0.84	14.33	17.1	114.1	228
3	197	1.02	19.52	19.14	123.2	246
4	195	1.01	16.9	16.75	116.1	232
5	185	0.96	19.52	20.4	127.9	256
6	184	0.95	19.19	20.16	126.3	315
7	165	0.85	10.48	12.33	97.7	244
8	168	0.87	11.21	12.89	98.6	198
9	191	0.99	19.86	20.08	127.3	254
10	192	0.99	21.77	21.9	132.8	266
11	181	0.94	16.16	17.21	114	285
12	159	0.82	13.48	16.44	113.5	227
13	153	0.79	11.32	14.32	105.6	176
14	188	0.97	16.18	16.68	114.7	286
15	184	0.95	15.95	16.79	116.3	233
16	185	0.96	16.18	16.85	116.1	290
17	184	0.95	19.52	20.54	129.9	258
18	160	0.83	11.32	13.64	104.5	261
19	160	0.83	13.81	16.64	116.6	233
20	202	1.05	20.8	19.81	135.7	339

Appendix II

East Indian Rosewood						
1	154	0.8	14.9	18.63	124	177
2	160	0.83	14.7	17.71	119.2	149
3	133	0.69	10.89	15.78	107.5	134
4	147	0.77	10.68	13.87	105	132
5	133	0.69	10.48	15.19	106	118
6	132	0.69	9.93	14.44	100.6	126
7	140	0.73	12.27	16.81	120.4	152
8	132	0.69	12.07	17.49	118.4	148
9	136	0.71	13.29	18.72	122.3	158
10	146	0.76	12.49	16.43	123.4	165
Chakte Viga						
1	181	0.94	18.26	19.43	123	176
2	157	0.82	14.52	17.71	118	168
3	179	0.93	17.69	19.02	122	174
4	187	0.97	20.22	20.85	124	177
5	185	0.96	19.52	20.33	123	206
6	182	0.95	19.19	20.2	124	177
7	167	0.87	18.26	20.99	126	210
8	159	0.83	15.3	18.43	119	171
9	192	1	19.19	19.19	121	172
10	166	0.86	18.26	21.63	125	178
Granadillo						
1	185	0.96	16.18	16.85	113	161
2	195	1.02	20.97	20.56	125	250
3	175	0.91	19.52	21.45	131	261
4	193	1.01	18.87	18.68	124	178
5	197	1.03	20.22	19.63	127	252
6	189	0.98	18.26	18.98	124	203
7	191	0.99	19.52	19.72	123	177
8	184	0.96	21.77	22.68	137	229
9	183	0.95	22.2	23.36	138	232

10	203	1.06	25.73	24.27	135	268
Ziricote						
1	208	1.08	13.17	12.19	98	164
2	211	1.1	13.98	12.71	99	165
3	174	0.91	12.72	13.98	106	211
4	177	0.92	13.01	14.14	106	176
5	195	1.02	12.31	12.05	99	165
6	178	0.93	12.87	13.84	106	151
7	204	1.06	13.48	12.72	101	202
8	199	1.04	13.32	12.81	99	99
9	177	0.92	13.48	13.32	107	178
10	177	0.92	16.85	18.26	105	176
African Padauk						
1	161	0.84	14.52	17.29	119	199
2	159	0.83	14.52	17.49	119	198
3	162	0.84	16.41	19.54	123	246
4	153	0.8	19.19	24.88	139	199
5	163	0.85	14.9	17.53	121	201
6	157	0.82	14.15	17.26	117	194
7	141	0.73	15.51	21.25	132	188
8	160	0.83	13.48	16.34	117	234
9	164	0.85	15.3	18	121	242
10	141	0.73	14.9	20.41	127	212

Glossary

Accelerometer	An accelerometer is an electromechanical device used to measure movement or vibration in solid objects for dynamic testing.
Anisotropic	Anisotropic describes a material that has different mechanical properties when measured in different directions.
CNC Router	A CNC router is an automated machining device that uses computerized instructions to determine the path of its cutting device, typically a rotating cutting bit.
Damping	Damping is the systematic reduction in vibrational oscillation amplitude due to energy loss from friction or transmission to another system.
Density	Density is the measurement of a substance’s mass for a given unit of volume.
Durometer	A Durometer is a device that measure the distance a steel probe can be pressed into a tested material using the pressure of a spring to measure surface hardness.
Dynamic Testing	Dynamic testing measures an objects response to a one-time impulse or continuous vibrational stimulation
Flat Sawn	Flat-sawn refers to lumber that has been cut so that the tree’s growth rings are parallel to the wide surface of the board.
Fundamental Frequency	The Fundamental Frequency is generally the lowest frequency of a wave form. This frequency defines the perceived pitch of a musical note.
Gigapascal (GPa)	A Gigapascal is an international systems of units (SI) measurement for pressure. One pascal (Pa) is equal to 1 Newton / meter^2. 1 GPa is equal to 1 billion Pa.
Megapascal (MPa)	One MPa is equal to 1 million Pa.

Impedance	Impedance is the resistance to vibrational energy transfer.
Impulse Hammer	An Impulse Hammer is used to tap objects during Dynamic Testing operations.
Inertia	Inertia describes an objects resistance to a change in its motion.
Mode of Vibration	A Mode of Vibration is a pattern of motion in an oscillating system that occurs at a defined frequency.
Modulus of Elasticity	The Modulus of Elasticity is the stiffness measurement of an object in a specified direction.
Modulus of Rupture	The Modulus of Rupture measures the amount of load required to break an object.
Moisture Stability	Moisture Stability is a measurement of an object's susceptibility to dimensional change due to changes in changing ambient humidity levels.
Node	The node is a location of zero vibration during a state of vibrating in a particular mode.
Q	*Q* is the symbol typically used to indicate a vibrational damping measurement.
Quarter-sawn	Quarter Sawn refers to lumber that has been cut so that the tree's growth rings run perpendicular to boards widest face.
Radial Grain Direction	The Radial Grain Direction in a tree is perpendicular to its center. See Quarter Sawn.
Rig	A Rig is device or apparatus constructed for scientific testing.
Rosette	The Rosette is the decorative inlay that typically surround a guitar's soundhole.
Soundhole	The Soundhole is the round aperture that is cut into a soundboard, typically at the end of the fretboard.

Specific Modulus	The Specific Modulus relates an objects modulus of elasticity to its density. This measurement is also commonly referred to as the strength-to-weight ratio.
Static Testing	Static Testing refers to a testing method that uses a fixed load to measure a response.
Tangential Grain Direction	The Tangential Grain Direction refers to the orientation of growth rings parallel to the trees center. See Flat Sawn.
Tap-tone	A tap-tone refers to the sound produced from physically tapping on an object.
Veneer	A veneer is wood that has been sliced thin for the purpose of gluing onto a surface to enhance the visual aesthetic.

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