Technische Universiteit Delft

Design of a composite guitar

Master Thesis Report

Max Roest

TU Delft

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by

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Summary

Today's acoustic guitars are getting increasingly expensive due to the worsening availability of the highest quality woods. Composites show great promise in replacing wood in acoustic guitars as they are lightweight, are not as sensitive to environmental effects and are much stronger. Current composite guitars however do not sound as good as their wooden counterparts. Therefore this thesis research has been set-up to create a composite material that can match wood acoustically and therefore have all the benefits in terms of environmental sensitivity and strength while not compromising the sound quality of the instrument. A new composite is developed and extensively tested. This composite consists of a carbon fibre reinforced polyurethane foam and has a comparable acoustic response to high quality spruce used for guitar soundboards. With this new composite a complete composite guitar is designed, manufactured and tested. The psychoacoustic analysis performed showed that the new composite guitar is considerably more wood like in its sound compared to current carbon fibre acoustic guitars.

Preface

Max Roest
Delft, July 2016

It is over 20 years ago that I received my first guitar. A few months later, at the age of 4, I had my first guitar lessons. Now at the age of 24, it is hard to remember any period in my life where guitars and music have not played a major role in my life. However, it is not only making and listening to music that interests me about this wonderful instrument. Understanding why guitars are built in a certain way and how a good sounding guitar distinguishes itself from a bad sounding one is still a mystery and keeps me looking inside the guitar body after I played some first notes.

Through my studies at the faculty of Aerospace Engineering at the Delft University of Technology, for me, the possibility to better understand guitars is now greater than ever. That is why, before even finishing my Bachelor degree, I approached professor O.K. Bergsma from the Structures & Materials department to discuss the possibility to conduct a Master's Thesis on the design and production of a high quality composite guitar.

Now almost three years later, I hand in this thesis report which contains a detailed description of the knowledge I have gathered on the topic of guitars and material acoustics relevant to musical instruments throughout the past year. My goal with this report is to provide a strong source of information for anyone with an interest in the topic of designing a musical instrument on a more scientific basis from either from modern composites.

During this past year I have had the pleasure of working with many amazing people. Without these people my project would have never achieved anything close to the goals that I can now proudly claim to have achieved. Therefore I would like to thank the following people.

Dr. Ir. O.K. Bergsma - For being the best supervisor I could have wished during this project. You have given me a great deal of trust and freedom to explore what I thought was most interesting and useful in my research. You were never too busy to listen to my latest updates, sometimes more than three times a day and acted amazingly quickly when I needed some urgent help.

C. van Erck - Thank you for being my lovely girlfriend who has shown to be an awesome and unmissable help in the lab too.

My parents Ada Brokers and Nico Roest - Thank you for buying me my first guitar at the age of 3 and everything that came after that.

Hans Pluk - Thank you for all the work you have done in correcting this report and helping me to bring the quality of this report and the research conducted to a higher level with your critical questions and thinking.

Fred Bosch - Thank you for all the hours you have helped me with my research and especially the complex production of the final guitar. Without your help the end result would by far not look this good.

Victor Horbowiec - Thank you for all the great help and tips during the past few months. Your extensive knowledge about the production of composites has taken away a great number of problems.

Gertjan Mulder - Thank you for helping me with your knowledge about testing and working with composites. More importantly I would like to thank you for your positivity that you radiate to others every day.

Frans van Oostrum - Thank you for helping and teaching me the fine arts of analysing and processing small samples and the fun talks during my second lunch of the day.

Other DASML technicians - A warm thank you to all other technicians, Cees, Johan, Bart, Berthil, Peter, Ed and Misja for helping me out with solving many of the tiny problems that occurred during the research.

Prof. Dr. Ir. R. Benedictus - Thank you for giving me the opportunity to design and produce two composite guitars. I value the trust that I received from you to bring this somewhat risky investment in this project to a good end.

Dr. Ir. F. Alijiani - Thank you for you support and dedication in bringing my project to a higher level. I consider it very special how fast you were able to help me out with one of the largest unknowns in my research, the damping analysis.

Luca Marinangeli - Thank you for the fun times building the LSV set-up and helping me out with your knowledge about vibrations.

Michael Greenfield - Thank you for answering my questions about the art of building guitars. Without your expert tips this guitar would not have sounded as good.

Thank you to the following sponsors and companies:

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Matthias Schubert (Toho Tenax) - Thank you for the sponsoring of the carbon filament and the lightning fast delivery.

Rohacell - Thank you for providing me with foam samples for the production of the sandwich panel.

Note to reader

This thesis report is written with a broad audience in mind. This is done to not only provide the research community with a detailed report but also consider builders of musical instruments which often have considerably less experience with the engineering terminology used.

The storyline of this thesis begins at the very broad question of how to change the sound of an instrument. The literature review presented in part one is therefore included in this thesis report as it provides the necessary scoping to understand the starting point for the main thesis content in part II and part III. Readers well-known with the engineering parameters relevant to structural mechanics and dynamics are therefore advised to read chapters 4 and 7 from part I as the other chapters provide a basic explanation of several engineering parameters and their respective measurement strategies.

Contents

1

Introduction

"I'm gonna make another little newsflash for all you guitar players out there. That beautiful two-piece top that you have, with really perfect grain, that's bit of vanity that we're all gonna have to shed pretty soon"

- Bob Taylor, Taylor Guitars -

Within ten years, the deforestation in Alaska will have reached a level that will introduce a huge problem for the worlds largest guitar building factories. The availability of high quality spruce tops for guitars will become extremely low requiring guitar builders to either raise their prices significantly or offer a different solution. In 2007, Greenpeace started the Musicwood association to bring together Martin Guitars, Gibson, and Taylor guitars to start a campaign and try to convince Sealaksa, the largest owner of forests lands in Alaska, to obtain FSC (Forest Stewardship Council) certification [1]. Although these guitar building factories are extremely small in comparison to other buyers of wood with only 150 logs a year, they are hurt the most by the increasing scarcity of high quality woods as only one in many logs is suitable for guitar building. Especially these old-growth larger trees are disappearing at an alarming rate.

The Musicwood coalition sadly was not successful in their campaign. Sealaska, although Native Americans are supposedly close to the "forces of nature", put their commercial interests above the sustainability of their forests and did not continue their efforts to obtain FSC certification. The result will be that guitar builders will need a different solution in the nearby future to replace their guitar tops.

For other components of the guitar such as the back and sides the story is similar. It was only a few decades ago that Brazilian rosewood was considered the number one wood for building guitars [2]. Known for its characteristic 'ring' and astonishing appearance, guitar builders all over the world were on a constant search for this superior wood. However, guitar builders were not the only ones looking for these types of tropical hard woods. Furniture, building and energy industries were also seeing an enormous increase in demand for these woods. Additionally farmers removed many of the trees to free up land for the increasing demand of agricultural products [3, 4]. The scale of their operations dramatically increased to a level that deforestation of the South-American tropics became unacceptable in the light of climate change effects and the need to protect of species of flora and fauna [5].

The problem found its way onto the radar of the government of the United States, which introduced a number of regulations to try and limit deforestation [6]. The most important one of these regulations for guitar builders being the Cites regulation [7, 8]. This imposed two big constrains on the world of musical instrument and especially guitar building as high quality guitars were predominantly made of tropical hard woods. The first constraint being the procurement of the correct Cites paperwork to be allowed to use the obtained wood for instrument building. As a large amount of the woods previously came from unspecified sources or sites, it is practically impossible to obtain the required certification. A second constraint is the reduction in availability of high quality straight grained woods suitable for instrument building. Whereas highly irregular grain patterns are often considered a positive visual feature on furniture and other wood products, for building guitars these woods are often untouched by luthiers because of their inferior acoustic properties [9].

New developments in the field of plastics and composites show possibilities to apply these materials in the field of musical instruments building. Nowadays a number of new companies have taken up the challenge of building high quality composite instruments [10]. Most of these instruments are made of carbon fibre reinforced plastics. While some of these instruments sound reasonably well, they do not have the same character as their wooden counterparts. The sound of these composite guitars is often considered 'brittle' caused by a dominant high end and high frequencies overtones [11]. Additionally carbon fibre guitars have a longer sustain uncharacteristic for traditional instruments as wood has considerably higher damping.

Composite instruments have a very large benefit over their wooden counterparts in terms of stability. Every year, many stories pop-up on the news about instruments being crushed during luggage handling at airports [12]. The risk of flying with an instrument is very high as airlines often prove to be unwilling to support artists by offering them the possibility to carry-on their instrument in the passenger cabin. With professional level guitars ranging from 3,000 EUR to over 40,000 EUR and some violins running into millions of Euros, this is a gamble most artists would rather refrain from [13]. Companies are jumping into this market by offering composite travel guitars which are able to withstand much higher loads than conventional guitars and practically ensure to be undamaged during handling.

The stability also comes in the form of environmental sensitivity. Wooden guitars are very sensitive to temperature and relative humidity changes. Fast temperature fluctuations cause uneven expansion or shrinkage of the instrument which has the potential to cause local stress concentrations cracking the lacquer or in some cases even the wood itself. High relative humidity above 60% introduces unwanted high damping of the instrument as the moisture content in the wood increases. Low relative humidity below 35% can induce stress concentrations similar to those of temperature changes causing cracking of wood or the detachment of internal components such as braces [9]. Composite instruments on the other hand are hardly affected by temperature and humidity [14]. Not having to worry about the relative humidity of an instrument can be a huge advantage both for the regular customer as well as the touring artist. Rainsong guitars, one of the major producers of composite guitars, even went as far as to use one of their guitars as a rowing paddle in an advertisement campaign as shown in Figure 1.1.

Figure 1.1: Rainsong advertisement illustrating the low environmental sensitivity of composite guitars by using it as a rowing paddle [15]

While composites have a large advantage in terms of stability, uniformity and sustainability compared to wood the most important requirement, the tonal quality of the instrument, is not satisfied. For this reason composite guitars are no real alternative yet for a high quality wooden guitar. To investigate the possibility of closing the gap in acoustic qualities of composite and wooden guitars a research thesis is set-up .

This first part of this report serves as an investigation into the academic research performed into the acoustics of materials and musical instruments. The knowledge obtained will be used to define a concrete research objective for the main thesis following the literature review. The literature review is build up as follows. First, a general introduction to modern steel string guitars is provided to investigate the developments the guitar has seen towards its current state today. Additionally the terminology and general sound producing system are introduced to provide the reader with the required knowledge to understand the following chapters and discussions. After the general introduction to guitars, the levels at which the acoustics of instruments can be modified will be discussed. From this the research scoping will be performed resulting in a concrete research objective and plan.

The research objective and plan will include several research questions that will be partially answered in the detailed literature review following the research scoping and more elaborately covered in the main thesis. The detailed literature review will cover an in-depth analysis of the parameters that modify the acoustic properties of musical instruments and will also provide analysis and measurement methods for these parameters. The analysis methods will form some of the basic methodology for the main thesis. At the end of the first part of this report, a short list of material options to be investigated in the main thesis is presented which is found using the information obtained in the previous chapters.

The main thesis body consists of two parts, part II and part III. Part II describes the process of the development of the composite. Additionally the final chosen composite is analysed on several aspects and checked against the requirements as set-out at the end of the literature report presented in part I. Part III of this report describes the design, production and psychoacoustic testing of a complete composite guitar. More detailed introductions will be provided at the beginning of each of the respective parts.

This report is written with a broader audience in mind. As many people involved with the field of guitars and acoustics do not have the same basic engineering knowledge, an attempt is made in this report to provide a minimum of knowledge about the engineering principles such that a reader previously unknown with the concepts will be able to follow the design process.

I

Project scoping and literature review

2

Introduction to modern steel string guitars

2.1. Origin of the acoustic guitar

As the start for this literature review, an investigation is conducted into the origins of the acoustic guitar to better understand the design choices and resulting construction of today's guitars. The origin of the modern acoustic steel string guitar as it is known today can best be understood by looking at three main time periods. First is the period of the early ancestors of the guitar from ancient times until the introduction of the Spanish gut and later nylon stringed guitar. The second period runs until the introduction of the American steel string guitar. Finally the American steel string guitar has seen a number of important developments to arrive at the common acoustic steel string guitar used by most artists and enthusiasts today.

2.1.1. Early history of the guitar

The first instruments that have a similar structure and sound producing system as today's guitars are the bowl harps and tanburs that were used by the ancient Babylonian and Egyptian civilisations over 4000 years ago [16]. Markings on Egyptian tombs and stone carvings show these instruments being played in ensemble with flutes and percussion instruments. The main difference between a guitar and these ancient instruments is the neck angle of these ancient instruments which was often curved or perpendicular to the body of the instrument. Dr. Kasha defined the guitar as an instrument with a long fretted neck, flat wooden soundboard, flat back and incurved sides [17].

The first instrument that can be classified as guitar-like was found in an Egyptian tomb for Sen-Mut who was the architect for the Queen [16]. Sen-Mut employed the singer Har-Mose who was buried close to his employer together with his tanbur as well as with his three string guitar. The instrument can still be found in the Archaeological Museum in Cairo. Although this instrument has a long fretted neck as well as a body largely made of wood, the soundboard was made of rawhide and the back was not flat. The first guitar known to satisfy all criteria by Dr. Kasha was seen on a 3300 year old stone carving in Turkey as shown in Figure 2.1.

The tanbur has seen a different development in the Arabian countries. The proportions of the instrument have largely changed featuring a shorter neck and much larger body as shown in Figure 2.2 [18]. The Moors brought their tanbur-like instrument which they called the "oud" to Spain where it obtained its European name "lute". This name is derived from the Arabic "Al'ud" which literally translates to "the wood" referring to the wooden construction of the instrument.

From Persia another influence migrated to the European musical instrument field with the family of "Tar" instruments. "Tar" literally translates to "string" and these instruments had names including the number

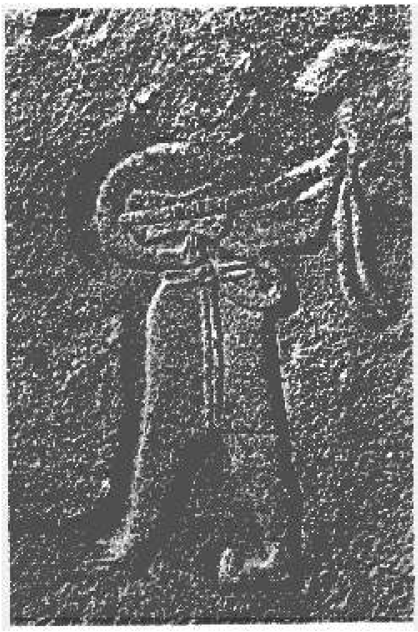


Figure 2.1: Stone carving at Alaca Huyuk in Turkey, of a 3300 year old Hittite "guitar" [16]

Figure 2.2: Picture of a lute showing the large body size compared to the neck.

of strings in the prefix such as Dotar (two stringed instrument), Sitar/Setar (three stringed instruments and Chartar (four stringed instrument). Travellers and merchants brought the persian Chartar to Spain where it evolved into the quitarra or chitarra. Unlike the Chartar, these instruments had not single but double in unison tuned strings. The five-course guitarra first appeared in Italy and had a very similar tuning to today's concert, flamenco and steelstring gutiars (A,D,G,B,E). Modern six-strings guitars incorporate another base string tuned to an E above the A of the five strings of the guitarra battente.

2.1.2. First gut-stringed and nylon string guitars

It was only in the 17th century that the first six course guitarra battente was introduced which led to the first six single string guitars in the 18th century. These instruments were often constructed by adjusting the nut and saddle of existing five course guitarra battentes. At the beginning of the 19th century the classical guitar as we know it today took shape. The neck length of the instrument increased while the body still remained fairly small.

Around 1850, Spanish guitar maker Antonio Torres increased the size of the body of the six stringed guitar and introduced the fan bracing system which made guitar sound very direct and punchy [9]. This was ideal for the flamenco music that was played in small cafés all around Andalusia and later also in Madrid.

2.1.3. North-American steel string guitar

Around the same time, German immigrants in the US developed the first steel string guitars. These guitars were designed to be much louder than their nylon stringed counterparts. However the enormous tension introduced by the steel strings on the soundboard of the guitar didn't allow for a stable instrument. Several solutions were tried but mostly yielded the same result of obtaining a far too crisp and brittle sounding guitar due to the large amount of reinforcement material to be displaced by a small amount of energy of the strings.

A solution was found around 1900 by Christian Fredrich Martin in the form of the X-brace as shown in Figure 2.3. This bracing pattern provides the necessary stiffness to withstand the tension and moment generated by the strings on the bridge and soundboard without limiting the acoustics of the instrument. This can be explained by the fact that the X-brace does not significantly suppresses the lower modes and thus lower frequencies of the soundboard in comparison with other bracing systems [9]. Modern steel string guitars still incorporate the X-brace design but vary greatly on other aspects such as secondary braces, guitar body shapes as well as scale-length.

Figure 2.3: Martin & Co. x-brace style bracing pattern used for most acoustic steel string guitars [19].

Later on, another change with respect to classical and flamenco style guitars was made. The neck length was increased slightly for steel string guitars and therefore the steel string guitar has 14 frets to the body compared to the 12 frets to the body on a flamenco or classical guitar. Although Martin is also credited for this change [20], some sources claim that Gibson was the first to introduce the 14 fret to body guitars [21].

2.2. Components of the acoustic guitar

In order to understand the acoustics of the guitar, it is important to understand the breakdown of components as well as their respective functions. In the following two subsections an overview of the components of the acoustic steel string guitar will be presented and the main sound producing system will be explained. Both these subsections will be an important basis for this research thesis as the knowledge will be used to understand the critical changes that changing the material from wood to composite will introduce. This will be further elaborated on in subsection 6.3.1.

2.2.1. Overview of components, features and terminology

In Figure 2.4 an overview of the externally visible components and features of the modern acoustic steel string guitar is presented. Each of the components in Figure 2.4 will be discussed below [9, 22].

Figure 2.4: Main overview of components of the acoustic guitar.

Soundboard/top The soundboard or top is the main front facing component of the guitar on which the bridge and fingerboard are mounted. It is only about 2.8-3.2 mm thick and is typically made of materials such as spruce or cedar which have a very high stiffness compared to the density. Typical values are around 10-12 GPa for the Young's modulus and a density of around 450 kg/m^3. The reason for this choice of wood will be further investigated in chapter 5.

Bridge The bridge is a component that is glued on the soundboard to which the strings are attached. This involves either a pinned or pinless design as shown in Figure 2.5. The bridge is often made of a much denser hardwood compared to the soundboard. High quality guitars often have an ebony wood bridge which typically has a density between 900-1150 kg/m^3 [23]. This type of wood is chosen as it is very efficient in transmitting the vibrations from the strings to the soundboard [9].

Figure 2.5: Photos of a pinned bridge (left) and a pin-less bridge (right)

Saddle The saddle is a small piece of material that is placed into the bridge and holds the strings in place with small slots. As the saddle is the main interaction component between the strings and the bridge it also is made of a relatively high density and efficient vibration transmitting material. In the early days of steel string guitar development the saddle was often made of ivory [24]. As this material became very controversial due to the large number of animals illegally killed for their ivory, most large guitar builders switched to other materials such as fossilized ivory and bone.

Sides The sides of the guitar are the rigid frame that allows for vibrational interaction between the back and soundboard of the guitar. The curved shape has two main functions. It provides a very stiff and stable structure and at the same time allows for a more ergonomic instrument compared to a square box type of body. The contribution of the sides to the overall sound of the instrument is relatively low. Therefore more visually appealing woods of lower acoustic quality are typically used. Often these are matched to the woods of the back. Common woods are maple, mahogany and walnut for more economical guitars whereas more expensive guitars may be build with rosewood, blackwood, koa and other more exotic woods [9]. As some of these exotic woods are very expensive, the sides are often laminated with a more economic wood type to allow for both the visual appearance and necessary stiffness while limiting the cost of the instrument [22].

Back The back of the guitar is often made of the same woods as the sides. While guitar design has focused mainly on the soundboard and the different bracing patterns, recent developments in the design of the acoustic steelstring guitar also focus more on the back design. Additionally the interaction between the back and soundboard is investigated more to improve the air column efficiency. This will further be explained in chapter 6.

Neck The neck of the guitar makes the connection between the headstock and the body of the guitar. Due to the string tension, a load as well as a moment is applied on the neck. Therefore the neck is made of a solid piece of wood which for most guitars is mahogany. Additionally the neck houses the truss rod which is a long steel or carbon fibre reinforced plastic element of which the function is explained below. The profile or shape of the neck is considered to be very important for the playability of the instrument. While typically steel string guitars have a smaller profile compared to nylon string guitars, recent development into neck profile design has seen a shift towards a more bulky neck as used for nylon string guitars to accommodate fingerstyle guitar players [9].

Fingerboard The fingerboard, also called fret board, is a thin component glued on top of the neck and the body which houses the frets. The strings are pressed against the fingerboard to produce sounds with different frequencies. The fingerboard in high-end guitars is typically made from ebony as the part is required to be more abrasion resistant [23]. A more economic alternative is the use of other Rosewoods for the fingerboard.

Headstock The headstock, also called peghead, is the component on which the tuning pegs which tension the strings are mounted. It is typically placed at an angle of 15-20 degrees to the fingerboard to ensure the strings are pressed properly against the nut.

Nut The nut is a component similar to the saddle over which the strings are tensioned at the end of the neck. It is made of the same material as the saddle.

Truss rod cover The truss rod cover is a small piece of wood that covers the adjustment pin of the truss rod inside the neck. While some guitars have the location of the adjustment pin pointing to the inside of the guitar body, several guitar designs feature a truss rod which can be adjusted on the head stock. The truss rod cover is a simple visual feature to improve the overall looks of the guitar and is connected to the head stock by either a fastener or a magnet system.

Cutaway The cutaway is a feature of the acoustic guitar allowing the player to access the higher registers on the fret board more easily. It is very common for acoustic guitars to have a cutaway while for nylon stringed instruments this feature is rather uncommon.

Rosette The rosette is a visual feature around the sound hole of the guitar. It is a feature that has been transferred from classical guitar building and is often a personal design feature of the builder of the instrument.

Strings The strings of the instrument are made from steel or other metal compositions. There are different thicknesses available for guitar strings ranging from very light to heavy gauge to accommodate different playing styles [25]. Some strings are coated to increase the lifespan as most strings are quickly damaged when being played [26]

Binding Binding is a visual feature that covers the edges of the guitar body where the top or back meet the sides of the guitar. To create a good-looking edge, the connection is partially trimmed and a liner of a different material is used.

The main internal components of the acoustic guitar are shown in Figure 2.6 and will be discussed below including their function.

Braces The braces in a guitar provide structural integrity to the thin soundboard as well to the back of the instrument. The large load applied by the strings cannot be carried by the soundboard alone. The braces help to distribute the stress over the full soundboard and make a better coupling with the sides and back. Additionally bracing has seen the bulk of developments and research in the design of the guitar. Voicing of the soundboard which is done by modifying bracing patterns and brace dimensions is considered the most important element of building a good sounding guitar. This will be explained further in chapter 6.

Truss rod The truss rod is the element responsible for keeping the neck straight. Most truss rods are adjustable and involve two pieces that can be tensioned such that the moment caused by the strings is counteracted less or more. In this way the slight curvature of the neck can accurately be modified such that the height of the strings above the fingerboard is optimal for playability. Additionally an optimal spacing between fingerboard and strings makes sure the intonation of the instrument is optimal.

Neckblock The neckblock is the component that allows for the attachment of the neck to the body by means of a dovetail or similar wood connection. It is glued firmly against the sides, back and top of the guitar to ensure proper load transfer and is often made of the same material as the neck.

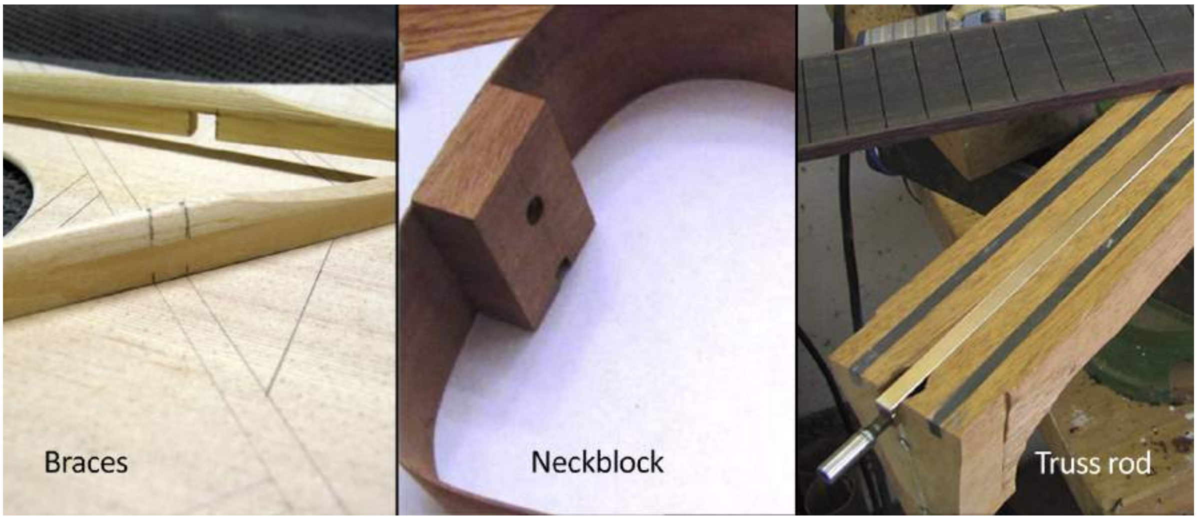


Figure 2.6: Photos of the main internal components of the acoustic guitar which are not externally visible. From left to right, braces, neckblock and truss rod.

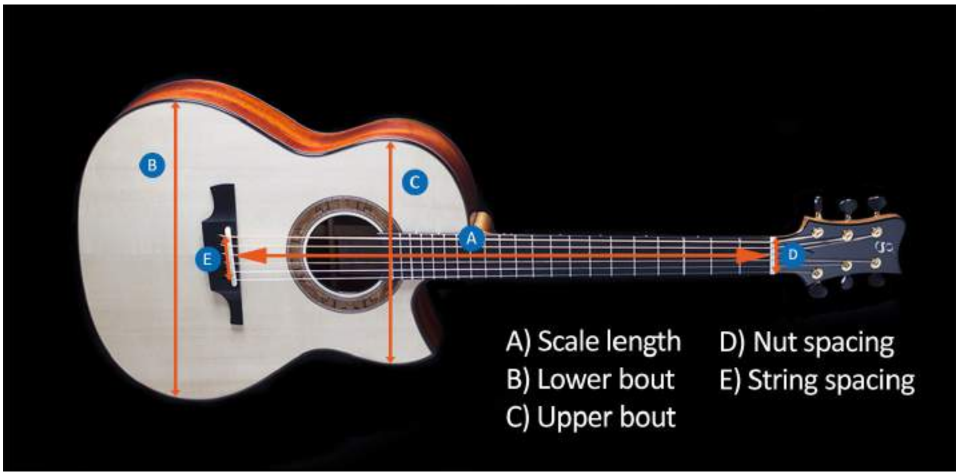


Figure 2.7: Photo of Greenfield guitar indicating the main dimensions and design parameters.

In addition to the main component names, a number of dimensions are of importance when discussing the different design parameters of guitars. These are shown in Figure 2.7

Scale length The scale length defines the length of the vibrating part of the string from the center of the nut to the center of the bridge. This length can vary between guitars from about 24-7/8" (630 mm) to 26" (660 mm) [27, 28].

Lower bout The width of the bottom curve of the guitar body. For a traditional guitar this is always the widest part of the guitar.

Upper bout The width of the upper curve of the guitar body.

Nut spacing The nut width indicates the string spacing on the nut measured from the first to the sixth string. Typically this is around 43 mm [9].

String spacing The string spacing is measured at the saddle on the bridge. The spacing is larger than at the nut and is typically slightly bigger than 60 mm [9].

2.2.2. Sound producing system

The sound producing system of a guitar is a complex system. In this section the basic mechanisms for the sound production are explained. However, it should be noted that in reality the vibrating components of a guitar have a continuous effect on each other. Therefore modelling the sound producing system after this basic description would likely yield very different responses compared to real life tests.

The sound producing system is explained with the aid of the steps below [9]. The system as explained by the steps below considers an instrument with a single string. The difference between a single- and multi-string system will be explained after the introduction of the single-string system.

1. **The player plucks/plays a string on the guitar**. The string starts to vibrate at its base frequency according to the tension, length and mass of the string. Additionally the string vibrates at multiple higher modes that have a frequency of n (1,2,3,..) times the base frequency. Depending on the location where the string has been plucked, the balance of the base and higher modes can be very different. Higher modes are more easily excited when the string is plucked near the bridge, giving a sharper and more punchy sound while plucking the string closer to the center of the string accentuates the lower modes more and will therefore generate a warmer and fuller sound.
2. **The string vibration is transferred to the saddle on the bridge**. The saddle transfers the vibration which causes it to apply a force on the bridge.
3. **Due to the force the bridge starts to move and vibrate**. This happens in three main modes as shown in Figure 2.8. All modes have a different effect on the sound and therefore can create a different sound if the balance between the modes shifts for example by a different bracing pattern. Therefore a flamenco guitar can sound drastically different than a classical guitar.
4. **The vibration of the bridge is transferred to the soundboard of the guitar**. The soundboard vibrates in many modes like the string. The design of the soundboard and the bracing pattern cause it to filter certain frequencies more than others by which the sound of two guitars can be very different. The balance between the different modes and the frequencies at which certain modes occur determines the timbre or character of the guitar.
5. **The vibration energy of the soundboard is transferred to the air**. The sound energy is transferred through the energy both away from the instrument as well as towards the back of the instrument. Additionally a part of the vibration energy is transferred via the sides of the guitar to the back of the guitar. The soundboard loses most of its energy by radiation of sound energy directly outwards. Therefore it is also the most important component in the sound producing system as it is responsible for the largest portion of the sound character [9].
6. **The back becomes part of the sound producing system by the energy transferred via the air in the body and via the sides**. Particulary in the past few decades, a number of luthiers have made huge developments in activating the back as a secondary soundboard and getting a much more responsive instrument in the process [9]. Some guitar designs will however still consider the back purely as a reflector instead of a coupled system with the soundboard [29].
7. **The air is pumped out of the body through the sound hole**. Recent developments have seen that the back and soundboard should work as an effective air pump. This is done by designing the relative compliances of the soundboard and back in such way that they work together instead of working against each other [9].

Energy is exchanged between the different components and the air until the total vibration energy is transmitted to the air or lost by friction damping in the system. The system presented above is only the linear system while in reality the interaction between all components is continuous and cannot be described by looking at these components separately and is thus non-linear. Referring back to the initial statement in this section that the sound producing system is a much more complex system can be illustrated by the following example. When a certain string is played on a guitar, each of the other strings will resonate with the played

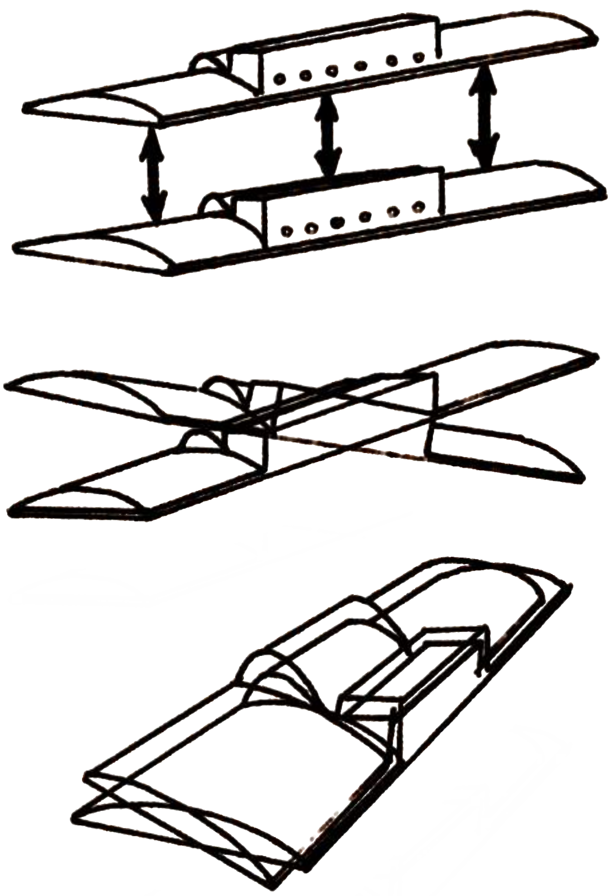


Figure 2.8: Three main bridge vibration modes, Figure modified from [9]

string. When damping the played string immediately after being played one can hear all the other strings and their respective sound producing systems. The strings will vibrate in different modes which will be either the same frequency or n-modes higher than the originally played string. This illustrates that, although for the first few milliseconds a single stringed instrument might follow the basic model described above, the guitar can only be described as a highly dependent and iterative system. As this is very complex, the components of the guitar are often described separately and also designed with their specific function in mind rather than designing the instrument as a whole. With increased computer power and knowledge about the guitar, attempts are being made to design the instrument as a system and have the different components work together [30, 31]. Especially with the move towards carbon fibre and other composite musical instruments, many companies are redesigning their instruments as a system rather than only changing the material of an existing guitar design [32].

2.2.3. Relative importance of the guitar components in producing sound

In order to understand on which components to focus when designing a composite guitar it is important to understand the relative importance of the components. Most sources describe the soundboard to be the most important contributor to the sound [9, 33]. It has a direct influence when transmitting sound energy to the surrounding air and additionally performs the interaction with the back to create the air pump functionality of the body. After the soundboard the air column design itself is the most important contributor to the sound. Therefore great care is taken into the relative stiffness of the elements of the body to ensure they are compliant enough to work together but stiff and strong enough to withstand the forces of the strings on the guitar. Finally the back of the guitar adds to the overall sound of the guitar but has a much lower influence than the soundboard as it is not directly in contact with the bridge/saddle and therefore only contributes indirectly.

A common misconception is that the sound is coming from the strings itself. While the energy is transmitted by the strings, the strings do mostly contribute indirectly by transferring the energy to the guitar body components. The same holds for the neck which vibrates slightly but is not designed to be an effective radiator of sound energy [9].

2.2.4. Fingerstyle guitar and recent developments

The wish to design a better guitar has, in recent years, mostly been driven by the fingerstyle guitar community. Fingerstyle guitar is a genre within acoustic guitar music that aims to make the guitar a capable solo performance instrument. This is achieved by playing all the parts of a musical composition that usually would be performed by a band on just one guitar resulting in a number of requirements on the instrument. The need for a more responsive instrument came from the fact that the traditional guitar bodies were not optimal to present the definition of different tones generated. Most of the sound becomes cluttered by which separate notes are not distinguishable anymore which negates the goal of fingerstyle music: to make the guitar sound as a one-man band. Many developments have been made on the voicing and bracing of acoustic steel string guitars to make them able to respond better to many more tonal inputs without becoming cluttered.

Another requirement is introduced by the percussive elements of fingerstyle guitar. The guitar is commonly used as a drum and has to withstand different impact forces on the body which sometimes requires additional reinforcement to be placed as shown in Figure 2.9. The challenge in this is to make the instrument capable of withstanding these forces without affecting the tonal balance of the instrument.

Figure 2.9: Fingerstyle guitartop by Marc Beneteau showing the additional patches to reinforce the soundboard against the impact of percussion on the guitar body [34].

Fingerstyle guitar also does not limit itself to the standard pitch tuning of the classical guitar (EADGBE) but opens up a whole new range of new tunings in which mostly strings are tuned lower compared to standard concert pitch. The accommodate for this, fanned fret guitars are designed with base strings which are longer and therefore better capable of producing a stable tone when the strings are tuned lower. An example of a fan fret guitar is shown in Figure 2.10.

Figure 2.10: Michael Greenfield G4.2LT model guitar with fanned frets has longer base strings and shorter trebles causing the frets to not be perpendicular to the neck direction.

2.3. Currently produced composite guitars

A number of composite guitars are already available on the market today. In this section the most well-known composite guitar manufacturers are introduced. Additionally a baseline for the pricing of the instruments is considered which will be used as input in the main thesis in consideration of the potential market of a newly developed composite acoustic guitar.

2.3.1. Rainsong Guitars

Rainsong guitars are the market leader when it comes to composite guitars. They offer a wide range of carbon fibre and graphite guitars ranging from 1800 EUR to about 4000 EUR. The sound quality of the instrument is considered fair. In Figure 2.11 a photo of the productline of rainsong guitars is presented.

2.3.2. Ovation Guitars

Ovation guitars is one of the largest manufacturers of acoustic guitars worldwide. In their product range they offer a hybrid model with a soundboard made of carbon fibre twill weave as shown in Figure 2.12. Additionally Ovation Guitars offers many guitars in their model line with the back bowl made of Lyrachord. This material is said to be a glass fibre composite although no sources are confirmed by Ovation [35].

Figure 2.11: Photo of the product range of carbon fibre and graphite guitars by Rainsong Guitars [15].

Figure 2.12: Detail photo of the carbon fibre top of the Ovation Adamas guitar [36].

2.3.3. Composite Acoustics

Composite acoustics is a large manufacturer of carbon fibre guitars. They offer a similar range of guitars as Rainsong guitars with the price range of their instruments matching those of Rainsong guitars.

2.3.4. Other composite guitar manufacturers

In addition to the major producers of composite guitars mentioned above there are several smaller producers of composite guitars. These producers mostly focus on different guitar designs and travel guitars which appears to be a good market for composite guitars. Like the guitar options above, most of these guitars are made of either carbon fibre unidirectional layers and two directional weaves or panels of graphite. Prices range from around 1200 EUR to 5500 EUR.

3

Levels of sound description and modification

3.1. State of the art / Literature review

To understand the implications of replacing wood in musical instruments by composites it is necessary to have a structured overview of the levels at which acoustic behaviour of musical instruments can be manipulated. Summarizing literature, it appears that there are four main levels on which acoustics can be changed. These are the micro material level, the macro material level, the structural level and the external level. The goal of this section is to provide a short overview and analysis of each of the levels. By doing this, the thesis work can be scoped towards the levels or areas that are found to be most promising in achieving the goal of designing a composite guitar with sound quality equivalent to a wooden guitar.

3.1.1. Micro material level

Sound waves require a medium to travel through [37]. The energy of the wave is transmitted to a neighbouring particle which in turn does the same to the adjacent particles. Due to the different masses and connection strengths between particles, there is a large difference in the speed at which a sound wave can travel through a respective medium [37]. For perfect isotropic, homogeneous and single structure materials this would give predictable results. However most materials have a number of imperfections such as dislocations, misalignment of atoms or a non-even distribution of molecules. These all have implications for the propagation of waves in a medium and therefore for the overall acoustic properties [38].

Research on the acoustics of materials on micro material level is scarce. Most research revolves around theoretical and complex mathematical models that aim to predict wave propagation in media [39]. The required level of computational power and the non-linearity of most models makes it very hard to make a proper comparison with test results. Additionally the difficulty of making changes to the micro material level is very high and expected to provide a much smaller influence than the changes that can be made on macro material or structural level. Therefore it has been decided to provide limited attention during the main thesis to the micro material level as it will have minimal impact on the development of a composite guitar with similar acoustic properties as a wooden guitar.

3.1.2. Macro/bulk material level

The macro material level is where selection of materials takes place. At this level it is possible to make a one-to-one comparison with wood and composites in terms of acoustic properties as long as the analysed structure remains simple. From research it appears there are a number of material parameters that collectively determine the acoustic properties of materials. These macro material properties are stiffness, density and internal damping. These parameters will be introduced below.

The stiffness of a material has a large influence on the acoustic properties [40]. Together with the density it determines the speed of sound in a medium [37]. Additionally the stiffness is strongly related to the mechanical damping and the visco-elastic response of materials. On the website of visco-elastic materials specialist R. Lakes the influence of these three material parameters is demonstrated on the acoustic properties of tuning forks of the same size but manufactured from different materials [41]. The experiment shows that stiffness and density together determine the frequency of the tuning fork while the internal damping is largely responsible for the duration of the tone and tone timbre. In literature, timbre is described as the main parameter that influences how we perceive sound at a certain frequency and allows the human ear to distinguish between the sound of a piano and a guitar. This difference in sound can be explained by the relative contributions of the fundamental tone and overtones produced when generating the overall tone of the instrument. When comparing a wooden and carbon fibre guitar this is caused by the different internal damping of both materials [42] as well as the different stiffness in longitudinal and transverse direction resulting in different frequencies at which the fundamental and overtones occur. Therefore certain overtones that might be close to resonance frequencies of a wooden guitar might not be close to resonance frequencies of a carbon fibre guitar. This results in a different amplitude of the overtone and therefore a different contribution to the overall tone of the instrument.

The internal damping coefficient is often expressed as a single number [43]. While the internal damping is practically constant for very low frequencies, far outside of what the human ear and brain perceive as sound, it has a large frequency dependency at higher frequencies [43]. Most research on internal damping is focused on determination of glass transition temperatures of polymers [44]. The internal damping has a distinctive peak at the glass transition temperature and is therefore extremely useful in research requiring information about the glass transition temperature. However very limited research is performed on internal damping at higher frequency regions. The reason for this is twofold. The high frequency range is of limited interest for most applications of materials. Secondly, measurements of high frequency damping poses a large challenge in designing equipment suitable to perform dynamic mechanical analysis tests at very high frequencies [45].

As the main aim of this thesis is the replacement of wood as the primary building element for musical instruments and in particular guitars, a good understanding of the macro material properties and their influence on the acoustics of a material appears to be a promising level to research.

3.1.3. Structural level

On a structural level a relatively small change in a component of a guitar can have a very large influence on the acoustic properties of the instrument [9]. The structure of a musical instrument determines the distribution and radiation of energy to the air and the human ear. A simple example is the difference between a banjo and a guitar sound. The top of a banjo, often a thin stretched material, generates a much louder but shorter sound compared to acoustic guitars even though the overall principle of the strings, neck and body is similar. This can be explained by the small amount of energy needed to excite the low weight banjo top in comparison with a heavier guitar top. Therefore the banjo top is more responsive which indicates that it reaches high amplitudes faster and is more effective in transferring the sound energy to the air.

Specifically for guitars there is a relative importance of the components considering the acoustics. Most sources agree that the soundboard (the top) is the main element responsible for transferring energy to the air followed by the air column inside the guitar and completed by a small influence of back and sides [9]. Therefore in designing a guitar, most effort is placed on a proper design and 'taptone' of the soundboard which is achieved by complex bracing patterns as shown in Figure 3.1. These braces are modified by scraping away material with tools until the builder achieves the desired acoustic properties [33]. The process of obtaining the right tap tone for the soundboard of a guitar is often not science based but rather based on the years of experience of the guitar builder. This experiences guides him or her in making the correct decisions with respect to removing material in certain areas of the braces.

Figure 3.1: Barcing pattern of a modern fingerstyle steelstring acoustic guitar by Marc Beneteau [34]

There is a relatively large amount of research around the influence of bracing patterns and the corresponding modal patterns of a guitar top [46], [47]. However most research fails to make a strong connection between the smaller scale or component tests and the overall effect on the instrument. Therefore most research could be considered interesting knowledge for guitar builders, but does not allow for the prediction of the acoustic properties of an instrument built according to the specifications laid out in research articles.

Interestingly, on the topic of the role of the back of the guitar on the overall sound there appears to be very mixed positions within the community. Somogyi describes in his books the importance of a responsive back to assist the soundboard and help to create a solid air column tone [9]. Others see the back purely as a reflector and consider it to be there to ’keep the dust out’ [29]. A simple experiment shows however that the back of a guitar can have a large influence on the overall acoustics of the instrument. By leaning against the back of the guitar, one can dampen the vibration of the back with a clear effect on the warmth and fullness of the sound produced. This indicates that while many people claim to have researched the topic of guitar building, a scientific basis is often lacking.

Although the structural components of the guitar can have a significant influence on the overall acoustic properties of the musical instrument, the enormous amount of freedom in the design creates a too large design space to cover in this research thesis. Therefore the structural level will only be studied in understanding the mechanics of a conventional guitar and the implications in the production of a composite guitar requiring to evaluate the potential difficulties. For the research thesis, it is assumed that the structural level has limited influence as long as the guitar design and interaction of the components remains largely the same.

3.1.4. External level

Finally the external level describes the influences on the sound that are not directly linked to the instrument. Most prominently are the musician playing the instrument, the effects of the room and potential electronic amplification and effects [48, 49]. While these effects are extremely big, especially when considering the art of recording musical instruments, it is only indirectly linked with the musical instrument material choice and therefore in this case of lower interest. A potential solution to remove the differences between a composite and wooden guitar would be digitally modifying the musical input signal to create a tonal character. However this is considered out of scope due to the lack of research value in the field of materials and structures engineering and bad repeatability with regards to different instruments.

3.1.5. Relevance to research project

From the analysis of levels to modify the acoustics of musical instruments it appears that in the case of moving to composite instruments, the macro material level is the most promising level to research. While there has been done some work on the acoustics of composites, there has been limited results in creating a composite capable of competing with wood on an acoustical level. Therefore the research goal and the research questions will largely revolve around this macro material level.

If the research thesis is extended towards the full scale development of a composite guitar, the structural level will have to be investigated in more detail. Therefore, to aid in the possibility of developing a full composite guitar for validation of the research conducted, the structural level will also be studied in more detail in this literature review.

4

Project research plan

4.1. Research question, aims and objectives

With the current status of research in the field of musical instrument acoustics as discussed in the previous sections and the current drawbacks of wooden instruments, the research objective can be established.

The research objective is to create a composite guitar that has similar acoustic properties to its wooden counterpart. This is achieved by developing a composite that has acoustic properties similar to that of wood currently used for guitars.

The research will be focused on the acoustic steel string guitar as this guitar type appears to be most prominently researched and has seen significant developments over the past few decades [22]. Since the soundboard of a guitar is considered the main sound producing component, development of the composite will primarily aim towards modelling the materials used for soundboards such as Spruce and Cedar [50]. Additionally types of tropical hardwood might be modelled since these types are generally used for the back and sides which can have a significant influence on the sound of the acoustic guitar.

This research project will have a strong theory-oriented as well as a practical component. The theory component holds the development of a basic computer model to aid in the designing of the composite. The practical component will support this theoretical model by validation and input of experimental results to iterate the model. Next to that the overall aim is to develop a complete guitar made out of composite materials which is to be validated by a psychoacoustic analysis. This will be further explained in section 4.3.

For the main research part of the project in developing a composite with similar acoustic properties as wood, the following research questions are set-up.

1. Which types of composites are to be considered for replacing wood?
    1.1. What is the complete design space of composites that should be considered?
    1.2. What are the main parameters required to make a pre-selection of composites for further investigation?
    1.3. What are the most promising types of composites to replace wood?

2. How can the acoustic properties of a material be modelled?
    2.1. What material parameters influence the acoustical characteristics of materials?

    2.2. What experimental methods are required to provide empirical data for the model?
    2.3. Which theories and methods are required to model these parameters?
3. What is a suitable production method for the development of the design composite?
    3.1. What type of machinery is required for the production of the developed composite?
    3.2. What are the production limits for the materials chosen for the composite?
    3.3. How can the quality of the composite be controlled?

The first research question and the respective sub-questions on the topic of pre-selection of materials for replacing wood will be covered in the detailed literature review in chapter 5 and chapter 7. Research question two will be covered mostly in the detailed literature review and further elaborated on in the main thesis. Research question three will mostly be covered during the main thesis after the pre-selection of potential materials is conducted.

As indicated before when the primary research into the composite design has been completed, a full composite guitar will be developed and validated with a psychoacoustic analysis. Therefore a second set of research questions is set-up and presented below.

4. How is a full composite guitar to be designed?
    4.1. How can the separate components of a composite guitar be designed?
    4.2. What is the geometrical set-up of the different components?
5. What is the most suitable production method for a full composite guitar?
    5.1. How will the separate components be produced?
    5.2. What is a suitable bonding method for the separate components?
    5.3. What machinery and production equipment is required?
6. How can the psychoacoustic evaluation be set-up?
    6.1. What should be the main test set-up be in terms of number of people involved and number of guitars demonstrated?
    6.2. What are the scoring parameters for the evaluation?
    6.3. What are other parameters that might negatively influence the validity of the results?

With the research objective, research questions and research project set-up known, a research framework has been constructed. This is shown in Figure 4.1

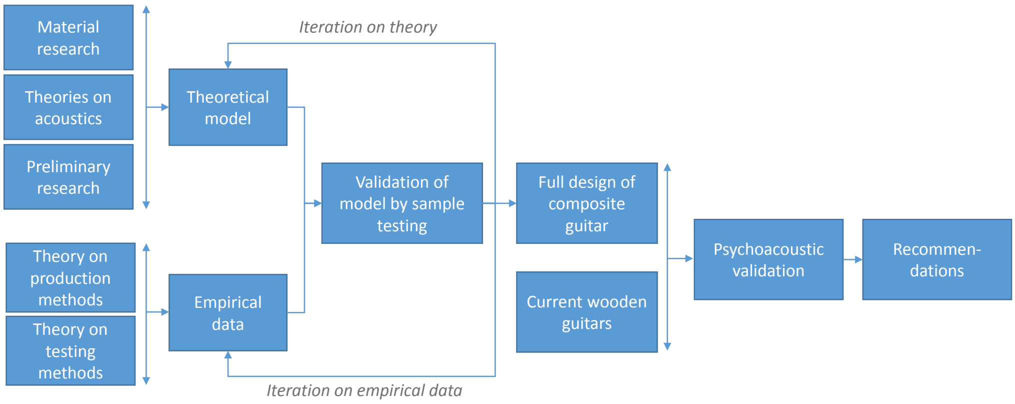


Figure 4.1: Research framework for research project including both research phases.

The overall scope of the project might be considered to be too large. Therefore it is important to understand that this project might not yield a complete composite guitar that can match its wooden counterpart in acoustic quality, but rather aims to provide insight in the feasibility of achieving such an instrument.

4.2. Theoretical Content/Methodology

As indicated in the research goal, the research project will have a strong theoretical component in predicting the parameters influencing the acoustic properties of the composite. The model will be programmed in MATLAB and will have input from a number of theories and experimental data. The experimental data will be further elaborated in section 4.3 and the main theories required are listed below.

Composite material theory: Basic rules of mixture and Halpin-Tsai model to estimate the material properties of a composite.

Laminate theory: Estimation of material properties of composites build up from separate lamina with specific properties.

Material visco-elasticity: Theory on visco-elasticity of materials and composites to understand the internal damping phenomena and loss tangent.

Material mechanics: Relations to understand the behaviour of materials under in-plane static and vibrational loads.

Structural mechanics: Relations to understand the behaviour of structural components made from composites or wood under out-of-plane static or vibrational loads.

4.3. Experimental Set-up

The experimental data gathered will be used to improve the theoretical model by including an empirical component in the parameter estimation. With the main parameters that will be researched known, it is predicted that at a minimum the following tests are required in order to support the theoretical model with suitable data.

- Tests to determine material stiffness in longitudinal and transverse directions. These tests can be normal ASTM standard inspired tensile tests or three point bending tests.
- Density tests or calculations. Considering the accuracy required, simple density calculated will likely suffice. For higher accuracy, testing equipment might be used.
- Tests to acquire insight into the damping or acoustic performance. These tests could be DMA (Dynamic mechanical analysis) or LSV (Laser Scanning Vibrometry) tests.

Each of these tests will be performed on both a wood type typically used for the soundboard as well as a composite designed with the theoretical model.

As introduced in chapter 1, the main benefits of composites over wood are in terms of environmental sensitivity. Therefore, to validate that the to be developed composite indeed performs better in terms of temperature and humidity sensitivity, two additional tests are to be performed.

- TMA (Thermal Mechanical Analysis) to determine the coefficient of thermal expansion.
- TMA on samples subjected to high humidity in order to find the sensitivity under humid conditions.
- High precision weight measurement on wet and dry samples to acquire data about the moisture absorption.

Next to the theories and experimental tests, knowledge around the production of composites is required. This is important to be able to design a repeatable production process to create high quality samples with a minimum spread in properties.

While a large number of common composite materials such as carbon and glass fibre reinforced plastics is already available for the research project, it is likely additional materials or equipment might be required. For this companies providing these materials to the market will be contacted to investigate the possibility of a sponsorship. As indicated earlier, the project scope is considerable. Therefore it is necessary to consider the planning implications of lead time of sponsoring companies as well as the production and testing equipment availability. This will result in parallel working streams to optimize the utilization of time available during the main Thesis.

Finally at the end of the project after a complete composite guitar has been produced, a psycho-acoustic test will be performed. Psycho-acoustics is the scientific study of sound perception [51]. In this specific case the experiment consists of a number of people judging the sound quality of a number of instruments both wooden as well as composite during a blind test. This test is considered the ultimate validation to determine whether the composite guitar produced during the research holds up against the wooden competition. The judging panel will contain both experts in determining the tonal qualities of guitars as well as inexperienced listeners.

4.4. Project Planning and Gantt Chart

As this project is quite intensive regarding the timing of the experiments and tests required, it is important to properly plan all phases of the research. In Figure 4.2 the time planning of the different phases of the project is laid out in the form of a Gantt chart.

Most importantly to consider in this planning are two major factors that are likely to introduce time schedule complications for the research. These are the dependency on materials to be provided by potential sponsors as well as the availability of the required test set-up both at the Aerospace DASML facilities as well as at external parties. To accommodate as much flexibility as possible in the planning, it was decided to move any material or equipment sponsorship requests as well as preliminary tests to the front of the project schedule. As sponsorships are requested before the end of the literature review period, some uncertainty towards the exact scope of the required materials and scope might still be present.

The project is divided in a number of phases which are listed and explained below.

0. **Project scoping** Investigation of the area/field of research in order to set-up a relevant research project. This research plan is the main output of this phase.
1. **Literature and information** Collection of relevant literature and understanding what knowledge and information is required for successful completion of the research project.
2. **Baseline model** Creation of a baseline model that is able to predict the parameters responsible for the acoustic behaviour of a composite material to match those of wood.
3. **Empirical data collection** Design and execution of tests that will provide information to improve and complete the theoretical model in predicting the parameters responsible for the acoustic behaviour of a composite material.
4. **Production and validation** Finalizing the design of the composite that matches the acoustic properties of wood, production of the samples and validation of the model. This is considered a highly iterative process where a number of composites are to be produced to obtain the required material parameters.
5. **Instrument design** Design of a composite instrument with the newly designed composite.
6. **Instrument production** Production of the designed instrument.
7. **Psychoacoustic validation** Testing the perception of sound quality of different guitars made from wood and composites by an expert and non-expert group of people.
8. **Project Finalization** Project wrap-up and finalization of deliverables.

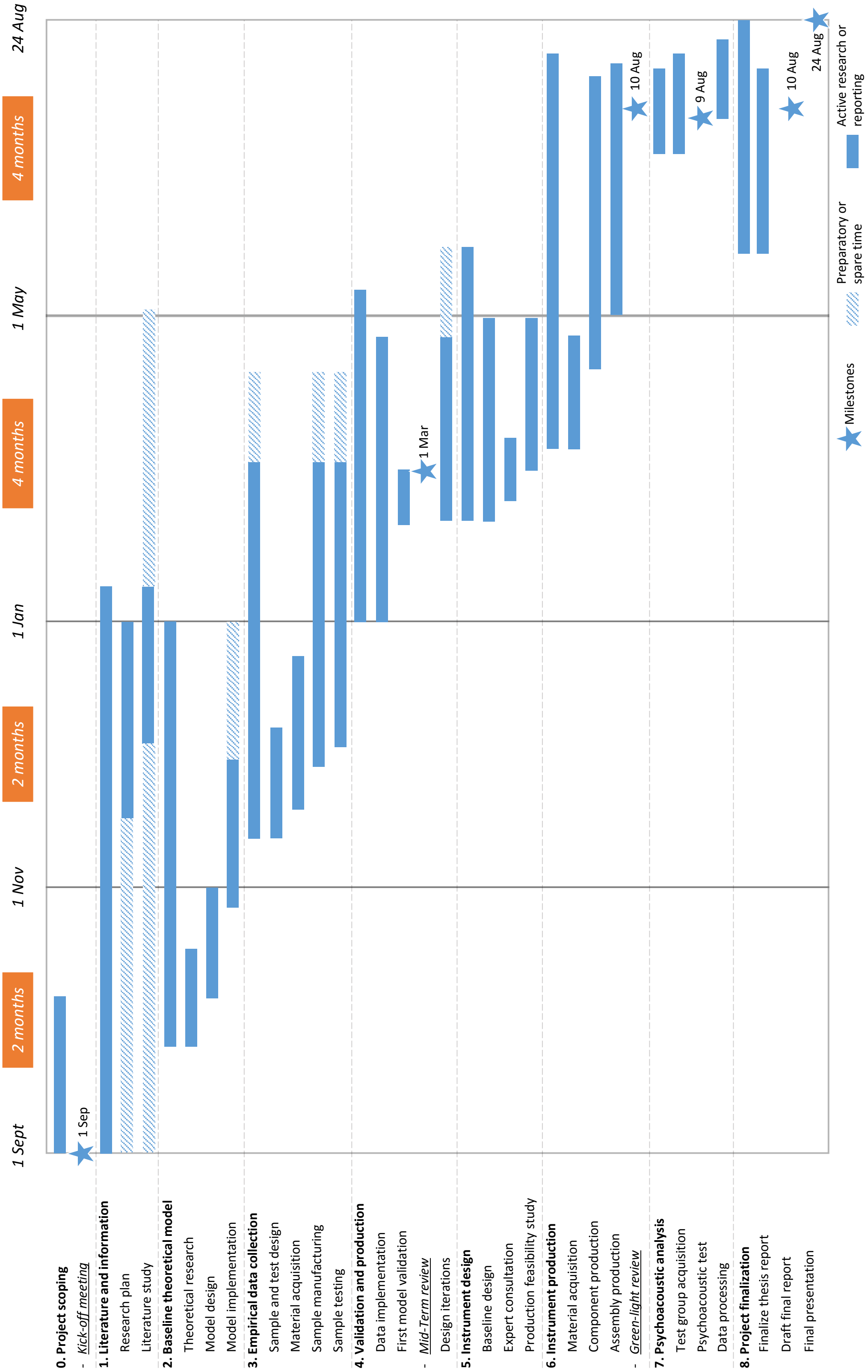


Figure 4.2: Project Gant chart with details of the phases and their projected timespan.

5

Detail on macro material level

As the macro material level has been found to be the most promising for researching the viability of a composite guitar with similar acoustic characteristics as the wooden guitar, a second, more in-depth literature review is conducted. This literature review dives into the material parameters that influence the acoustic properties of a material. These parameters will first be introduced and their importance will be assessed. Additionally, the parameters combined provide an additional set of design criteria as these parameters appear in a number of formulae that indicate the acoustic performance of a material.

5.1. Introduction to material parameters

From literature it appears that three material parameters are dominant in determining the acoustic performance of a material [40]. These are the stiffness, density and the damping of the material. In the following subsections each of these three parameters will be discussed. Additionally an investigation on how these parameters change the acoustics of a material will be performed including a description of potential methods to measure or analyse the parameters.

5.1.1. Modulus of Elasticity/Stiffness

The modulus of elasticity, also known as the Young's Modulus, is an indicator of the resistance against strain of a material under a certain applied stress [52]. A high modulus of elasticity indicates that a material is deforming little when placed under a certain stress. In Equation 5.1 the relation for the computation of the modulus of elasticity is provided. In this relation σ indicates the stress applied and ϵ is the strain measured.

$$E = \frac{\sigma}{\epsilon} \tag{5.1}$$

For an isotropic material the properties in terms of stiffness of a material are the same in all directions. For other types of materials such as composites including natural composites such as wood, the stiffness properties are highly dependent on the orientation of the material with respect to the direction of the loads applied. E_x is the stiffness in longitudinal direction while E_y is the stiffness in transverse direction. Often the E_x component is taken as the direction in which the main reinforcement is applied. When considering in-plane stiffnesses E_x and E_y, the ratio of the two stiffnesses is called the anisotropy ratio as provided in Equation 5.2. This ratio can be greater than 10 in case of high quality quarter sawn tonewoods [50].

$$r_{anisotropy} = \frac{E_x}{E_y} \tag{5.2}$$

The acoustics of a material are mainly determined by the out-of-plane or bending stiffness of a material. This can be explained by the fact that the plate vibrates in the out-of-plane direction (z-direction) to transfer sound energy to the surrounding air.

For isotropic materials, the relation between in-plane stiffness and out-of-plane stiffness is linear and can theoretically be approached by Equation 5.3 [53]. In this equation, D is the flexural rigidity of a panel, t the thickness of the plate material and v the Poisson's ration which defines the strain of a material due to a load in a perpendicular direction.

$$D = \frac{Et^3}{12(1-v^2)} \tag{5.3}$$

This relation holds only for materials that have a uniform in-plane stiffness throughout the thickness of the material. For composite materials which are often build-up from thin layers with considerably different orientations and therefore stiffnesses, laminate theory is to be used [54]. This theory will be explained below.

The ABD matrix presented in Equation 5.4 can be used to describe the properties of a laminate [54]. The A terms describe the in-plane properties of the laminate while the D terms describe the out-of-plane properties. The B properties describe the in-plane reaction of the laminate when subjected to out-of-plane loads and vice versa. This is also called the membrane-bending coupling. The loads and moments applied to the laminate are depicted by N and M respectively.

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \epsilon_{x0} \\ \epsilon_{y0} \\ \gamma_{xy0} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} \tag{5.4}$$

Before the components of the ABD matrix can be calculated, the in-plane properties of the plies are to be determined. For fibre-reinforced composites this is done using the rules of mixtures. The stiffness in both directions can be determined by Equation 5.5 and Equation 5.6. In these equations, v_f is the fibre volume fraction and E_f and E_m are the moduli of elasticity of the fibres and matrix material respectively.

$$E_x = E_f * v_f + (1-v_f)E_m \tag{5.5}$$

$$E_y = \left(\frac{v_f}{E_f} + \frac{1-v_f}{E_m}\right)^{-1} \tag{5.6}$$

In many cases the rule of mixtures does not fit the data obtained from experiments. Therefore an alternative method is the Halpin-Tsai method which includes an extra factor ξ to fit experimental data better. The Halpin-Tsai relation is provided in Equation 5.7

$$E = \frac{E_m\left[E_f + \xi\left(v_f E_f + (1-v_f)E_m\right)\right]}{v_f E_m + v_m E_f + xi E_m} \tag{5.7}$$

With the stiffness in both directions known, the Poisson's ratio ν_{yx} can be determined using the stiffnesses E_x, E_y and the Poisson's ratio ν_{xy} as shown in Equation 5.8 [54]. The Poisson's ratio ν_{xy} is to be obtained using experiments or could be taken as a reference value from literature.

$$\nu_{yx} = \frac{E_y}{E_x}\nu_{xy} \tag{5.8}$$

Using Equation 5.9 through Equation 5.12 the in-plane strain relations for an arbitrary ply of the laminate can be obtained.

$$Q_{xx} = \frac{E_x}{1-\nu_{xy}\nu_{yx}} \tag{5.9}$$

$$Q_{yy} = \frac{E_y}{1-\nu_{xy}\nu_{yx}} \tag{5.10}$$

$$Q_{xy} = \frac{\nu_{xy}E_y}{1-\nu_{xy}\nu_{yx}} \tag{5.11}$$

$$Q_{ss} = G_{xy} \tag{5.12}$$

These ply properties can be displayed in the matrix system shown in Equation 5.13.

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Q_{xx} & Q_{xy} & 0 \\ Q_{xy} & Q_{yy} & 0 \\ 0 & 0 & Q_{ss} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{5.13}$$

When rotating this ply the in-plane properties change. Using the relations in Equation 5.14 through Equation 5.19 these in-plane properties of a ply with an arbitrary rotation θ can be found.

$$Q_{11}^{\theta} = m^4Q_{xx} + n^4Q_{yy} + 2m^2n^2Q_{xy} + 4m^2n^2Q_{ss} \tag{5.14}$$

$$Q_{22}^{\theta} = n^4Q_{xx} + m^4Q_{yy} + 2m^2n^2Q_{xy} + 4m^2n^2Q_{ss} \tag{5.15}$$

$$Q_{12}^{\theta} = m^2n^2Q_{xx} + m^2n^2Q_{yy} + (m^4+n^4)Q_{xy} - 4m^2n^2Q_{ss} \tag{5.16}$$

$$Q_{66}^{\theta} = m^2n^2Q_{xx} + m^2n^2Q_{yy} - 2m^2n^2Q_{xy} + (m^2-n^2)Q_{ss} \tag{5.17}$$

$$Q_{66}^{\theta} = m^3nQ_{xx} - mn^3Q_{yy} + (mn^3-m^3n)Q_{xy} + 2(mn^3-m^3n)Q_{ss} \tag{5.18}$$

$$Q_{26}^{\theta} = mn^3Q_{xx} - m^3nQ_{yy} + (m^3n-mn^3)Q_{xy} + 2(m^3n-mn^3)Q_{ss} \tag{5.19}$$

Since the plies are not all located at the same distance from the mid-plane, the contribution of the bending stiffness is different for each of these plies. Therefore the location of each ply from the mid-plane of the composite must be known. Using Equation 5.20 the location of the midply can be found. In this equation n is the number of plies, $t_p l y$ the ply thickness and k is the k^{th} ply of the laminate. Using the mid-plane location the distance of each ply from the mid-plane can be determined using Equation 5.21

$$z_0 = \frac{1}{2}\sum_{k=1}^{n} t \tag{5.20}$$

$$z = \sum_{k=0}^{n} -z_0 + k t_{ply} \tag{5.21}$$

With the Q matrix of each ply known as well as the distance from the mid-plane for each of the plies, the ABD matrix entries can be computed by filling in Equation 5.22 through Equation 5.24

$$A_{ij} = \sum_{k=1}^{n} Q_{ij}(z_k - z_{k-1}) \tag{5.22}$$

$$B_{ij} = \sum_{k=1}^{n} \frac{Q_{ij}}{2}(z_k^2 - z_{k-1}^2) \tag{5.23}$$

$$D_{ij} = \sum_{k=1}^{n} \frac{Q_{ij}}{3}(z_k^3 - z_{k-1}^3) \tag{5.24}$$

Using the inverse of the ABD matrix it is easy to determine the strains of the material under a certain load. This matrix is called the abd and is shown in Equation 5.25.

$$\begin{bmatrix} \epsilon_{x0} \\ \epsilon_{y0} \\ \gamma_{xy0} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{12} & a_{22} & a_{26} & b_{12} & b_{22} & b_{26} \\ a_{16} & a_{26} & a_{66} & b_{16} & b_{26} & b_{66} \\ b_{11} & b_{12} & b_{16} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{26} & d_{12} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix} \begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} \tag{5.25}$$

Using the ABD matrix, the in-plane stiffness of the laminate can be found using the relations in Equation 5.26 and Equation 5.27 [54]. In these relations h is the thickness of the laminate. The 1 direction corresponds to the x-direction while 2 direction corresponds to the y-direction.

$$E_1 = \frac{1}{h a_{11}} = \frac{1}{h}\frac{A_{11}A_{22} - A_{12}^2}{A22} \tag{5.26}$$

$$E_2 = \frac{1}{h a_{22}} \tag{5.27}$$

The Poisson's ratio of the laminate is given by Equation 5.28. The requirement for this relation to hold is that the laminate is symmetric and balanced. Balanced means that for every ply at a $+\theta$ orientation, there is another ply at $-\theta$ orientation while symmetric means that for every ply above the laminate mid-plane, a ply with the exact same orientation is present below the mid-plane at the same distance from the mid-plane [55].

$$\nu_{12} = \frac{A_{12}}{A_{22}} \tag{5.28}$$

5.1.1.1. Measurement techniques for the determination modulus of elasticity

For the determination of in-plane stiffness, a simple tensile test can be performed. Most commonly used is the ASTM D638 tensile test standard for testing of tensile properties of plastics or a variation on this method [56]. In this set-up a sample, with certain dimensions as defined by the plate material thickness out of which the samples will be cut, is positioned in a tensile testing machine. In this tensile testing machine a load cell is placed which can accurately measure the load applied on the sample. Additionally the elongation of the sample can be measured using different methods which will be discussed below.

The sample is dogbone shaped (as shown in Figure 5.1) such that failure of the sample occurs near the center of the sample. Straight samples are very likely to fail at the clamps of the test machine due to a local stress increase by the clamps providing a much lower tensile strength than would be the case for real applications. In case the researcher only measures stiffness the sample can have straight edges.

Figure 5.1: Dogbone shaped test samples for the determination of stiffness and strength of a material [57]

Long-stroke extension meter The long-stroke extension meter accurately measures the length of a section on the sample. Often this method is used on larger samples as the method becomes more accurate when the sample strain is measured over a longer distance of several centimetres. Additionally most extension meters have a limited resolution of for example $5\mu m$. For very stiff materials the measurement resolution might therefore not be high enough causing the researcher to resort to other measurement techniques such as the application of strain gauges.

Strain gauges For physically smaller test samples or when the long-stroke extension meter is not accurate enough and does not provide a high enough resolution, strain gauges can be used. These are micro resistance wires positioned such that if a strain is applied on them, a difference in resistance can be measured which in turn can be converted to an absolute strain. The benefit of strain gauges is that they can measure more accurately as they provide an analogue output via their resistance [58]. Therefore the accuracy is limited by the amplifier and resolution of the analogue to digital converter used. One downside of straingauges is the high price of several Euros per strain gauge. This makes them cost inefficient when testing a large number of samples and a time consuming process when a large number of strain gauges is to be applied correctly on the samples.

Digital Image Correlation (DIC) For larger structures, or structures with local stress concentrations, DIC provides a measurement solution to obtain the full strain field. The method requires the sample to be coated with a back and white paint spray to create a speckled surface. The surface image is captured at several instances during loading or testing of the sample. Using the least-squares method the displacement of the speckles is tracked and the strain field can be obtained. DIC method is always contaminated by noise and is not as accurate as a normal, local strain measurement solution such as the long-stroke extension meter or a strain gauge set-up.

As the strength of the to be developed composite is only a secondary requirement, the samples that are to be tested do not have to be dog bone shaped. Additionally the sample dimensions can be varied to obtain for example values to estimate the uniformity of the material. By taking smaller samples of wood or composite, it is expected that wider range of stiffness values will be obtained which can be used as a benchmark to design a new composite which is more uniform. To determine this uniformity for the smaller samples, it is likely that strain gauges are to be used as an extension meter does not have high enough accuracy. Otherwise the long-stroke extension meter will be the preferred method of stiffness measurements. As the method of strain field does not provide any additional information useful for this work, this method will likely not be used.

Another option is to directly measure the flexural rigidity of the samples. However this requires the samples to be large enough and will therefore not give any indication about the uniformity of a material. Smaller samples allow small weak spots in materials to considerably influence the properties as the largest portion of the sample is influenced by the weak spot. A large benefit of directly measuring flexural rigidity is that it will be directly linked to the resonance frequencies of the plate material. For a composite, it is also possible that the strongest reinforcement layers are placed as far as possible from the mid-plane resulting in a higher flexural rigidity than a isotropic material with the same stiffness. This can also be seen from the laminate theory as explained above where the distance from the mid-plane has a cubic influence on the flexural rigidity matrix (D-matrix).

5.1.2. Density

The density of a material is defined as the mass of a material per unit volume as presented in Equation 5.29.

$$\rho = \frac{m}{V} \tag{5.29}$$

The mass has a direct influence on the acoustic characteristics of a material by Newton's second law as provided in Equation 5.30 where F is the force applied to mass m which will thereby accelerate with acceleration a. Considering a panel that is excited by a string with a given force, the acceleration will be lower when the mass of the system is higher. From this it can be concluded that the mass of a system and thus the density of a system directly influences the speed at which the system can vibrate which is the frequency.

$$F = ma \tag{5.30}$$

5.1.2.1. Measurement techniques for the determination of density

The measurement of density can be done using different methods. The most common method of density determination is done by placing a material with a measured volume on a scale and following the calculation as presented in Equation 5.29. The determination of volume can be done by measuring the three dimensions length, width and height for simple shaped samples or by fluid displacement by adding the sample to a set-up in which the rising fluid level can be measured.

A more accurate method is pycnometry as presented schematically in Figure 5.2 [59]. This measurement method consists of a number of steps which are listed below.

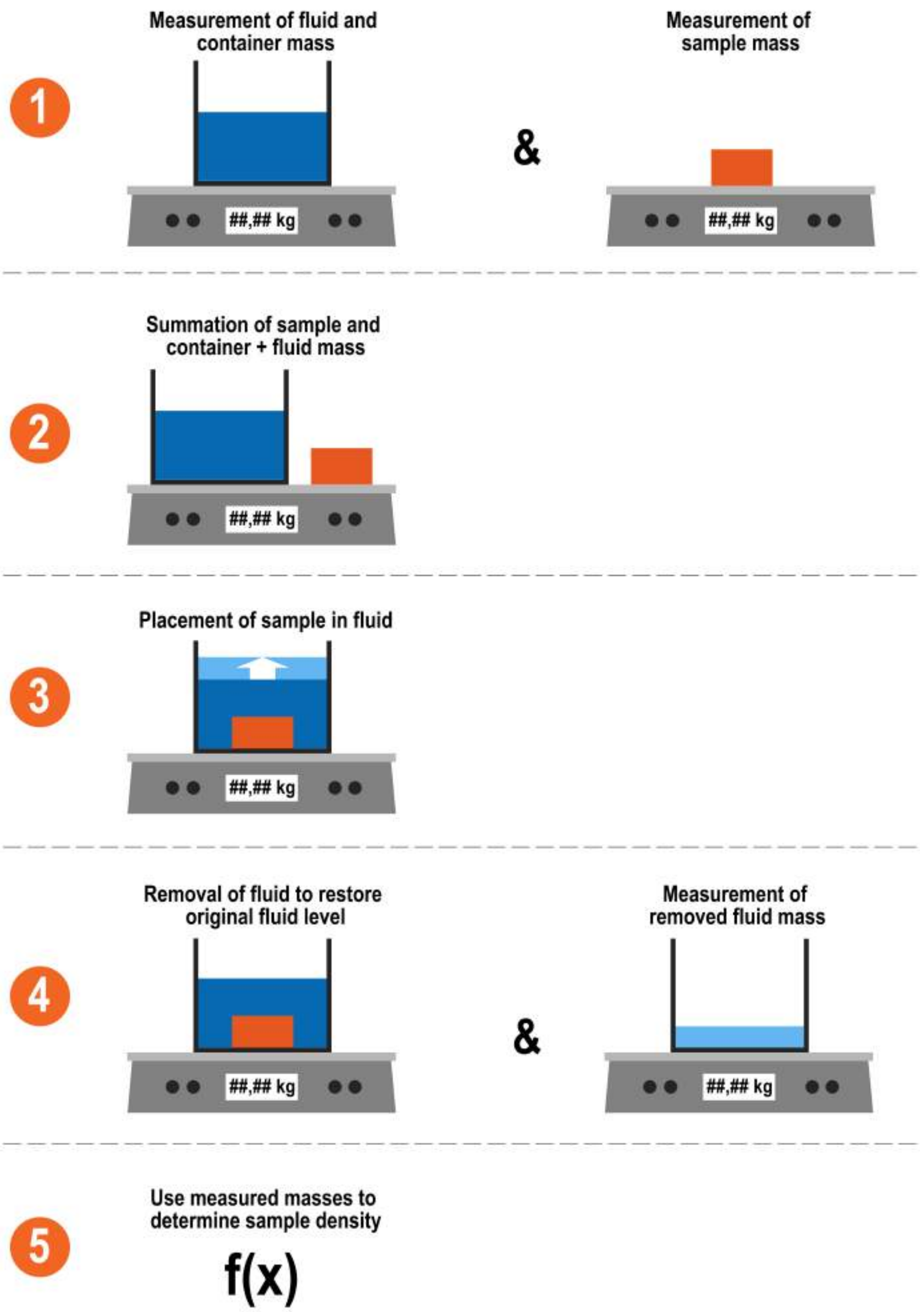


Figure 5.2: Schematic overview of the manual process of pycnometry using a fluid such as water.

1. The mass of a container or flask filled with a fluid such as water and the sample of which the density is to be obtained are measured separately on a precision scale.
2. The mass of a container or flask filled with a fluid such as water is measured together with the sample on a precision scale or the resulting masses from step 1 are summed.
3. The sample is placed in the fluid by which the fluid level rises.
4. Fluid is removed carefully until the original fluid level is restored. The removed fluid is placed in a container on a precision scale to determine the mass of the fluid removed. Using the known density of the fluid, the volume of the removed fluid which is equal to the volume of the sample can be obtained. Additionally the mass of the container with remaining fluid and sample is recorded.

5. Finally the mass of the sample can be found by summation of the mass of the fluid removed in step 4 and the difference between the initial weight of the fluid and container (step 2) and the weight of the container, fluid and mass after the fluid is removed (step 4).

The benefit of this method is the reduction of uncertainties compared to measuring the sample dimensions with the use of a caliper or ruler. Additionally, the process as described above is usually conducted multiple times and the average is taken to arrive at a higher reliability.

Machines are available that automate the process of pycnometry [60, 61]. These machines often use closed systems with inert gas instead of open systems with fluids as shown in Figure 5.3.

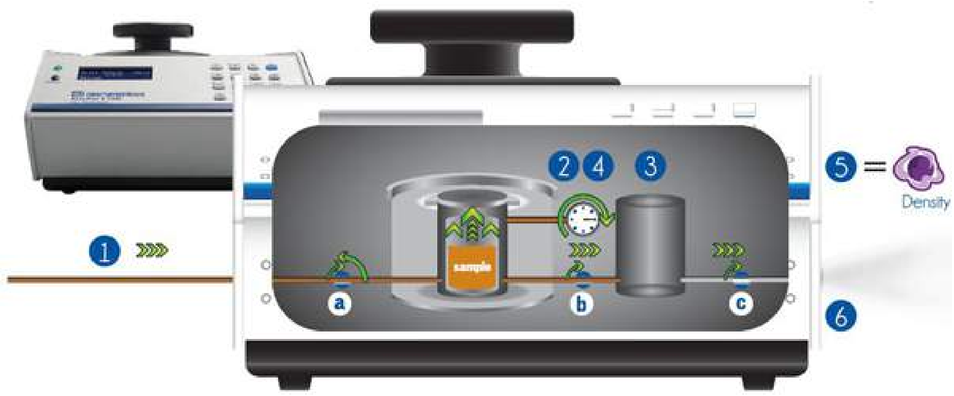


Figure 5.3: Comercially available pycnometer by Micromeritics using inert gas for its operation [61].

For the determination of the densities of the samples that are to be tested in the main thesis research, it is likely that the rough method of measuring the dimensions of the sample will provide enough accuracy to make accurate conclusions towards the research questions. Moreover the samples to be measured might be bigger than suitable for common pycnometry equipment.

5.1.3. Damping

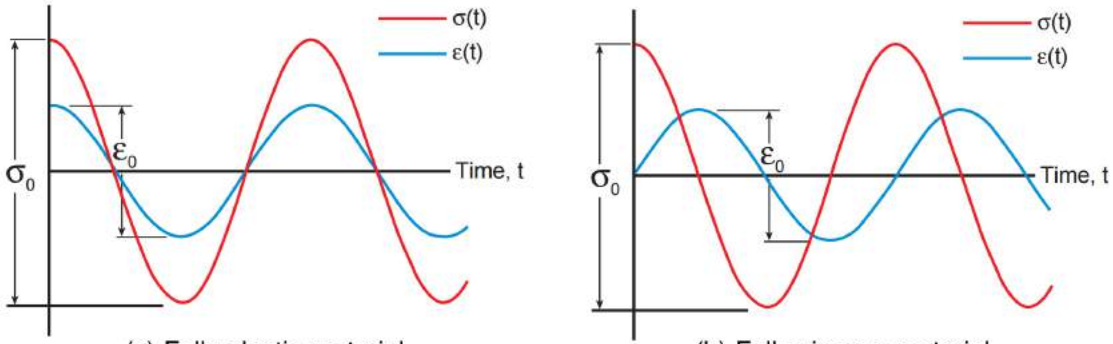
The basic theories on internal damping of materials are derived from the theory of viscoelasticity [62]. This theory describes how the reaction of a viscoelastic material to an external force consists of both an elastic as well as a viscous component. This is best observed when considering a sinusoidal load applied to a viscoelastic material as shown in Figure 5.4 [63].

As can be seen from Figure 5.4 (a), for a fully elastic material, the stress and strain are exactly in phase. There is an instant strain response to the applied stress. For a fully viscous material the strain follows the stress at a phase difference of 90 degrees. Therefore the strain reaches its maximum when the stress is already back at zero. For a viscoelastic material, the behaviour is somewhere in between of fully elastic and fully viscous models. The phase difference between stress and strain is smaller than 90 degrees but also not instant (0 degrees).

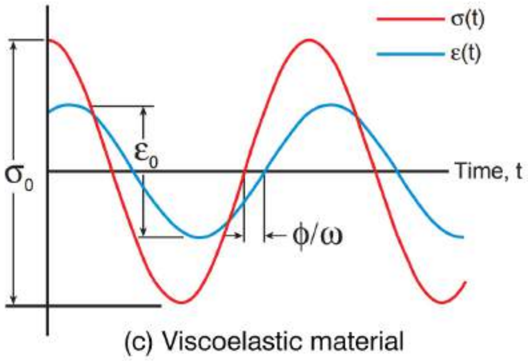
As viscoelastic materials have both a viscous and an elastic part, the modulus is represented by a complex quantity as shown in Equation 5.31 [63].

$$E = E_1 + E_2 i = \frac{\sigma_0}{\epsilon_0} e^{i\phi} \tag{5.31}$$

The elastic part of the modulus stores energy and releases it again when the load is removed while the viscous part releases its energy into heat. Therefore the two moduli are called storage modulus and loss modulus



(a) Fully elastic material (b) Fully viscous material



(c) Viscoelastic material

Figure 5.4: Reaction of different materials to an applied sinusoidal load. (a) a purely elastic material response, (b) a purely viscous response, (c) a viscoelastic response.

respectively. Together, as shown in Equation 5.32 these moduli define the loss tangent which is considered a measure for the internal damping of a material [62].

$$\tan\delta(\omega) = \frac{E^{''}(\omega)}{E^{'}(\omega)} \tag{5.32}$$

In Equation 5.32, $E^{''}$ is the loss modulus, $E^{'}$ the storage modulus and δ the phase angle difference. Additionally the loss tangent can be expressed by Equation 5.33 which is a relation commonly used for the expression of damping within a system [62]. This expression allows for easy analysis of the response of a classically under-damped single degree of freedom system.

$$\delta = \frac{1}{m} ln \frac{x_{n+m}}{x_n} \tag{5.33}$$

5.1.3.1. Internal damping of several material groups

Internal damping of materials has been of great interest in many research groups for the reason that it can potentially provide a large noise reduction in vehicles, buildings and machinery. Additionally it can reduce the risk of fatigue damage in materials [64]. Lakes provides an illustration of the different damping characteristics of material by comparing a set of tuning forks of the same dimensions and capturing the decay of the vibrations [41]. When plotting a stiffness versus damping map of several common materials it can be observed that there is a inverse relation between stiffness and damping. Generally materials with a high modulus have a much lower damping and vice versa. In Figure 5.5 a number of basic material groups is plotted using material database CES Edupack to illustrate this relation.

Composite materials allow for the design of very stiff and strong materials with a relatively high damping compared to most isotropic materials [65]. The combination of a structural phase which has very high stiff-

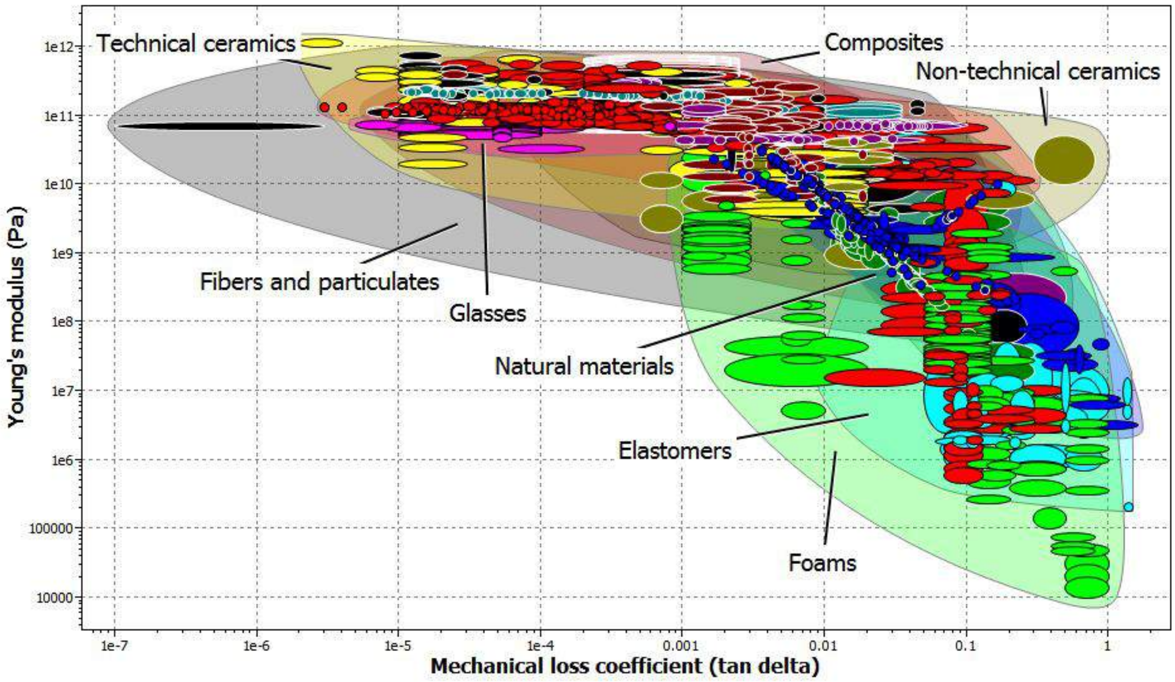


Figure 5.5: Young's modulus versus loss tangent plot of a number of common materials created using CES Edupack material database software. It shows the inverse relation of materials mostly being high stiffness low damping and vice versa.

ness and low damping and a damping phase with lower stiffness and high damping allows for the design of high stiffness and relatively high damping compared to non-composite materials. However, this is only true when the damping layer has a sufficiently high stiffness compared to the structural phase of the composite as can be seen from Equation 5.34. This equation provides an estimate of the effectiveness of the damping phase in bending. $E_d^{'}$ is the storage modulus of the damping layer, $\tan\delta_d$ the internal damping of the damping layer, $E_p^{'}$ the storage modulus of the structural layer and t_d, t_p the thicknesses of the damping and structural layers respectively.

$$\tan\delta_{eff} \approx 3\frac{E_d^{'}\tan\delta_d}{E_p^{'}}\frac{t_d}{t_p} \tag{5.34}$$

Successful results have been obtained by addition of stiff particles into the damping layer such as ceramic inserts in polymers [66]. This increases the stiffness of the polymeric layer increasing the effective damping according to Equation 5.34 while the original damping $\tan\delta_d$ of the polymer is barely affected according to the Reuss model [65].

5.1.3.2. Internal damping of materials in musical instruments

Wood is one of the most important materials in the manufacturing of instruments. According to Fouilhéa et. al., wood for musical instruments can be categorised into three groups: tropical hardwoods, European hardwoods and alternative woods to overcome shortage in supply of the first two groups [67]. Each of these groups of wood has specific characteristics when it comes to acoustics and internal damping. Consequently the builders of different types of instruments will choose different woods for their respective instruments [68].

Wood is a highly anisotropic material which influences the internal damping in different directions of the material [69]. The highly crystalline cellulose micro fibrils have very low damping compared to the lignin regions [69, 70]. Therefore the damping in the grain or longitudinal (L) direction is orders of magnitude lower compared to the transverse (T) direction.

As shown before, different types of wood are found in different musical instruments. Some instruments require woods from multiple groups [50]. One class of instruments that requires different woods is the class of stringed instruments. For stringed instruments, the top plate or soundboard is typically made of a different material than the back and sides. The soundboards require a high c/ρ ratio where c is the speed of sound through a medium and ρ the density [71, 72]. This ratio provides an indication of the efficiency of sound energy radiation. For the back and sides a high transmission is considered beneficial and therefore a low internal damping is of great importance. For back and sides a high cQ number indicates effective transmission where again, c is the speed of sound through a medium and Q is the quality factor which is the inverse of $\tan\delta$.

Attempts have been made to reproduce the acoustics of wood in acoustic guitars by development of a composite material. Most of the research focuses on the development and use of carbon fibre-reinforced polymers [73, 74]. Ono et.al. have come closest in reproducing the acoustic qualities of wood with carbon fibre-reinforced polyurethane foam [75–77]. Compared to Sitka spruce, a common wood for the soundboards of guitars, the acoustic response was found to be very similar. Although generally carbon fibre-reinforced polymers show orders of magnitude lower damping than Sitka spruce [78, 79], the reinforced polyurethane foam came close to 40-50% of the damping values obtained from the Sitka spruce samples. It is therefore likely that with additional modifications of the composite near exact matching can be achieved.

5.1.3.3. Measurement techniques for the determination of loss tangent

Measurement of internal damping can be done in a number of ways. Below the two most important categories are reviewed. Note that for most applications internal damping or loss tangent is used to determine the glass transition temperature [62]. This is done at low frequencies below the threshold of what is considered sound (below 20Hz). As the loss tangent is frequency dependent as shown in Equation 5.32, it should be considered that some of the measurement methods might have their limitations with regards to the goal of developing a composite that has similar acoustics in the audible frequency range (20Hz-20kHz).

Dynamic mechanical analysis (DMA) One of the most common methods of measuring the loss tangent is by the use of dynamic mechanical analysers (DMA) or rheometers. These devices excite a material at a certain frequency and measure their response giving information about the storage modulus, loss modulus and $\tan\delta$. Common DMA and rheology devices have a limited frequency range of 0.01Hz-200Hz. Therefore these devices are not suitable for determining the $\tan\delta$ in the full audible frequency range (20Hz - 20kHz).

However, there is one machine that is capable of performing DMA tests at much higher frequencies [45]. This machine, the Metravib VHF104 has a frequency range of 100Hz-10KHz which would be an acceptable range for comparison of damping in composites against the damping in wood [80]. However this machine has three major downsides. Firstly the test samples have to be cylindrical in shape which is not very suitable when considering the production of certain composites. Secondly the determination of $\tan\delta$ is not the direct result of measured data but relies on a curve fitting principle using a MATLAB script developed by Metravib. As this script is not published, it becomes very hard to properly assess the obtained data when it has been processed. Finally, as the machine is primary used for the determination of damping in rubber, it is unknown if these machines are capable of testing very stiff composites or wood.

Amplitude decrement analysis When the research into loss tangent focuses on the acoustic performance rather than the determination of the glass transition temperature, a simple amplitude decrement analysis is suitable. This generally consists of a set-up holding a relatively long and small test sample that is excited by a mechanical pulse, either by hand or with a small device, after which the response is measured by a piezoelectric transducer connected to a oscilloscope [81]. The frequency response is analysed and by inserting the reduction in amplitude in Equation 5.33 the loss tangent can be determined. As there are many different devices that can generate a large range of frequencies, there is very little limitation on the frequency range that can be tested. Therefore the amplitude decrement analysis method is very suitable for determination of the loss tangent within the audible frequency range.

Although this method of determining the loss tangent is relatively easy and offers a lot of flexibility, it comes with a number of downsides. When comparing the different test set-ups reported in several papers there are considerably differences in several parameters such as sample size, sample holding mechanisms and also transducer types [81–85]. The result of this is that only the relative internal damping can be determined of the samples tested with one specific set-up. A second downside is that environmental effects, which have a large influence on the loss tangent, are often not reported [69]. Finally, when using an amplitude decrement analysis to determine the loss tangent of low loss materials, the analysis should ideally be conducted under vacuum as the sound energy radiation can be quite large with respect to the damping.

As long as the downsides of the amplitude decrement analysis are taken into consideration, it is possible to design a suitable test set-up to obtain good data for the development of a composite that has similar acoustic properties to wood used in guitars. In the design of the test set-up, additional information should be gathered on the type of vibration the soundboard of an acoustic guitar experiences. By combining this information with already proven amplitude decrement analysis set-ups a new set-up can be developed for the specific purpose of matching the acoustic properties of a material used in guitars.

Modal analysis using laser scanning vibrometry Another method for analysing the damping of a material is looking at the structural damping of a small and simple structure by modal analysis. When considering for example a set of two dimensionally equal panels with the only difference being the material they are made of, a damping comparison can be made. This method is particularly useful in the case of designing acoustic materials as these are reinforced panels themselves and are thus close to the scale of the actual test case in contrast with the other methods discussed which work with smaller samples.

In Figure 5.6 a schematic overview of the principle of laser scanning vibrometry is provided. Additionally the basic principles of the test set-up are described below based on research done using laser scanning vibrometry by Dr. Ir. Farbod Alijiani at McGill University in Montreal, Canada [86].

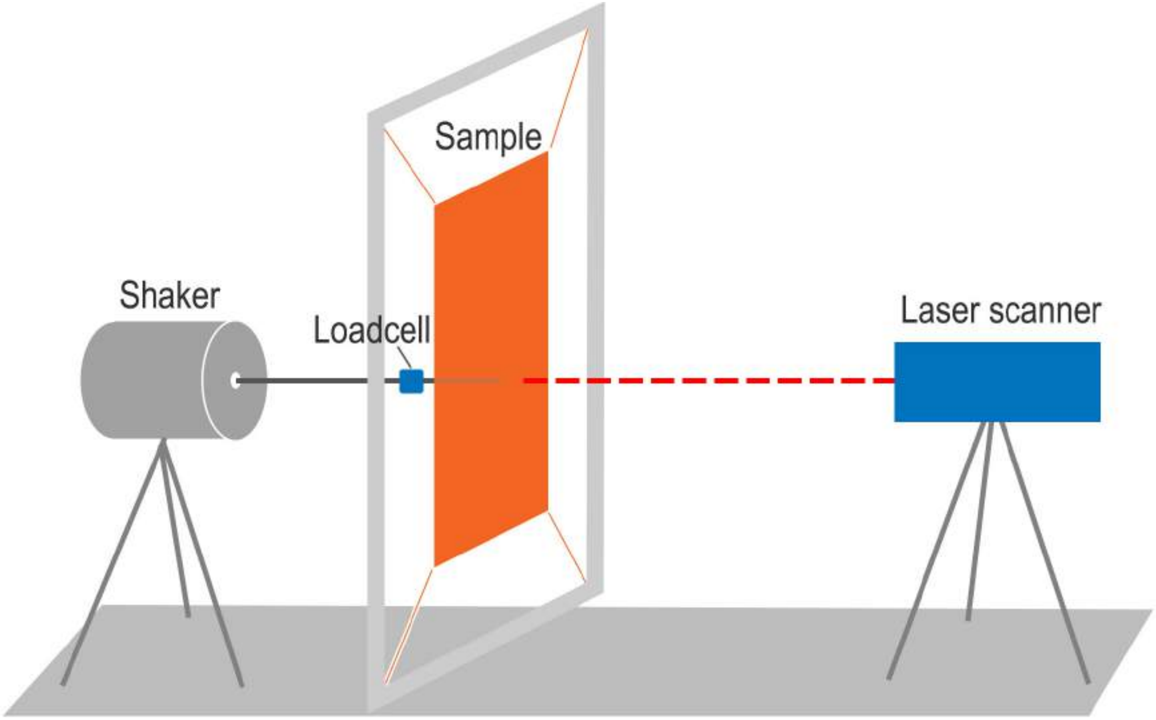


Figure 5.6: Schematic overview of laser scanning vibrometry

This particular set-up uses a thin rectangular panel of dimensions 450mm x 300mm x 0.8mm suspended in a frame by very thin cords or elastic bands. This is done to obtain near free boundary conditions as clamping of the panel results in bad reproducibility of results caused by the large effect on the clamped panel when the temperature or the clamping forces change.

On the back side of the panel a load cell is mounted which connects to a shaker via a stinger. This stinger is a thin metal wire which removes the largest portion of lateral excitation forces that are produced by the shaker. The shaker itself is connected to an amplifier which receives a signal type from the controller. This signal is specified by the user in the computer which is in turn connected to the controller. Common signals include a white noise signal or a sinusoidal frequency sweep. In this way the whole desired frequency spectrum can be excited.

The load cell signal is used as a reference signal to obtain a clear and noise free Fourier analyses and look only at the panel response peaks as the laser scanning signal is a combination of both the panel response as well as the continuous input signal. Therefore looking only at the laser scanner signal it is not possible as the response is heavily contaminated by the input noise.

The laser scanner itself is a Polytec PSV400 system which makes use of the Doppler effect by measuring the frequency of the received signal compared to the output laser signal. The laser scanner scans multiple points on the surface of the panel by which the modal shapes can be obtained with high accuracy.

The time domain signal of the laser scanner is send to the junction box and converted to a digital signal after which a Fourier transform is applied on the signal. Multiple measurements are taken on one single point and averaged to reduce noise.

The damping value for each of the modes can be obtained by the so called peak picking method or peak-amplitude method [87]. This method is the simplest of single degree of freedom methods to obtain damping parameters. For a full frequency response function dataset, it is assumed that all response at a peak can be attributed to a single mode. This method therefore works well with not extremely lightly damped systems. As this method is very simple, it is often used as a first estimate. The peak-picking method can be described in the following three steps.

1. A single peak is being identified on the FRF data plot. The frequency of the peak ω_r is recorded at the point of highest amplitude.
2. The bandwidth of the 'half-power points' is determined by finding a point left and right on the peak where the response level is equal to $|\hat{H}| \cdot \sqrt{2}$ where $|\hat{H}|$ is the maximum response level at ω_r.
3. The damping can be determined by using the relations in Equation 5.35 and Equation 5.36 where

$$\eta_r = \frac{\omega_a^2 - \omega_b^2}{2\omega_r^2} \cong \frac{\Delta\omega}{\omega_r} \tag{5.35}$$

$$\zeta_r = \frac{\eta_r}{2} \tag{5.36}$$

Many software packages that perform modal analysis are also able to extract modal parameters automatically. These programmes often use multiple estimation methods of which the peak-picking method is the simplest [87].

5.1.3.4. Relevance of damping to research question

With the research goal in mind of developing a composite with similar acoustic properties as wood used in acoustic guitars, a number of observations can be made based on the literature reviewed on the topic of internal damping. These observations will be taken into consideration in the selection of materials to research as an alternative for wood. Additionally the observations serve as a basis for the development of a test set-up suitable for a proper comparison between materials.

- Generally, stiffer materials introduce a lower damping and vice versa. Composite materials allow for the creation of relatively high damping materials relative to their high stiffness. As wood is a relatively stiff material in relation to its weight, the creation of a composite alternative will likely introduce complications in finding a material with high enough damping as the most suitable composite materials such as carbon have very low damping.

- Between instruments as well as within one instrument, the different functions of the structure may require different types of wood. Regarding the internal damping in guitars, there is a relatively high importance to have low damping for the back and sides as these structural components need to have efficient transmission. In contrast, the internal damping can be higher for the soundboard as this component is mostly responsible for the radiation of sound energy and therefore not greatly affected in its task by a higher damping. With respect to the research goal this means that, into the development of a composite to replace wood, the different types of wood should be analysed and modelled to be able to create a full composite guitar.
- There has been done a limited amount of research in the development of an alternative for wood used for the soundboards of guitars. Some good initial results have been obtained with polyurethane foam reinforced with carbon fibres in terms of internal damping and acoustic response. Therefore fibre-reinforced foams should be further investigated as this will likely yield more usable results.
- Of the measurement methods the laser scanning vibrometry method shows greatest potential in measuring the damping of several materials. As the method of testing is relatively close to the actual use case of a soundboard of a guitar, reliable results are expected to be obtained. If the difficulty of building the full laser scanning vibrometry test set-up is too high the amplitude decrement analysis might provide a suitable alternative.

5.2. Combined quantities indicating acoustic performance

With the main material parameters introduced, an evaluation of the acoustic relations can be performed. These consist mostly of the the main material parameters discussed in section 5.1. Of the quantities discussed below, the two most important ones are considered to be the characteristic impedance and the sound radiation coefficient of the material [40]. Additionally the speed of sound is often considered as this characterizes the vibrational frequencies of a material.

5.2.1. Speed of sound

The speed of sound through a material in a certain direction is given by the relation in Equation 5.37

$$c = \sqrt{\frac{E}{\rho}} \tag{5.37}$$

As can be seen from this relation, an increase in density results in a lower speed of sound. This can be explained by the nature of the sound wave. A sound wave is kinetic energy being transferred through the material. The denser material results in a slower kinetic energy transfer. A higher stiffness results in the opposite effect making the sound wave travel faster though the medium.

5.2.2. Characteristic impedance

Similar to the speed of sound, the characteristic impedance is dependent on the modulus of elasticity as well as the density [88]. The characteristic impedance is important when considering vibrational energy transfer from one medium to another. In the case of a guitar this would be from the soundboard or body to the air but also from the string to the bridge and vice versa [89]

The impedance of the material can be expressed by the relation in Equation 5.38

$$z = \sqrt{E\rho} = c\rho \tag{5.38}$$

With the material impedance the transmitted (I_t) and reflected (I_r) sound intensity can be calculated using Equation 5.39 and Equation 5.40 [40]. In these relations $z1$ and $z2$ are the impedances of the materials that are involved with the sound energy transfer and I_0 is the incoming sound intensity.

$$\frac{I_t}{I_0} = \frac{4z_2z_1}{(z_2+z_1)^2} \tag{5.39}$$

$$\frac{I_r}{I_0} = \left(\frac{z_2-z_1}{z_2+z_1}\right)^2 \tag{5.40}$$

As can be seen from these relations, when $z1$ and $z2$ are very different, the transmittance is very low while the reflectivity is very high. A benefit of this is that the sound energy stays in the guitar body or in the string which creates a longer sound duration also called sustain. On the other side a large impedance mismatch results in a very low sound volume of the instrument. Therefore guitar builders have the task of controlling the characteristic impedance of their instruments to find a proper balance between enough sound volume and a long enough sustain [90].

5.2.3. Sound radiation coefficient

The sound radiation energy coefficient has a direct relation to the sound level produced. When designing a loud guitar, the sound radiation coefficient of the soundboard should be as high as possible. As the soundboard of the guitar transmits energy it is effectively dampened by the air. To optimize this, the goal is to maximize the amplitude of the vibrational response of the soundboard for a certain force.

The derivation of the sound radiation coefficient involves a number of steps. The starting point is the mean value of the amplitude which according to Skudrzyk's mean value theorem is equal to the driving-point admittance shown in Equation 5.41 In Skudrzyk's paper an infinite isotropic plate is considered however this theorem is applicable to ortothropic panels such as wood. In Equation 5.41, h is the panel thickness and v the Poisson's ratio.

$$Y = \frac{1}{4h^2}\sqrt{\frac{3(1-v^2)}{E\rho}} \tag{5.41}$$

The modal density is given by the relation shown in Equation 5.42. This relation can be rearranged for the panel thickness h and substituted in Equation 5.41 to provide the mean amplitude for a panel of given area and certain material properties given in Equation 5.43.

$$n(\omega) = \frac{A}{h}\sqrt{3(1-v^2)\frac{\rho}{E}} \tag{5.42}$$

$$Y = \frac{n(\omega)}{4A^2}\sqrt{\frac{E}{\rho^3}\frac{1}{3(1-v)^2}} \tag{5.43}$$

Considering the parameters that are most affected when changing the material the relation can be simplified and the sound radiation coefficient R for a material is obtained as shown in Equation 5.44.

$$R = \sqrt{\frac{E}{\rho^3}} \tag{5.44}$$

As for most other parameters, the sound radiation coefficient is dominated by the modulus of elasticity and the density of the material. For this parameter however, the density is much more dominant compared to the modulus of elasticity which might prove to be a considerable requirement for composites considering the much lower density of most woods used in guitar soundboards.

6

Detail on structural level

For the validation of the applicability of a newly developed composite and the performance on an acoustic level, the aim is to construct a complete acoustic guitar made of composite materials. Because the switch from wood to composite materials might have a considerable impact in the production methods and possible construction of the composite guitar, a basic understanding of the design process of an acoustic guitar is required.

This chapter will first go into the design of the soundboard as this is the most important sound producing component of the instrument. Second, the body as an air pump formed by the interaction between the soundboard and back via the air column of the guitar is discussed. Finally, with these design considerations in mind, an outlook is given on how these components might change the structure of the guitar due to the trinity relation between materials, production methods and design.

6.1. Structural acoustics of the soundboard

As described in chapter 2 the soundboard is the most important part of the guitar in generating the sound. On a structural level it is a stiffened panel that has boundary conditions in between simply supported and clamped conditions [46]. Over the years the developments on the soundboard of the acoustic guitar have been limited mostly to the secondary brace while the main x-brace as described in chapter 2 has remained largely in place. Even though this limitation has been in place, experimentation with the overall size of the body and thus the soundboard as well as with the secondary reinforcements has resulted in many guitar designs with very different acoustic characters [91].

Equally important to the bracing patterns, is the shape of the braces. The bending stiffness provided by the brace to the soundboard has a cubic dependency on the height of the brace and only a linear dependency on the width. Therefore in order to optimize the radiation efficiency as explained in subsection 5.2.3, it is beneficial to make the braces as slender and heigh as possible. In this way the stiffness of the soundboard is very high while the weight increase due to the braces is minimal.

The soundboard also has the greatest influence on the body modes of the guitar [46]. These are the lower resonance modes of the guitar body that define the guitar's fundamental sound. Most luthiers make sure that the body is adequately tuned, often to a tone just below 110Hz which is between a G and A tone [22]. The goal of luthiers is to create a soundboard bracing structure that causes the guitar to have an even response level across the whole frequency range. As the body modes are quite strong this is not fully achievable. Most guitars have a stronger response around the A and G tone due to the tuning of the guitar body to these resonance frequencies.

Inexperienced guitar builders tend to struggle with under- or overbuilding the instrument. This refers to the amount of reinforcement on the soundboard which can either be too little or too much. Under-built guitars with too little reinforcement sound cluttered making the separate tones hard to distinguish. Since the acoustic guitar is an instrument more and more used for solo performances, an under-built guitar is extremely hard to use for melody intensive compositions as these tones disappear in the other tones and base sound of the composition. Additionally under-built guitars can be structurally much weaker than normal built guitars making the risk of damage due to exposure to environmental or physical forces even higher. On the other side over-built guitars are equally disturbing to play for the artist as these guitars often sound very brittle and do not provide a balanced sound that is pleasing to the ear. Additionally as the soundboard is less compliant the overall sound intensity can dramatically drop resulting in a necessity to amplify the instrument. To obtain a comfortable listening sound level amplification might even be required for practising at home.

6.2. The guitar body as airpump

While most of the discussions and development on the acoustic guitar focus on the bracing patterns of the soundboard, top builders in North America such as Ervin Somogyi and Michael Greenfield have made instruments considered to be the best in the world by focusing on the understanding of the physics of the guitar body as an airpump [9, 92]. The guitar body should be a very efficient airpump to obtain a responsive and well balanced instrument. Crucial in the design of active guitars with an efficient airpump is the relation between the soundboard, the back and the aircolumn. As indicated in subsection 2.2.2 the soundboard radiates most of the sound energy, but is not only vibrating directly by activation of the bridge and strings. It also delivers energy to the aircolumn inside the guitar which activates the back which in return delivers energy back to the soundboard. Ervin Somogyi describes this as the ping-pong effect in the guitar body which creates the airpump [92].

The effect of interaction between the soundboard, aircolumn and back is best illustrated by a mass spring system as shown in Figure 6.1. The soundboard is represented by the upper mass ($m1$) which is excited by the energy of the strings which is transferred through the bridge. The aircolumn is represented by the spring which can only transfer the sound energy at a certain speed and therefore can be represented by a constant stiffness. The back is represented by the lower mass ($m2$) which is activated by the aircolumn.

On the left-hand side of Figure 6.1, an ineffective airpump is shown. When exciting $m1$ with a certain frequency the energy that is transferred to the air is not transferred to $m2$ as the resonance frequency ratio of $m2$ and $m1$ is not compatible for generating an effective airpump. On the right-hand side of Figure 6.1, a representation of an effective airpump is illustrated. In this example the frequency relationship between the two masses is correct and results in active driving of $m2$ by $m1$ and vice versa. From the responses of the m2 of the effective airpump it can be observed that, when an effective airpump is created, the amount of energy needed to drive m2 is relatively low and will result in higher amplitudes in the system. For the ineffective airpump with incompatible resonance frequencies the sound energy is effectively lost as the top and back are working against each other.

While the representation shown in Figure 6.1 is a single degree of freedom system, the conceptual idea holds for multi-degree of freedom systems such as the guitar body in which the different components will have many more resonance frequencies. Guitar makers can spend many years on finding the optimal resonance relationship between the soundboard and the back.

6.3. Outlook on trinity compliance

With the biggest considerations in the design of modern acoustic guitars known, a review can be done on the potential difficulties that might arise when converting the acoustic guitar from a wooden instrument to a full composite one. This section focuses on the trinity compliance of the modern acoustic guitar design when making this transition to composites. First a general introduction on the trinity principle will be given after

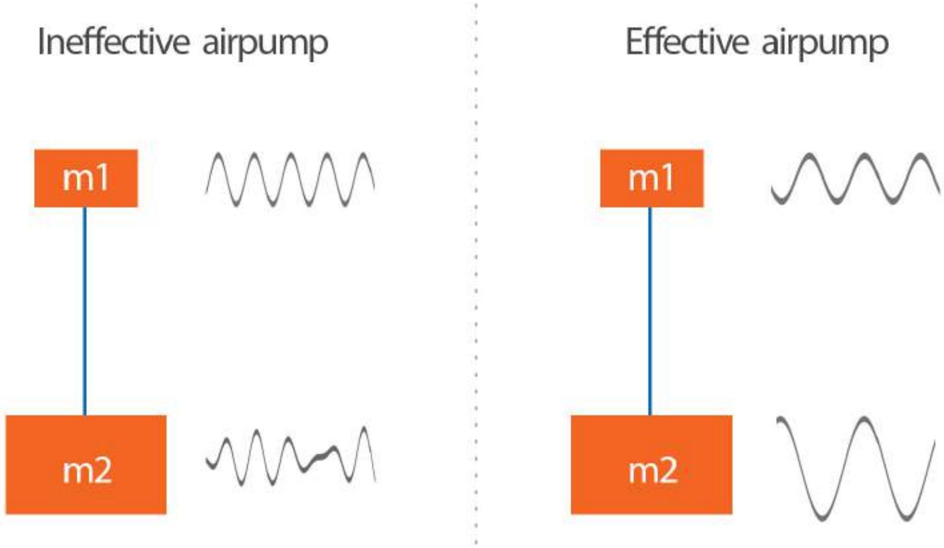


Figure 6.1: Mass-spring system representation of the coupling between soundboard, aircolumn and back of a guitar. Left: ineffective system, Right: effective system

which the most critical design processes of the instrument are discussed in the light of these principles.

6.3.1. General introduction to trinity principle

The trinity principle states that there is a strong connection between the three aspects materials, production method and geometrical design when considering a product. This is shown in Figure 6.2

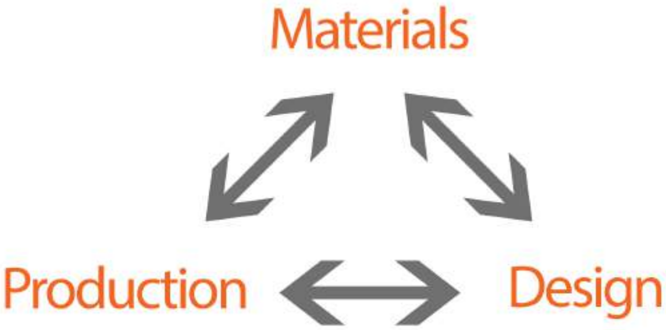


Figure 6.2: Schematic overview of trinity relation between materials, design and production. [93]

The connection indicates that if any of these three parameters is subject to a change, the other parameters are also likely to change. An example of this is shown in Figure 6.3 of a aluminium car rim and a comparable product from a carbon fibre reinforced polymer material. The different material properties and anisotropy of the carbon fibre reinforced polymer makes a more effective and lightweight design possible. Additionally the production of the aluminium rim is done by deforming sheet materials while the composite rim is made using compression moulding of pre-impregnated carbon fibre reinforced polymer layers.

Failure to comply with the new design, production method or material characters can result in an inferior product. With the trend to move away from metal structures in favour of carbon fibre reinforced composites can result in so called 'black metal design' where a properly functioning metal part or component is now produced out of carbon fibre reinforced polymers without taking into consideration the required design changes. Metal parts are often connected by mechanical fasteners. In case one of a set of bolted components is replaced by a equally sized carbon fibre reinforced polymer part to reduced weight, additional stress concentrations will be introduced effectively lowering the lifespan of the carbon fibre part.

Figure 6.3: Two eight spoke car rims. Left: Aluminium rim, Right: Carbon fibre reinforced polymer rim. [94, 95]

6.3.2. Potential difficulties in designing a composite guitar

When changing the materials of a conventional wooden guitar with composite materials, a similar analysis can be made as done above with the car rim. Below the most important design challenges that are expected to occur are listed.

Formability of resin materials While wooden materials are used as bulk material and modified until the desired shape is obtained, composite resin materials are likely not processable in the same manner. Thermoset resins are required to have a shape as close as feasible to the shape of the desired end product as machining of the materials can be very time and labour intensive. For thermoplastic materials, more freedom could potentially be obtained, however the required production materials might be considerably more complex.

Stiffness of components To perform their respective function in the guitar the components require a certain stiffness. The best example is the guitar neck which is stiff enough to carry the loads of the strings while being compliant enough to form a slight arc to increase the playability of the instrument. Aditionally a truss rod is often installed to provide more freedom in the neck tension and the set-up of the instrument. For composite materials, the stiffness could be made similar to the wooden materials. This however introduces a lot of uncertainty in the product. Making the neck stiffer compared to a normal wooden guitar neck is a viable option as the need for a truss rod is diminished. This results however in less flexibility in the set-up of the guitar and might therefore require higher accuracy when the components are assembled.

Assembly connections Due to the higher stiffness of several parts of the instrument, there is a chance that certain components or adhesive connections become more stressed. An example of this is the increased neck stiffness which will more effectively transfer the load to the neck-block and body. The result might be an overstressed connection in the neck block requiring additional reinforcement.

Brace forming and shaping Braces in a guitar are often shaped and modified using simple hand-tools. This is not possible using composite materials. The machining of composite parts requires more hardware to be used to help shape the braces to the desired dimensions.

Health issues Working with composite materials can be unhealthy for humans. The resins used can cause severe allergic reactions [96]. Additionally fibre dust when sanding or milling for example carbon fibre reinforced composites poses a health risk to the respiratory tract [97].

7

Material comparison and design space

In the previous chapter a number of material parameters was found that ideally should be matched as closely as possible to obtain a composite that has similar acoustic properties to wood. To start off the investigation, a baseline from literature and a set of requirements will be established for the woods typically used for the soundboard as well as the back and sides of the guitar. The baseline will be validated during the main thesis using experiments to obtain the exact parameters such as stiffness, density and damping. After the baseline has been introduced, the design space of material options will be set out in a design option tree. With the material parameters influencing the acoustic properties in mind, a pre-selection of best contenders will be created which will then be further investigated during the main research phase as set-out in chapter 4.

7.1. Wood baseline and requirements for soundboard and back

The baseline of wood focuses mainly on the acoustic parameters for which a number of requirements is to be created (A1,A2,.. requirements). Additionally, as stated in chapter 1, there are a number of downsides to current wooden acoustic guitars which are to be solved by the introduction of composites. These are the sensitivity to humidity and temperature. Therefore next to the parameters that define the acoustic properties, a number of requirements is to be set-up for the evaluation of a newly designed composite on environmental sensitivity (E1,E2,.. requirements). Finally to be adopted by the market, it is important that the composite can compete on a price level. Therefore a number of requirements is set-up to cover the cost performance (C1,C2,.. requirements). It should be noted that although an estimation can be made about the cost effectiveness of the composite by itself, it is unlikely the design and production method will be exactly the same. Keeping the design and production method the same might result in so called "black metal design" as explained in section 6.3. This results in an additional requirement on the overall cost of the instrument which will be covered in a later stage of the research project during the build of a full composite guitar.

7.1.1. Soundboard wood materials

7.1.1.1. Requirements on Acoustic parameters

In chapter 5 it was found that soundboard materials should predominantly be chosen on their effectiveness in radiating sound energy. Therefore a high stiffness and a low density ratio is required where the density is the most important parameter to consider. Soundboard materials for acoustic guitars are generally a medium- or softwood such as spruce or cedar [40]. These woods typically have a density in the range of 400-500 kg/m^3 combined with relatively high stiffnesses between 10-15 GPa in the grain direction. The stiffness parallel to the grain is often a factor 9-15 lower compared to the longitudinal stiffness making the material highly anisotropic. Since the soundboard materials are medium- or softwoods, they have a higher damping compared to the hardwoods often used for the back and sides of high quality acoustic guitars [9].

Considering the above mentioned material parameter quantities and the combined material parameters as presented in section 5.2, a list of requirements can be established.

A1. Stiffness and density The material should have a longitudinal stiffness of at least 12GPa up to a maximum of 16GPa. The transverse stiffness should be between 0.8 and 1.2 GPa where the anisotropy ratio is between 10-12. Additionally the density should be between 400-500 kg/m^3.

A2. Sound radiation energy The composite material should have a similar sound radiation coefficient as spruce resulting in a value for $\sqrt{E/\rho^3}$ of around 12.5.

A3. Speed of sound The speed of sound through the material should be comparable and therefore a ratio of E/ρ of around 5.5 km/s for the longitudinal, along the grain direction and 1.5 km/s for the transverse direction.

A4. Damping As seen in section 5.1.3.3 there are a number of very different measurement methods for the determination of internal damping making one-to-one comparison of the obtained results not possible. Therefore the damping baseline will be determined with high quality wood once the set-up is determined. This ensures that measurement conditions are equal for the tests of the composites which allows for an unbiased comparison.

As can be seen from the requirements on sound radiation energy and speed of sound, both can only be satisfied when both the stiffness in longitudinal and transverse direction as well as the density values are a close match to the those of wood.

7.1.1.2. Requirements on environmental sensitivity

As stated in the introduction of this section, the main goal is to create a composite that has similar acoustic properties to wood without the downsides of wood in terms of sensitivity to humidity and temperature. Therefore additionally two additional requirements can be set-up.

E1. Humidity sensitivity The composite should be at most half as sensitive as wood to changes in relative humidity of the air. This means a humidity expansion or shrinkage coefficient of the composite which is two times lower compared to spruce.

E2. Temperature sensitivity The composite should be at least two times less sensitive as wood to changes in temperature of the air compared to wood. This means a thermal expansion coefficient of the composite which is two times lower compared to spruce.

7.1.1.3. Requirements on costs

The requirements on the costs of the composite are twofold as listed below.

C1. Composite cost efficiency The cost of the new composite should be comparable with the cost of high quality guitar woods.

C2. Design and production efficiency With the introduction of composite instead of wood, the design and production method of the instrument will most likely be affected. The introduction of the composite should not significantly increase the costs of the design and production.

7.1.2. Back (and sides) wood materials

For the back and sides of the instrument a much wider selection of woods is being used for acoustic guitars [9]. Most commonly used are mahogany for budget or entry level guitars while rosewood will generally be used for more expensive and often better instruments [29]. Due to strict regulations on the harvesting of a large number of rosewoods [7], the availability of rosewoods, that used to be considered common for high quality guitars such as Brazilian rosewood, has decreased significantly. East Indian rosewood is one of the more common types of rosewood nowadays since these woods are less regulated and currently have better availability [98].

Below in Table 7.1 a list of common back and sides woods is presented. As can be found from the table, there is a very large spread in properties [99, 100].

Table 7.1: Material properties of several common back and sides woods for acoustic guitars from two sources.

Name	**Stiffness (L)**		**Stiffness (T)**	**Density**	
	[Gpa] [99]	[Gpa] [100]	[Gpa] [99]	$[kg/m^3]$ [99]	$[kg/m^3]$ [100]
Indian rosewood	12.1-14.8	11.50	4.82-5.38	840-1020	830
Brazilian rosewood	10.9-13.3	13.93	4.23-4.72	800-980	835
Honduran mahogany	10.2-12.5	10.06	0.82-0.92	460-570	590
Ziricote	-	10.93	-	-	805
Koa	-	10.37	-	-	610
Cocobolo	-	18.7	-	-	1095
Wenge	-	17.59	-	-	870
African blackwood	-	17.95	-	-	1270
Macassar ebony	9.7-11.9	17.35	6.75-7.54	940-1140	1120

As the back and sides of the acoustic guitar do not have the same significance in sound radiation as the soundboard, there is room for more lenient requirements. The main difference as reported by luthiers is the colouration of the sound. While this is very noticeable for professional acoustic guitarists, it is most likely not recognized by the inexperienced ear. Because of this lower importance in the overall sound of the instrument, the back and sides woods will only be considered in the design of a full composite guitar and will not be considered in the main research for creating a composite with similar acoustic properties.

7.2. General material tree

With the baseline for the wood material set-up, an investigation can be done into the potential composites that can replace wood as material for acoustic guitars. This will be done by setting up a material design tree in which the most important categories of materials are considered. Each of the material categories will be explained after which in section 7.3 a pre-selection is conducted on the materials that will be investigated as set-out in the research plan.

The main material tree as considered in this review is shown in Figure 7.1. Each of these categories and subcategories will be further explained in the subsections below.

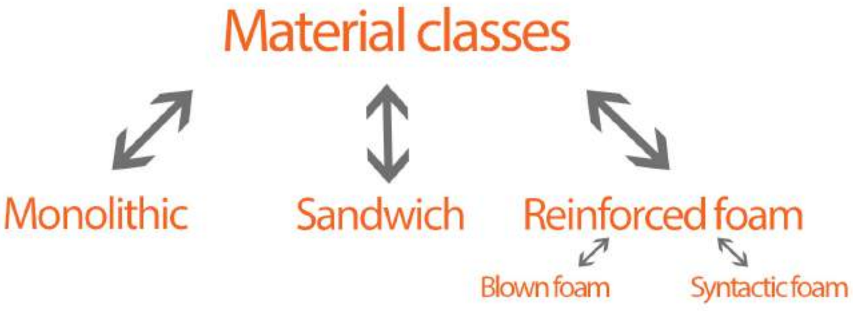


Figure 7.1: Main material categories and subcategories considered for replacement of wood in acoustic guitars

7.2.1. Monolithic composite material

Materials that are monolithic consist of one or more individual components that are combined in such way that it is not possible to distinguish them. In case of a composite such as carbon fibre reinforced plastics, it is possible to distinguish the carbon from the matrix material making it technically speaking not a monolithic material. To distinguish the different types of composite structures such as sandwich and skin-stiffened structures from (thin walled) unsupported structures, the latter is often referred to as a monolithic composite. In this context it refers to for example a fibre reinforced plastic which does not have any other constituents such as a core material or stiffeners.

Monolithic composites can be considered for replacement of wood. As wood has very high anisotropy the most suitable composite alternative is a fibre reinforced plastic as this type of monolithic composite allows a huge freedom in design of the stiffness in longitudinal and transverse direction by varying the number of fibres placed in certain orientations.

Below in Table 7.2 a list of common fibre materials used in fibre reinforced composites are presented [55, 99, 101–105]. Additionally in Table 7.3 the most used matrix materials are presented [55, 99, 102].

Table 7.2: Overview of high performance fibres used in fibre reinforced plastics and their properties in terms of stiffness, strength and density.

	Young's Modulus $[GPa]$	**Strength** $[GPa]$	**Density** $[kg/m^3]$
Carbon fibre (high strength)	230-290	4.1-7.0	1770-1800
Carbon fibre (high stiffness)	390-540	4.6-4.7	1780-1830
Glass fibre (S glass)	81-89	2.7-4.3	2580-2620
Glass fibre (E glass)	72-74	2.5-3.5	2550-2600
Aramid fibre (Kevlar)	60-120	2.4-3.6	1440-1450
Polytethylene fibre (Dyneema)	52-132	2.3-3.9	970-985

Table 7.3: Overview of common matrix materials used in combination with fibre reinforcements as presented in Table 7.2.

	Young's Modulus $[GPa]$	**Strength** $[MPa]$	**Density** $[kg/m^3]$
Thermoset			
Epoxy	2.8-5.5	56-75	1120-1300
Vinyl ester	3-3.7	73-81	1120-1320
Polyester	2.1-3.5	34-103	1100-1430
Polyimide	2-2.8	60-126	1280-1340
Thermoplastic			
Polyether ether Ketone (PEEK)	3.2-3.9	70-103	1300-1320
Poluphenylene Sulfide (PPS)	3.2-3.4	48-83	1340-1360
Polyetherimide (PEI)	2.9-3.1	105	1260-1280

An example of a monolithic composite which is commonly used is a carbon fibre reinforced epoxy. For many applications the loading of a structure is not equal in all directions. Therefore the layup of carbon fibre material can be done in relation to the expected loads acting on the structure. As there is a limit on the volume percentage carbon fibres that can be added to a laminate the properties of a unidirectional layer of carbon are considerably lower than the properties of only the fibres. Below in Table 7.4 the properties of both a glass fibre and carbon fibre unidirectional laminate are presented. These parameters will be used for the comparison with wood in section 7.3.

Table 7.4: Overview of two common UD materials and their properties

		Young's Modulus	**Strength**	**Density**
		[GPa]	[MPa]	[kg/m$\hat{3}$]
Carbon (65-70% weight) epoxy	longitudinal	129-154	1700-1740	1550-1580
Carbon (65-70% weight) epoxy	transverse	8.5	46.8-56.7	1550-1580
S-glass (50-55% weight) epoxy	longitudinal	47.6-47.8	1700-1760	1840-1970
S-glass (50-55% weight) epoxy	transverse	12.7-13.3	62-63	1840-1970

7.2.2. Sandwich materials

Sandwich materials are mainly used to increase the bending stiffness of a structure without considerably increasing the weight. By placing a core material in between two very stiff skins which can be a monolithic composite material, the area moment of inertia is greatly increased making the material deform less under bending loads.

Core materials used for sandwich panels vary greatly. Commonly used are polymer foam cores which vary in density from only a few kilograms per cubic meter to values a fraction higher than the density of water (~1000 kg/m^3) [106]. Additionally honeycomb structured core materials from aluminium and nomex (meta-aramid) can be used but are generally much more expensive [107, 108]. Some good results are obtained with the very light balsa wood but due to the aim of this project to replace wood by a composite, this type of core material will not be considered [109].

For the skins most monolithic materials can be used such as the ones presented in Table 7.4

7.2.3. Reinforced foam materials

Inspired by the work of T.Ono e.a. a reinforced foam material can potentially be created to match wood in acoustic properties [75–77]. Within foam materials two main categories of foam can be considered. These are the gas-blown foams and syntactic foams where the former are created by a chemical reaction creating air bubbles in polymeric material while the latter consists of a polymeric material mixed with a balloon material such as micro scale glass or nomex bubbles. Both categories are discussed below in more detail.

7.2.3.1. Gas blown foam materials

The most well known gas blown foam is Polyurethane foam used for insulation purposes in buildings and many other products [110]. Both open cell flexible Polyurethane foams as well as rigid closed cell foams are available. Closed cell foams can be used for structural applications and can be created in many densities ranging from 25 kg/m^3 to over 850 kg/m^3 [111, 112]. As the application in a musical instrument requires a high stiffness, flexible foams are considered unsuitable.

The unfoamed mixed Polyurethane foam compounds can be poured into a closed mould by which the density of the final foamed product can be increased. This results in a high pressure build-up inside of the mould which should therefore be able to withstand the loads exerted by the foaming process.

The process of foaming of Polyurethane is very quick. Most foam materials have a retarder added to one of the compounds [113]. This delays the start of the reaction to about 45-55 seconds after combining the compounds and start of mixing. The foam expansion speed can be increased or slowed with additives. Generally the foaming takes about 30-75 seconds after which in a few minutes the foam becomes rigid and can be processed further.

Another gas blown foam that can be considered is an epoxy foam material. These materials are generally created by adding a blowing agent to the epoxy [114, 115]. This blowing agent reacts during the hardening process of the epoxy and decreases the cure time. As the cure time of many epoxies can be several hours, the foaming process is very slow and does hardly build up any pressure even in a closed mold [116]. The density of epoxy foams is much higher than those of Polyurethane foams ranging between 250 kg/m^3 to 600 kg/m^3.

7.2.3.2. Syntactic foam materials

By adding hollow glass or plastic bubbles to a resin the density of the system can be greatly reduced without an enormous effect on the properties of the original material. Hollow glass bubbles are available in densities ranging from 125 kg/m^3 to 600 kg/m^3 [117]. There is a significant crush strength difference between the different densities. The glass bubbles will crush under a too high load while the plastic bubbles will flatten but tend to recover after pressure release [118].

The maximum volume percentage of glass bubbles which can be added to a resin is around 60%. Adding a higher quantity of glass bubbles results in dry spots on the surface of the glass bubbles creating a very weak product. Additionally the viscosity of the mixture will increase dramatically when reaching the maximum of 60% glass bubbles making it impossible to further process the mixture. The maximum volume percentage of glass bubbles induces a limitation on how low the density of the syntactic foam can potentially be. When adding fibre reinforcement to the mixture the quantity of glass bubbles has to become even lower as the addition of more particles would otherwise cause not all particle surfaces to be fully wetted. Therefore the limitation on the amount of additives added to the resin system holds not only for the glass bubbles but also for the other reinforcement particles combined.

Another concern that should be taken into consideration is the potential brittleness of the system when high volume percentages of resin are added. While the bubbles can be treated to form very strong bonds with the resin, the bubbles can make the resin system considerably weaker.

7.3. Pre-selection of materials to be investigated in thesis

As can be identified from the previous sections, there is a very large design space to consider when designing a composite to replace wood in acoustic guitars. To allow for a more detailed analysis of potential designs, the goal of this section is to further refine the scope the research and to point out the options that are unlikely to succeed in matching wood acoustically. Additionally a list will be developed of material designs that have the potential to succeed in matching wood acoustically. Each of the categories will be discussed in the same order as presented in subsection 7.2.1 through subsection 7.2.3 after which the final list of material designs to be investigated will be presented in section 7.4.

7.3.1. Monolithic composite material

Most critical in the design of a monolithic composite material to replace wood is the density. As shown in subsection 7.1.1 soundboard wood such as spruce is very light at around 450 kg/m^3. The lightest monolithic material possible is still near 1000 kg/m^3 when looking at Table 7.2 and Table 7.3. Therefore having both equal density and stiffness to satisfy both requirements A2 and A3 in subsection 7.1.1 is impossible.

Looking at the sound energy radiation requirement as the more dominant requirement also shows that monolithic composite designs are not feasible. Taking a very stiff unidirectional laminate of 65% high stiffness carbon in combination with a high quality epoxy results in a stiffness of around 350 GPa and a density of 1580 kg/m^3. This results using Equation 5.44 in a sound energy radiation coefficient of 9.4 which is still considerably lower than the 12.5 achieved by a high quality spruce. Also polyethylene fibre materials, which are considerably lighter than carbon, will only potentially achieve a sound energy radiation coefficient of 7.5-8 when making a 65% filled composite.

Considering the back and sides materials some of the woods could potentially be matched as they have a much higher density than spruce. However since the soundboard is of much more interest for the overall sound of the guitar the monolithic composite materials will not be further investigated in the main part of the thesis.

7.3.2. Sandwich materials

As seen from Equation 5.44 in subsection 5.2.3, the sound radiation energy is dependent on ρ^3. A high stiffness and a low mass to displace makes a material an effective radiator of sound energy. As can be seen from Equation 7.1, the flexural rigidity increases by t^3. Therefore by increasing the thickness of the material the flexural rigidity is greatly increased while the density of the material is effectively lowered. This results in that a sandwich panel is much better in terms of sound energy radiation compared to the monolithic composite materials discussed before.

$$D = \frac{Et^3}{12(1-\nu^2)} \tag{7.1}$$

From Equation 5.34 in section 5.1.3.1 it has been identified that the damping of a composite consisting of two phases with a large stiffness mismatch have a relatively low effective damping. From this it can be anticipated that a carbon UD layer will likely not be damped enough by a core material with factors lower stiffness. Therefore in order to investigate sandwich panels with the highest damping possible while maintaining a low density it was decided to focus on polyethylene which has, according to material databases, a much higher damping than carbon fibre.

7.3.3. Reinforced foam materials

Reinforced gas-blown foam materials show a very high potential to replace wood in acoustic guitars. Carbon reinforced polyurethane foam has already shown great potential in the research of T. Ono e.a. and provides great flexibility in designing the composite by varying the amount of foaming material as well as amount of carbon added to the final product [75–77].

In terms of stiffness and density the gas-blown fibre reinforced foams can be manufactured to specification of a very wide range of values around those of wood making it potentially possible to satisfy all the primary acoustic requirements A1-A3. In terms of damping they are likely to have much lower damping as they do not transfer loads in the same way as sandwich panels do via phases. Since the stiff carbon fibres are largely not in contact with each other they can more easily be damped by the polyurethane foam.

The syntactic foams show a larger restriction in achievable densities due to the limitation on how much glass or plastic bubbles can be added before the surface of the additives cannot be completely wetted anymore. Therefore designs with either glass or carbon are unlikely to succeed. Considering the stiffness of normal carbon fibres about 7% volume of carbon fibres in the longitudinal direction is required to satisfy requirement A1. This results in a requirement on the weight of the resin combined with the glass or plastic bubbles of around 350 kg/m^3. Considering the lightest 3M K1 glass bubbles with a density of 125 kg/m^3 results in a weight of the resin and bubbles combination of at least 550 kg/m^3.

Taking polyethylene fibres such as Dyneema or Endumax will make a combination of syntactic foam with reinforcement feasible to satisfy at least requirement A2 on the sound energy radiation coefficient. Therefore this type of composite will be further investigated while the others will not be further evaluated.

7.4. Material options to be research in main thesis

From the analysis done in the previous sections a list can be constructed of potential materials to be evaluated. These are presented below with a short description. Each of these materials will be further investigated in the main thesis taking in consideration the requirements as set-up in subsection 7.1.1.

Polyethylene reinforced syntactic foam Layup of polyethylene fibres or tape layers glued together with a resin material mixed with glass or plastic micro-balloons.

Polyethylene sandwich material Layup of layers of polyethylene tape material as stiff skins with a polymer foam core material.

Carbon reinforced polyurethane foam Carbon fibres infused with foaming polyurethane.

Carbon reinforced epoxy foam Carbon fibres infused with foaming epoxy.

8

Concluding remarks

The decreasing availability of high quality wood and many considerations on the topic of environmental sensitivity of guitars, there is an increasing need for an alternative to wood in the field of guitar building. Wood supply in some regions is only expected to last up to a decade and many news stories pop-up about artist's instruments being destroyed by airliners.

Composites appear to be able to solve most of the problems in terms of availability and sensitivity but at this time do not offer the same acoustic qualities as their wooden counterparts. Therefore a research thesis is set-up towards the development of an composite acoustic guitar with similar acoustic qualities to wooden guitars. The focus of the thesis will be on the development of a material capable of approaching the acoustic parameters of wood. The three main acoustic parameters were found to be stiffness, density and damping of the material.

To scope the thesis and focus the research on the most promising areas to achieve the goal of obtaining a composite guitar able to compete with wooden guitars, a pre-selection was done on several material groups. In this way four main material options were discovered and will be further evaluated in the main thesis. These are a syntactic foam reinforced with a UHDPE material such as Endumax, a sandwich material with UHDPE and a foam core, and two reinforced blown foam options with Polyurethane or Epoxy foam.

Next to the scoping of the thesis, this overview of relevant literature is written as a knowledge fundament for anyone interested in building guitars and especially composite guitars. For each of the parameters that influence the acoustics of a material, a comprehensive introduction and overview is provided as well as a short-list of potential measurement methods.

A number of insights were discovered in conducting this literature review which are of high importance for the main thesis. These are summarized below.

- In acoustic guitars, the most important component in producing the sound of the instrument is the soundboard. Therefore most attention should be placed towards materials capable of replacing the woods typically used such as spruce.
- In designing a composite capable of replacing spruce, the main design problem is to obtain a high enough stiffness while keeping the density low as most composite materials are too heavy to provide a large enough sound radiation coefficient.
- The damping of the material is the main parameter defining the character and timbre of the instrument. As measurement methods for determining damping are either incompatible for comparison or

are too complex and expensive, focus should be placed on finding a proper method to measure material damping. Additionally there will be a challenge in increasing the damping of the composite as most high stiffness materials have considerably lower damping than wood.

- The redesign of a guitar towards a full composite instrument has many challenges. These revolve mostly around the production method as well as the stiffness differences of several components which might induce playability problems. Therefore great attention should be placed on the final assembly of the instrument.
- For the design of the soundboard, bracing patterns as well as bracing geometry can have a very large influence on the overall sound of the instrument. Similar to the sound radiation coefficient of a simple panel, the braces should provide maximum stiffness while adding as little weight as possible.

II

Development of a composite acoustically similar to wood

9

Introduction to main thesis research

The main thesis research starts at the point where the literature review and project scoping ends with the conclusion that four main types of composites are to be investigated. In order to do this the analysis methods of the main parameters identified as influencing the the acoustics are discussed first. With the analysis methods identified a baseline of wood types can be set-up. This baseline is used as the main reference point for the development of the composites.

In the chapters after the baseline the main composite options are discussed in detail and their viability as a replacement of wood in guitars is assessed. The process of researching these composite options is slightly different than would generally be expected for an academic thesis research. Usually the focus is on answering the main research question which will deliver a certain result of the researched topic on all aspects to be investigated. An example related to this research would be the analysis of differences in soundboard woods used for guitars or the difference in performance of the relative visual grades of a specific type of spruce. The goal is to answer if there is a difference and to describe the difference found on all aspects. The main difference of this thesis is that the aim is to develop a new composite by researching a relatively large design space. To reach the goal of arriving with a feasible result rather than covering all relevant aspects of a composite options, it is decided at several points in this thesis to stop the investigation of a particular option as it shows a lower probability of resulting in a feasible option to replace wood in acoustic guitars. This results in some options being investigated in considerably less detail than others.

Once a feasible composite option is obtained and the acoustic requirements as discussed in chapter 7 are met, the other requirements in terms of environmental sensitivity and cost efficiency are discussed. With the composite analysis complete, a short initial investigation is done on the potential applications of the developed composite in the field of Aerospace engineering. Finally the main thesis research on the development of the composite is concluded and recommendations are presented for further development and research.

10

Methodology of material parameter analysis

This chapter provide the main testing methodology used for the analysis of both the wood and composite samples. In chapter 5 the main acoustic material parameters were found to be the stiffness, density and damping of the material. The methodology used to analyse these parameters is discussed below and builds on the main testing methods found in chapter 5.

10.1. Stiffness analysis method

The stiffness tests are performed using two methods. The first method is used for smaller test samples as described in subsection 10.1.1 while the second method uses larger samples and therefore uses a slightly modified test set-up as described in subsection 10.1.3

10.1.1. Stiffness method 1

The first soundboard wood baseline stiffness is obtained using small tensile samples. The decision to use smaller test samples than is customary was made in order to amplify the potential defects of small areas in a larger sample. A small defect on a small sample will show a considerable effect on the performance while the same small defect on a larger sample will have less effect. A secondary goal for the soundboard baseline is to establish if there is a considerable difference in performance of the different wood grades tested the samples are scaled down to provide information about the uniformity of each of the grades. This is done to provide additional scientific insights for the companies sponsoring the baseline wood materials.

Stiffness testing is done by placing the samples in a 20kN Zwick tensile testing machine. As the samples are quite small, sanding paper was positioned between the sample and clamp to ensure proper gripping of the samples to prevent them from sliding out at higher loads. The tests were conducted over a timespan of 2 days. The temperature and relative humidity which are known to potentially affect the results were constant for both testing days between 47-49% relative humidity and 22 degrees Celsius.

The software used to read-out the machine values is TestXpert which allows for good visualization of the test results and offers an easy export to Microsoft Excel for further processing of the obtained data. The main data recorded is the tensile force exerted by the machine on the samples and the change in voltage measured by an amplifier with a built-in Wheatstone bridge. This change in voltage is caused by a change in resistance of the strain gauge attached to the wood specimen. The strain gauges used are KYOWA KFG-5-120-C1-23 type strain gauges with a gauge factor of 2.12±1.0%. The strain gauges were attached to the wood specimens using Kyowa CC-33A strain gauge cement. In Figure 10.1 the attached strain gauge to a master grade sample is shown. Additionally in Figure 10.2 the test set-up is shown.

Figure 10.1: Strain gauge attached to a master grade sample (MA-L-4) used for the determination of stiffness.

Figure 10.2: Wood sample set-up in the Zwick 20kN testing machine with the strain gauge attached to the Wheatstone bridge amplifier.

10.1.1.1. Determination of strain

For the longitudinal samples of the wood the amplifier was set-up so that a difference of 10V would indicate a strain of 1% whereas for the transverse samples the device was set so that 1V would correspond to 1% strain. This was done as the transverse stiffness of spruce is often at least a factor 10 lower than the longitudinal (along the grain) direction and a lower accuracy therefore offers enough resolution to accurately determine the stiffness.

10.1.1.2. Determination of stress

To determine the stress applied to the wood specimen Equation 10.1 can be used. In this equation σ is the stress, F the force, w the width of the sample at the location of the strain gauge and t the thickness of the sample at the location of the strain gauge.

$$\sigma\,[MPa] = \frac{F\,[N]}{w\,[mm]\cdot t\,[mm]} \tag{10.1}$$

10.1.1.3. Determination of stiffness

Finally the stiffness can be calculated by using Equation 10.2, where ϵ is the non dimensional strain converted from the voltage data obtained from the strain gauge.

$$E\,[GPa] = \frac{\Delta\sigma\,[MPa]}{\Delta\epsilon\,[-]}\cdot 10^{-3} \tag{10.2}$$

The Δ illustrates that the calculation of stiffness is done over a certain portion of of the stress-strain curve that is created using the output of the test and formula in subsubsection 10.1.1.1. For each of the test output curves, a section of the curve was chosen on which the stiffness calculation was performed. The aim was to not include any section where an artefact was visible such as a small slip in the clamps during the test. Furthermore an as large as possible and artefact free section of the curve was used to obtain most accurate results.

10.1.2. Results processing

All results were processed using Microsoft Excel. The output data presented in chapters 11 through 14 is all a direct output of the calculations made in the Microsoft Excel model.

10.1.3. Stiffness method 2

The second stiffness method used for wood used for back and sides of guitars as well as for all composite samples tested has two main differences compared to the stiffness measurement method 1 as described above. First the test samples are considerably larger with a width of 25 mm and a length of 200 mm. This allows for a larger grip separation of 140 mm. The second modification to stiffness measurement method 1 could therefore be made on the strain measurement. Using the larger grip to grip separation the long stroke extension meter provides a high enough accuracy and additionally provides the stiffness measurement over a larger portion of the sample. A photo of a sample in the 20 kN Zwick tensile testing machine using the long stroke extension meter is presented in Figure 10.3

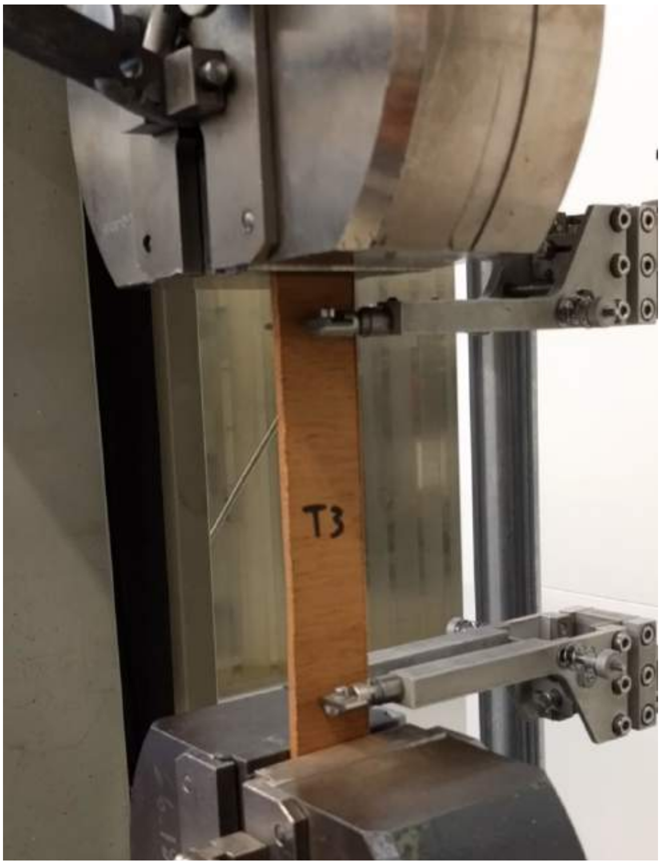


Figure 10.3: Wood sample positioned in the Zwick 20kN testing machine with the long-stroke extension meter attached.

10.2. Density calculation

The density of each of the samples is determined by measuring the dimensions of the specimen at several locations and calculating the volume. The sample mass is measured on a high accuracy scale after which the density can be calculated with the formula in Equation 10.3

$$\rho\,[kg/m^3] = \frac{m\,[kg]}{V\,[m^3]} \tag{10.3}$$

The reason for using this method is that a higher accuracy of density determination does not add significantly to the outcome of the baseline. Therefore this simple method is considered enough and no other density determination methods as described in chapter 5 will be used.

10.3. Modal analysis and damping

The modal analysis set-up is built according to the set-up as used by Dr. Ir. Alijiani [86]. This set-up is described in subsubsection 5.1.3.3. The same laser scanning head, a Polytec PSV400, was used. Similarly a frame for hanging the test panels was constructed. Using a test with a steel plate several suspension systems were used to find the optimal boundary type. This was done to limit the damping caused by the chords and have no additional peaks in the FRF (frequency response function) data due to resonance of the chords. Elastic chords proved to be highly influencing the damping and caused additional resonance peaks close to the first two modes of the panels tested. Thin elastic chords did not provide enough support to the panels and introduced an additional 4 resonance peaks as the chords are not uniformly loaded. In the end it was decided to use thin fishing lines to suspend the panel which dramatically improved the noise performance of the test set-up and also provided more repeatable data. A stinger was constructed by drilling a small hole in an M8 screw which fits in the Bruel & Kjaer type 4809 shaker. In the small hole in the screw a thin aluminium chord with a diameter of 1 mm is glued and on the other end a M3 screw is connected in a similar fashion. This screw fits in a connection piece which connects the stinger to the load cell which in turn is screwed on the test-sample. The full test set-up and a detail of the stinger connection is provided in Figure 10.4

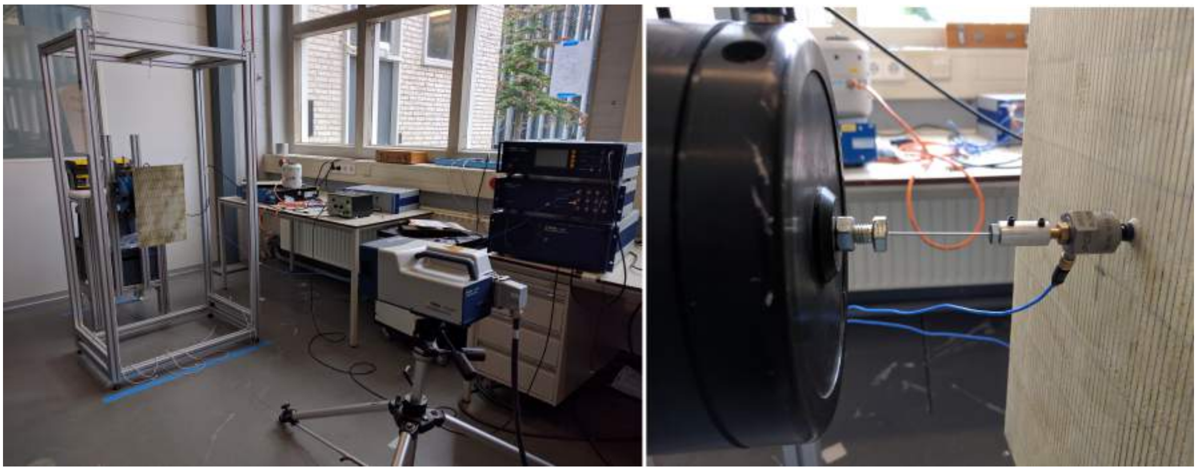


Figure 10.4: Left: overview of the test set-up as used. Right: detail of the stinger connection.

An investigation was done on the maximum achievable frequency range that would provided accurate data. Preferably data should be obtained up to 20 kHz as this covers the full audible frequency range. It was found however that due to the limitation of the used load cell, a PCB 288D01, a frequency up to only 2 kHz could be used to provide accurate data. As the dominant modes of the panels are all occurring below 500 Hz the analysis was chosen to be done on a frequency range from 0-1000 Hz which provides, due to the maximum of 6400 FRF lines, a higher resolution which allows for a more accurate damping analysis.

The extraction of modal damping values was originally conducted with MeScope which performs accurate damping analysis. However the results obtained from this analysis did not provide realistic numbers. For several modes the damping was found to be extremely high while for other modes the damping was found to be factors lower when comparing two panels of wood. Additionally depending on the selected analysis range and damping analysis method a large difference in results was obtained. As MeScope is a closed programme and no additional support could be arranged in time it was decided to use the peak amplitude method as described in subsubsection 5.1.3.3. The data from the Polytec data acquisition system was exported to a universal file and loaded into Matlab. The averaging of data was performed using a script and plotted to obtain the same plots as shown in the interface of the Polytec system. The data points needed for performing the peak amplitude on five of the most dominant models were extracted and copied to Microsoft Excel where interpolation was used to find the frequencies at half amplitude. Finally the damping formulae defined in subsubsection 5.1.3.3 are used to calculate the damping values. The five dominant modes are visualised in Figure 10.5.

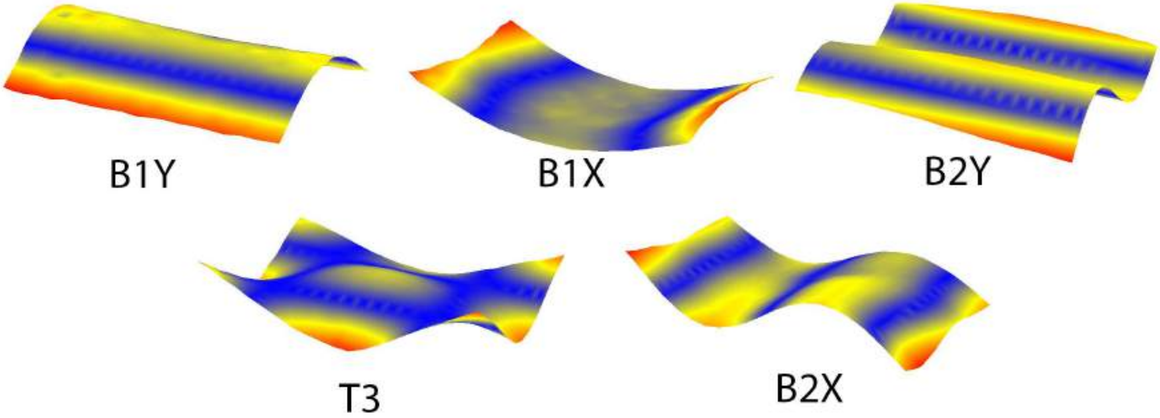


Figure 10.5: Five modeshapes investigated in detail. Form left to right, top to bottom: first bending in Y direction (B1Y), First bending in X direction (B1X), second bending in Y direction (B2Y), third torsional mode(T3), second bending in X direction (B2X)

10.4. Environmental sensitivity

The environmental sensitivity of the composite and wood samples is determined by analysing both the thermal sensitivity as well as the sensitivity to a change in relative humidity. Due to the limitation of the equipment available to perform tests under a controlled humidity, two different tests are used to obtain insights in the sensitivity to humidity of the composite relative to wood. These methods do not provide direct insight in the damage risk of exposing a full instrument to environmental effects. But they will provide early indications regarding the performance of the composite (compared to wood) with respect to more severe environmental conditions.

10.4.1. Thermal sensitivity

The thermal sensitivity of the samples is analysed using Thermal Mechanical Analysis (TMA). Cubic samples of approximately 3.5 mm are positioned under the probe after which the chamber is cooled down using liquid nitrogen to below -10 degrees Celsius. Once the chamber temperature nears -10 degrees Celsius after overshooting the test is started and the sample is heated up using a ramp up of 2 degrees Celsius per minute to 90 degrees Celsius. This temperature is then held for 15 minutes after which cooling down is done with 2 degrees Celsius per minute. A photo of the sample inserted under the measurement probe of the TMA machine is shown in Figure 10.6

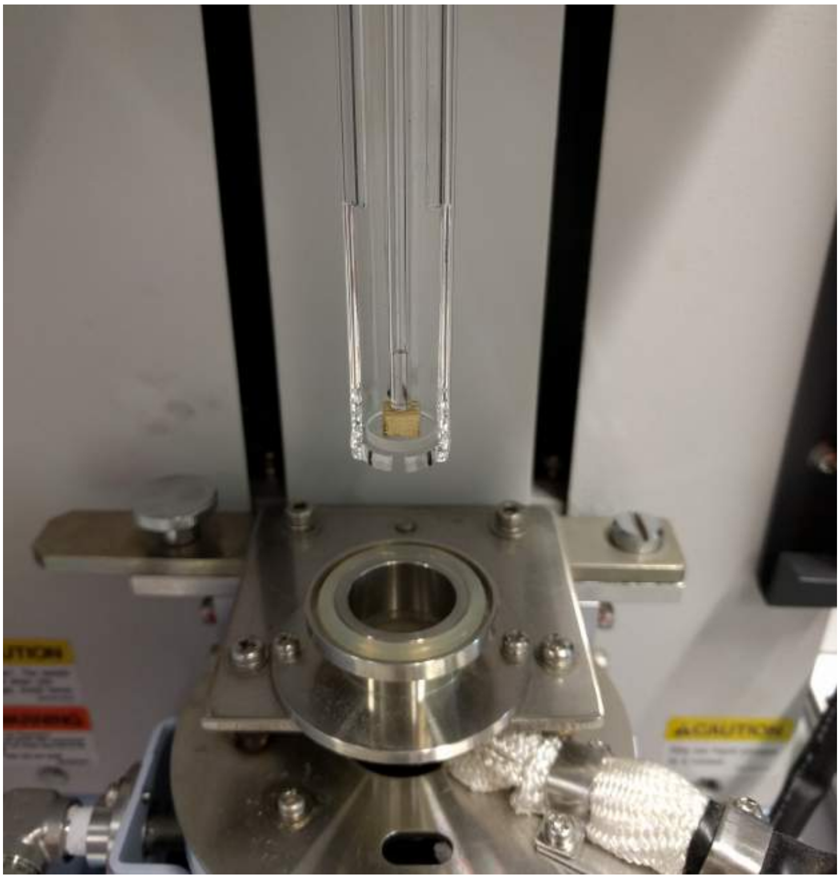


Figure 10.6: Wood sample positioned under the measurement probe of the TMA machine.

The results are exported to an ASCII format text file and loaded in Microsoft Excel. The data is further processed by calculating the relative expansion of the each of the measurement points. The thermal expansion coefficient is calculated over a large linear portion of the resulting curve.

10.4.2. Relative humidity sensitivity

The relative humidity sensitivity analysis is conducted using two tests. These tests are described below.

10.4.2.1. Wet TMA method

A second TMA test such as described above was conducted using an additional set of samples. The samples, after being placed in water for 24 hours and left to dry for one hour. As the TMA test takes roughly 2 hours before the next sample can be loaded, a schedule was used to place the samples in and take them out of the water to ensure the total time in the water and drying time is the same for all samples. The data is processed like the normal TMA test.

10.4.2.2. Water absorption test

The second test measures the moisture content of a sample after being placed in water for a certain amount of time. All samples are first dried in an oven for 4 hours on 60 degrees Celsius and measured immediately afterwards on a high precision scale. For both the wood and the composite three samples are tested for each test set. The first test set is left on a dry table for 24 hours after which the mass is remeasured and the difference in mass is calculated. For the second test the samples are placed under water for 1 hour after which they are left to dry on a dry table for 1 hour. Again the samples are weighted and the difference in mass is calculated. The third test set extends the time of the samples in the water to 24 hours after which the same procedure is followed as for the other test sets. The data is processed using Microsoft Excel.

11

Baseline of relevant wood species

With the goal to match the acoustic properties of a composite with those of wood a baseline is to be set-up to establish a number of baseline parameters. While reliable data about the density and stiffness of wood is available in literature as shown in chapter 7, there is almost no comparable data with respect to the modal analysis and damping behaviour. In this chapter both the soundboard woods as well as three common back and sides woods will be investigated with the aim of establishing the baseline. Additionally both sections have a secondary focus to provide the sponsors of the materials with additional information about their products. For the soundboard woods this secondary focus is around the uniformity of the woods and the difference between visually graded woods provided by Florinett AG in Switzerland. For the secondary focus of the back and sides woods as provided by Madinter in Spain an attempt is made in quantifying and providing a scientific basis to the perceived acoustic characters of each of the three types of woods as reported by many luthiers around the world.

11.1. Soundboard wood baseline

The woods investigated for the soundboard wood baseline are several grades of moon harvested Alpine spruce provided by Florinett AG in Switzerland. Small samples of Moonspruce in three different grades A, AA/AAA and Master Grade were provided and for the modal analysis woods in these three different grades were purchased. A photo of the material from which the small stiffness and density test samples were sawn is presented in Figure 11.1.

11.1.1. Density baseline

In Table 11.1 the volume, weight and density measurements are presented.

In order to arrive at the conclusion whether there is a difference in density between different grades of wood the average of the samples as well as the standard deviation is calculated and presented in Table 11.2. Samples A-L-2 and AA/AAA-L-2 can be considered outliers because they show a large deviation from the other samples. Therefore for the analysis of the results both cases with and without outliers are considered to be able to tell something about the overall performance of different grades of wood.

As can be seen from Table 11.2 the density of longitudinal samples shows an increasing density towards higher grades as well as a higher uniformity (lower standard deviation). The transverse samples however show a completely opposite result. In this case the density difference is negligible while the standard deviation is lowest for the A grade samples. Therefore it can be concluded that the density and uniformity in terms of

Table 11.1: Overview of sample dimensions, weight and density

Sample	t [mm]	w [mm]	l [mm]	volume [mm^3]	mass [g]	ρ [kg/m^3]
A-L-1	4.53	7.48	97.1	3290	1.37	416
A-L-2	4.57	8.11	97.3	3606	1.24	344
A-L-3	4.42	6.68	97.7	2885	1.12	388
A-L-4	4.51	7.35	97.5	3232	1.26	390
A-T-1	5.23	7.49	96.4	3776	1.52	403
A-T-2	5.07	7.27	96.2	3546	1.42	400
A-T-3	4.86	7.75	96.2	3623	1.45	400
A-T-4	4.92	7.55	96.1	3570	1.45	406
AA/AAA-L-1	4.39	7.70	96.4	3259	1.45	445
AA/AAA-L-2	4.22	7.69	96.3	3125	1.29	413
AA/AAA-L-3	4.31	7.73	96.3	3208	1.45	452
AA/AAA-L-4	4.35	7.88	96.7	3301	1.53	463
AA/AAA-T-1	4.47	7.25	98.2	3182	1.33	418
AA/AAA-T-2	4.51	7.98	97.9	3523	1.48	420
AA/AAA-T-3	4.62	7.21	98.5	3281	1.4	427
AA/AAA-T-4	4.53	8.05	98.1	3577	1.52	425
AA/AAA-T-5	4.43	7.8	98.0	3386	1.42	419
MA-L-1	4.85	8.03	97.2	3786	1.65	436
MA-L-2	4.83	7.07	97.4	3326	1.53	460
MA-L-3	4.74	8.15	97.0	3747	1.68	448
MA-L-4	4.76	7.78	97.1	3596	1.64	456
MA-L-5	4.82	7.57	97.4	3554	1.62	456
MA-T-1	4.84	7.98	96.8	3739	1.49	399
MA-T-2	4.83	8.08	96.4	3762	1.54	409
MA-T-3	4.75	7.32	96.9	3369	1.42	421
MA-T-4	4.79	7.91	97.0	3675	1.55	422
MA-T-5	4.77	7.74	96.6	3566	1.45	407

Table 11.2: Average sample density and standard deviation by grade and by orientation including and excluding outliers

Grade	Avg. ρ [kg/m^3]	Std. ρ [kg/m^3]	Avg. ρ [kg/m^3]	Std. ρ [kg/m^3]
Incl. outliers	*longitudinal*	*longitudinal*	*transverse*	*transverse*
A	385	26.04	402	2.40
AA/AAA	443	18.82	422	3.40
MA	451	8.56	412	8.96
Excl. outliers				
A	398	12.90	402	2.40
AA/AAA	453	7.64	422	3.40
MA	451	8.56	412	8.96

Figure 11.1: Photo of each of the three grades used for the tests.

density are sample dependent. Considering the small number of samples used in the tests no solid conclusion can be made about the relation with uniformity and density towards the different grades of wood. At this point the samples do not show a clear link with the grade of wood.

11.1.2. Stiffness baseline

In Table 11.3 and Table 11.4 the results for the stiffness calculations are presented. This includes the force and voltage raw data points used to indicate which section of the results curve is used. The corresponding results curves are shown in Appendix II.

Table 11.3: Stiffness calculation table for transverse test samples

Sample	**t** $[mm]$	**w** $[mm]$	**area** $[mm^2]$	**strain1** $[V]$	**strain2** $[V]$	**Δstrain** [-]	**Force1** $[N]$	**Force2** $[N]$	**ΔStress** $[MPa]$	**Stiffness** $[GPa]$
A-L-1	4.53	7.48	33.9	0.251	0.850	0.000600	73.5	326.1	7.45	12.43
A-L-2	4.57	8.11	37.1	0.800	2.500	0.001700	196.0	693.4	13.42	7.89
A-L-3	4.42	6.68	29.5	0.500	1.500	0.001000	136.2	455.7	10.82	10.82
A-L-4	4.51	7.35	33.1	0.500	1.500	0.001000	216.6	609.2	11.84	11.84
AA/AAA-L-1	4.39	7.7	33.8	0.500	1.400	0.000900	213.2	576.2	10.74	11.94
AA/AAA-L-2	4.22	7.69	32.5	0.201	1.500	0.001300	74.4	457.1	11.79	9.07
AA/AAA-L-3	4.31	7.73	33.3	0.501	1.501	0.001000	193.6	578.1	11.54	11.53
AA/AAA-L-4	4.35	7.88	34.3	0.501	1.500	0.001000	237.3	684.7	13.05	13.06
MA-L-1	4.85	8.03	38.9	0.500	1.250	0.000750	271.2	636.5	9.38	12.51
MA-L-2	4.83	7.07	34.1	0.501	1.500	0.000999	257.6	692.9	12.75	12.76
MA-L-3	4.74	8.15	38.6	0.500	1.251	0.000751	277.7	644.6	9.50	12.64
MA-L-4	4.76	7.78	37.0	0.751	1.251	0.000500	448.1	717.1	7.27	14.52
MA-L-5	4.82	7.57	36.5	0.501	1.250	0.000749	336.3	684.1	9.53	12.72

As can be observed from the values for the longitudinal samples in Table 11.3, all of the tested grades show one outlier. These results are considered outliers as there are no two possible sets of results for the stiffness

Table 11.4: Stiffness calculation table for transverse test samples

Sample	**t** [mm]	**w** [mm]	**area** [mm^2]	**strain1** [V]	**strain2** [V]	**Δstrain** [-]	**Force1** [N]	**Force2** [N]	**ΔStress** [MPa]	**Stiffness** [GPa]
A-T-1	5.23	7.49	39.2	0.100	0.3506	0.002506	11.00	98.55	2.23	0.892
A-T-2	5.07	7.27	36.9	0.100	0.3507	0.002507	19.35	104.82	2.32	0.925
A-T-3	4.86	7.75	37.7	0.101	0.3509	0.002501	8.82	85.74	2.04	0.817
A-T-4	4.92	7.55	37.1	0.100	0.3500	0.002497	13.46	83.06	1.87	0.751
AA/AAA-T-1	4.47	7.25	32.4	0.101	0.3498	0.002493	16.62	101.72	2.63	1.053
AA/AAA-T-2	4.51	7.98	36.0	0.100	0.3498	0.002502	25.63	136.39	3.08	1.230
AA/AAA-T-3	4.62	7.21	33.3	0.100	0.3507	0.002506	22.31	134.25	3.36	1.341
AA/AAA-T-4	4.53	8.05	36.5	0.100	0.3506	0.002503	38.75	182.31	3.94	1.573
AA/AAA-T-5	4.43	7.8	34.6	0.100	0.3499	0.002497	31.90	158.54	3.67	1.468
MA-T-1	4.84	7.98	38.6	0.101	0.3508	0.002501	32.26	146.12	2.95	1.179
MA-T-2	4.83	8.08	39.0	0.100	0.3495	0.002494	25.42	136.45	2.85	1.141
MA-T-3	4.75	7.32	34.8	0.100	0.3509	0.002507	21.47	127.78	3.06	1.220
MA-T-4	4.79	7.91	37.9	0.100	0.3508	0.002505	45.02	164.05	3.14	1.254
MA-T-5	4.77	7.74	36.9	0.101	0.3502	0.002494	26.69	143.97	3.18	1.273

that have an equally big difference. For the A and AA/AAA grade samples the outlier shows a huge stiffness drop while for the master grade samples the outlier shows a much higher stiffness. For the transverse samples, there is no clear indication of any outliers. Although for the AA/AAA samples the difference in stiffness can be considered quite big, there is no indication that the results contain outliers.

In the Table 11.5, the results are averaged and a standard deviation is calculated for each of the respective grades. The calculations are performed both including as well as excluding the outliers samples (A-L-2, AA/AAA-L-2, MA-L-4).

Table 11.5: Summarized results of stiffness test showing the average and standard deviation for both longitudinal and transverse samples

Grade	avg. Stifness [GPa]	std. Stifness [GPa]	avg. Stifness [GPa]	std. Stifness [GPa]
	longitudinal	longitudinal	transverse	transverse
Incl. outliers				
A	10.74	1.74	0.846	0.068
AA/AAA	11.40	1.45	1.333	0.181
MA	13.03	0.75	1.213	0.049
Excl. outliers				
A	11.70	0.67	0.846	0.068
AA/AAA	12.18	0.64	1.333	0.181
MA	12.66	0.10	1.213	0.049

11.1.3. Review of longitudinal stiffness

From Table 11.5 it can be derived that the higher grade wood samples consistently show a higher longitudinal stiffness than the lower grade samples. This holds both for the calculations including and excluding the perceived outliers. Therefore it can be said with reasonable certainty that Master grade wood is most interesting when an instrument builder is looking for the material with the highest stiffness.

More interesting is the standard deviation between the different grades as this is the main indicator of uniformity of the wood grade. As can be seen from Table 11.5 the higher grade wood samples show a much smaller standard deviation indicating a better uniformity throughout a larger piece of the wood. This indicates that musical instrument builders that work largely with hand-tools and do the voicing of their musical instruments will have an easier task as the wood has a more predictable character throughout the soundboard.

A note should be made on the quantity of samples tested. For both the A as well as the AA/AAA only 4 samples were tested of which 1 of each set is considered an outlier. While this sample quantity is considered enough to answer the question if there is a considerable difference in uniformity to decide to build with higher quality woods, it is not enough to give a conclusion about the severity of the difference between the different grades.

When considering the outliers, it has been observed that the outliers (A-L-2 and AA/AAA-L-2) show local differences in grain orientation which is not visible on the other samples. From the photos as provided in Appendix I it can be observed that these two samples have a considerable less straight grain orientation than the other samples. As wood is highly anisotropic, the angled or curved grain orientation dramatically drops the stiffness in the longitudinal direction. The stiffness of the outlier samples is around 30% lower than that of the other samples. The difference between the stiffness of the different grades excluding the outliers is less than 10%. Therefore the importance of straight grained wood samples appears to be much higher than that of smaller grain separation often found in higher grade woods. As the test was performed with a limited number of samples, these numbers for relative importance give only a preliminary indication. For more reliable results a test with a higher quantity of small visually graded samples should be used.

11.1.4. Review of transverse stiffness

As for the transverse samples no outliers were registered and therefore the values for including and excluding outliers in Table 11.5 are equal. Interestingly there is an increase in stiffness when going from A grade to AA/AAA grade while there is a slight drop in stiffness when going from AA/AAA to MA grade. This difference might potentially be caused by the limited quantity of samples tested.

Next to the higher stiffness of the AA/AAA samples, there is also a much larger standard deviation for these samples indicating a larger non-uniformity. Again this is unexpected as the A grade shows a lower standard deviation. The master grade samples show the lowest standard deviation as was expected.

A number of samples was not able to withstand the maximum load of 200 N applied to each of the specimens. Interestingly the AA/AAA grade and master grade samples failed in 3 out of 5 tests per set while only 1 out of 4 samples of the A grade failed. However as not all samples were tested to maximum load these results do not provide any reliable insights towards the strength difference between the grades. Additionally the limited width of the samples makes the set-up very sensitive to a slightly angled tensile pulling direction and can therefore not be considered to provide accurate results.

11.1.5. Modal analysis baseline

In Figure 11.2 the frequency responses of three different grades of wood are presented. From the response it can be seen that below 100 Hz two main peaks are visible for every type of wood. These are the first bending modes in Y and X direction respectively.

The damping and frequency values of the five dominant modes are presented in Figure 11.3. When comparing the damping and frequency values of the woods a relatively large difference can be observed. This again illustrates that the mechanical properties of a wood sample can be very different from the next sample due to the growth conditions of the three.

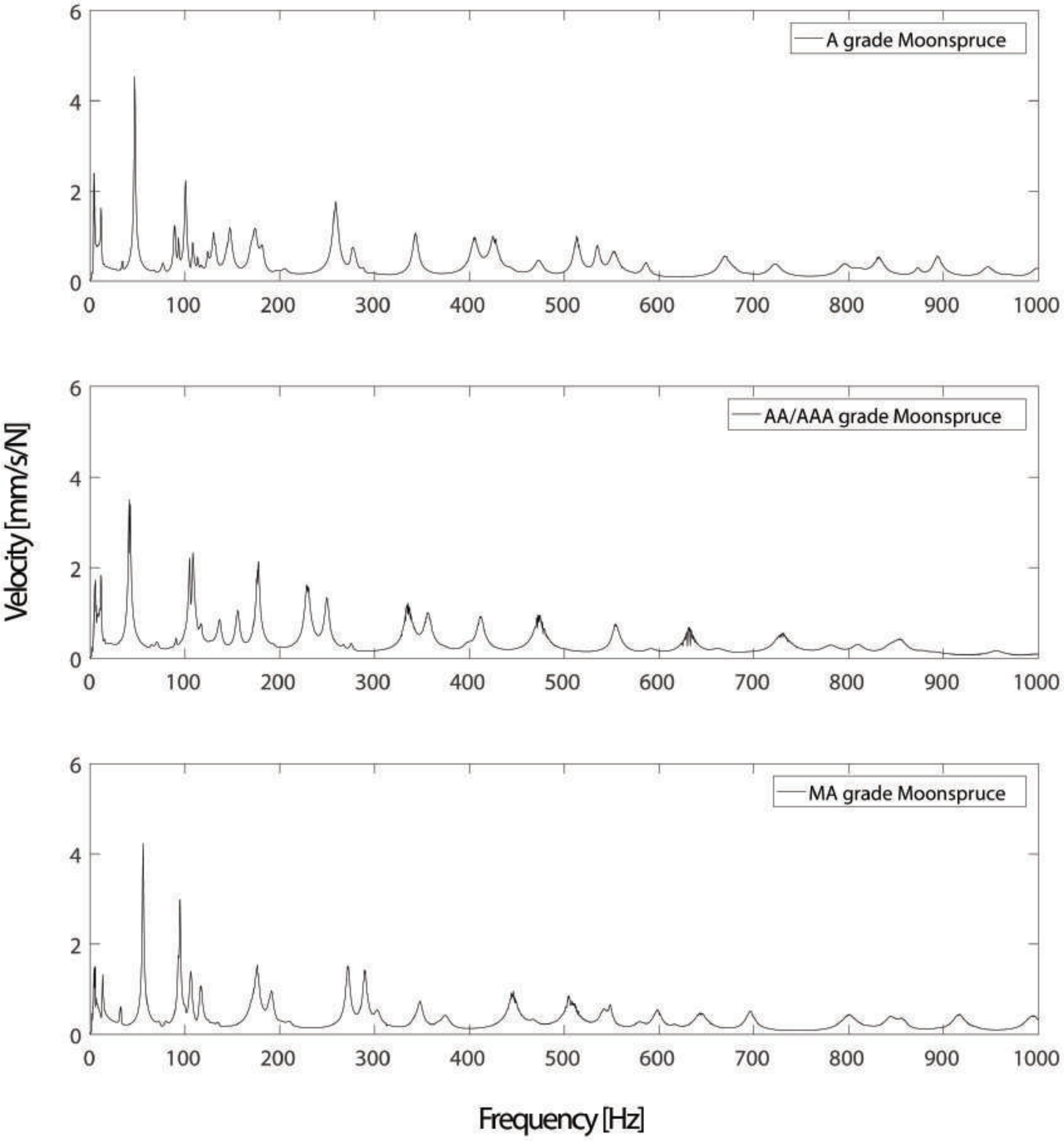


Figure 11.2: Frequency response curves of three grades of wood from 0-1000 Hz

11.1.6. Conclusion on soundboard woods

Considering the values obtained for the analysis of density and stiffness of the Moonspruce samples it can be stated that the initial targets as set-out in chapter 7 can remain in place. These targets are restated below.

- The material should have a longitudinal stiffness of at least 12GPa up to a maximum of 16GPa
- The transverse stiffness should be between 0.8 and 1.2 GPa.
- The anisotropy ratio should be between 10-12.
- The material should have a density between 400-500 kg/m^3

In terms of damping a baseline is established. The difference in damping between the grades is relatively large. Therefore the main goal will be to create a composite that has damping values for these modes close to

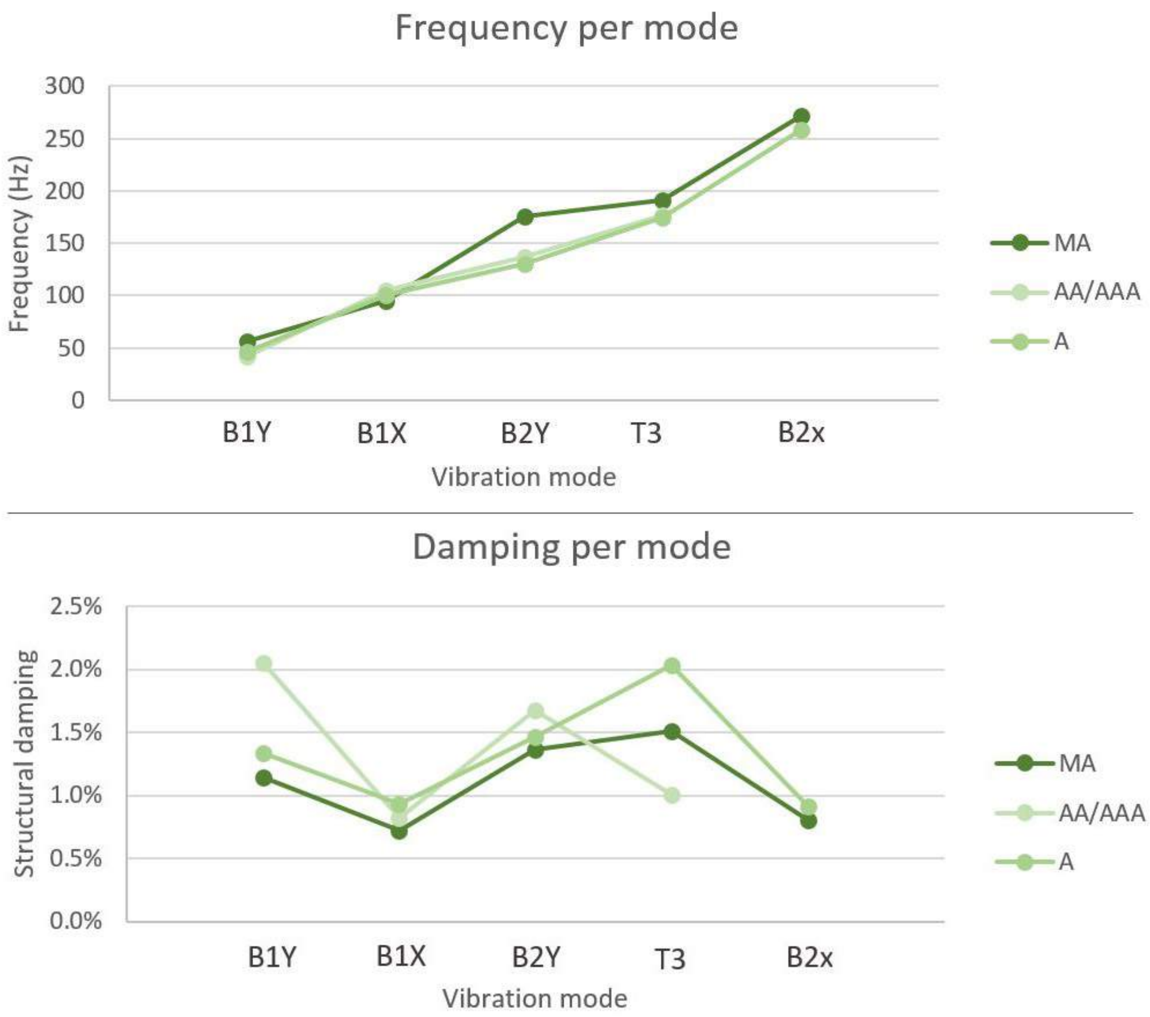


Figure 11.3: Top: frequencies of the 5 dominant modes investigated. Bottom: damping values of the 5 dominant modes investigated.

or between the three grades of wood tested.

11.2. Back and sides wood baseline

As the back and sides wood are considered less important than the soundboard woods and also has more lenient requirements on density and stiffness a consolidated version of the results will be presented concerning the density and stiffness. The woods tested are East-Indian rosewood, mahogany and wenge. No wenge wood samples were tested in terms of stiffness due to a limitation in the quantity of material which could be obtained. A photo of the wood types is presented in Figure 11.4.

11.2.1. Density baseline

The density of the panels was measured by measuring the weight of the complete panels as used for the modal analysis. The panels are all flattened to a thickness of 3.4 mm using a thicknesser and both the length and width of the panels was sawn and sanded to 450 mm by 300 mm respectively. The resulting densities are listed below.

Figure 11.4: Back and sides woods investigated. From left to right: mahogany, wenge, East-Indian rosewood.

- East-Indian rosewood: 806 kg/m^3
- Mahogany: 542 kg/m^3
- Wenge: 693 kg/m^3

11.2.2. Stiffness baseline

The stiffness of the East-Indian rosewood and mahogany samples was tested using the stiffness testing method as described in subsection 10.1.3. The results of the measurements is presented in Table 11.6. The EIR samples correspond to the East-Indian rosewood samples where L1 stands for the first sample tested in longitudinal or grain direction. Similarly T1 is the first sample tested in transverse or parallel to the grain direction.

As can be seen from the results the East-Indian rosewood samples are highly different in stiffness although they are sawn from the same board and are positioned next to each other. This is caused by the waving grain pattern which causes the main reinforcement to be under an angle for some of the samples. The stiffness ranges from around 7.5 GPa to almost 15 GPa which is almost a 100% difference. The waving grains also have a large effect on the transverse stiffness. The increased reinforcement by the grains in transverse direction results in a much higher transverse stiffness compared to the spruce samples tested before. Additionally for the transverse stiffness the results are however considerably more uniform. In order to determine if these characteristics are common for rosewood more samples including those with a more uniform and straight grain pattern should be obtained and tested. The number of samples tested is considered too low to provide a definitive conclusion.

11.2.3. Modal analysis baseline

In Figure 11.5 the frequency responses of three different types of back and sides woods are presented.

The damping and frequency values of the five dominant modes are presented in Figure 11.6. It can be seen that the frequency of the first and second bending mode in Y direction of the East-Indian rosewood panel is significantly higher. This is in line with the results in terms of stiffness. Additionally the damping values of the East-Indian rosewood are decreasing towards higher frequencies. As luthiers often attribute a more

Table 11.6: Stiffness calculation table for East-Indian rosewood and mahogany samples in longitudinal and transverse directions.

Sample	**t** [mm]	**w** [mm]	**area** [mm^2]	**strain1** [V]	**strain2** [V]	**Δstrain** [-]	**Force1** [N]	**Force2** [N]	**ΔStress** [MPa]	**Stiffness** [GPa]
EIRL1	3.59	26.23	94.09	0.200	0.600	0.003618	2577.8	5121.4	2.70	7.47
EIRL2	3.47	25.74	89.23	0.300	0.600	0.002731	3909.7	6690.2	3.12	11.41
EIRL3	3.38	25.20	85.09	0.200	0.600	0.003645	2997.6	7582.0	5.39	14.78
EIRL4	3.33	26.19	87.20	0.100	0.300	0.001823	1722.0	3634.9	2.19	12.03
EIRL5	3.30	26.06	85.92	0.200	0.500	0.002734	2080.7	4021.8	2.26	8.26
EIRT1	3.32	26.29	87.21	0.150	0.300	0.001367	356.7	587.0	0.26	1.93
EIRT2	3.41	26.47	90.25	0.100	0.400	0.002735	273.2	746.9	0.52	1.92
EIRT3	3.39	27.04	91.74	0.100	0.500	0.003646	284.4	955.6	0.73	2.01
EIRT4	3.40	26.40	89.86	0.100	0.500	0.003638	182.5	835.4	0.73	2.00
EIRT5	3.38	26.17	88.36	0.100	0.300	0.001822	190.5	493.2	0.34	1.88
MAHL1	3.56	28.22	100.55	0.200	0.600	0.003646	2256.9	6080.0	3.80	10.43
MAHL2	3.47	28.17	97.67	0.200	0.600	0.003646	2071.6	5823.8	3.84	10.54
MAHL3	3.50	28.12	98.43	0.200	0.600	0.003647	2070.2	5469.0	3.45	9.47
MAHL4	3.37	28.05	94.42	0.200	0.600	0.003647	1639.7	5081.9	3.65	10.00
MAHL5	3.52	28.09	98.96	0.200	0.600	0.003648	1551.3	4919.4	3.40	9.33
MAHT1	3.28	28.02	91.81	0.200	0.600	0.003650	183.8	404.7	0.24	0.66
MAHT2	3.40	27.76	94.48	0.200	0.600	0.003649	198.6	451.1	0.27	0.73
MAHT3	3.33	28.15	93.65	0.200	0.600	0.003640	148.0	376.3	0.24	0.67
MAHT4	3.40	27.95	95.12	0.200	0.800	0.005475	161.1	527.9	0.39	0.70

active ringing tone to the qualities of rosewood it is expected that the rosewood has lower damping at higher frequencies. This is indeed the case. Next to that the peaks following in the higher frequency ranges are sharper and more well defined compared to the other two back and sides woods which also confirms the findings from luthier that rosewood is more active at higher frequencies. To provide a definitive conclusion about this more samples of each of the types of wood should be tested and the frequency range of the modal analysis should be extended to include higher frequencies.

11.2.4. Conclusion on back and sides woods

The back and sides woods tested show a great diversity and therefore allow a large design space for the development of a composite for the back and sides of the guitar. Ideally the tests should be performed on a wood sample which is known to have produced a high quality responsive guitar. This will provide a much clearer target for the composite.

The difference in acoustic properties of the three back and sides woods tested is significant. With decreasing stiffness of the East-Indian rosewood and higher density it is predicted to be more active for higher frequencies. This is in line with what is commonly known about rosewoods as used for guitars in comparison with for example mahogany. However this should be studied in more detail to confirm these initial findings with only one sample per wood type tested.

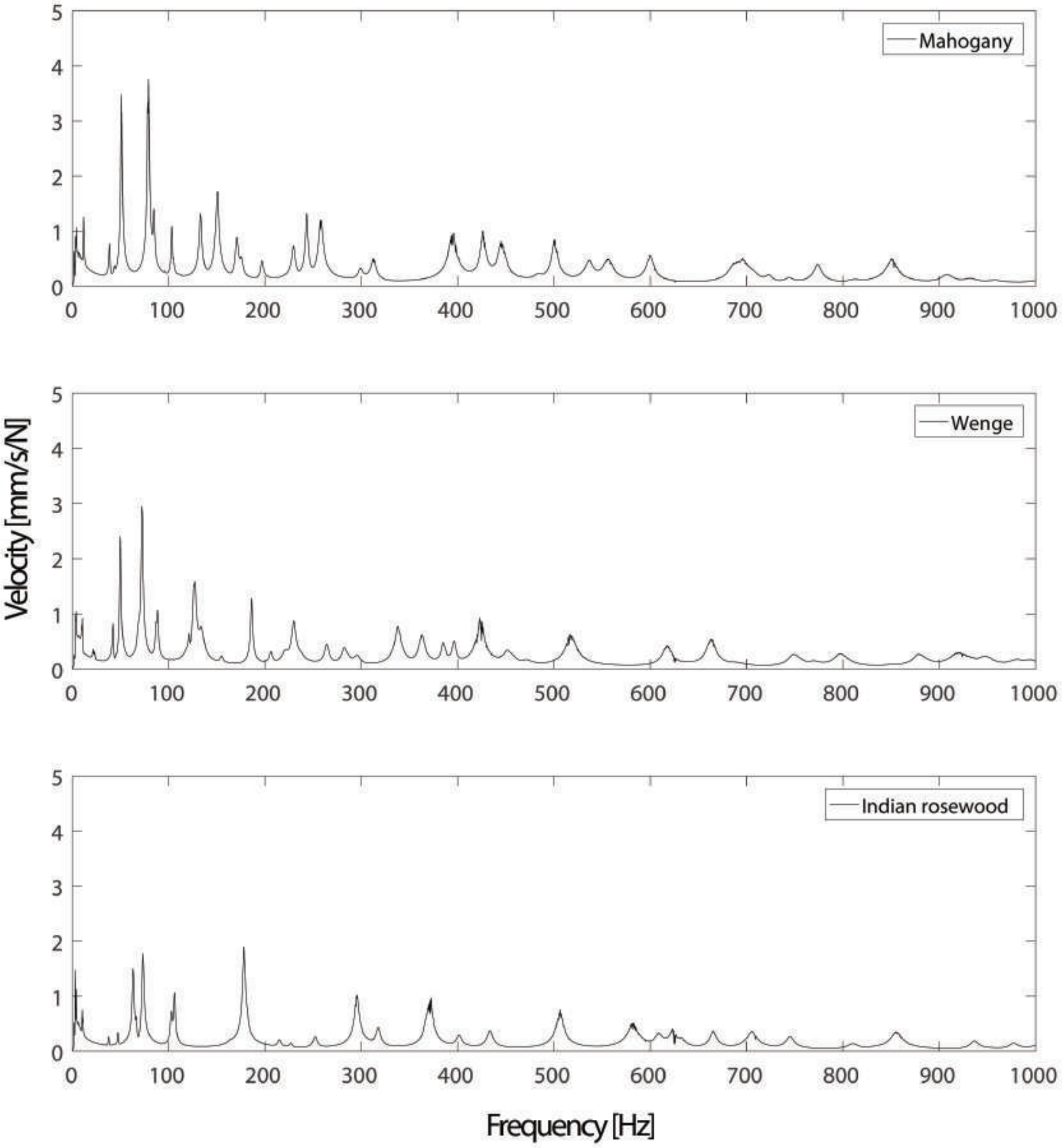


Figure 11.5: Frequency response curves of three types of back and sides woods from 0-1000 Hz

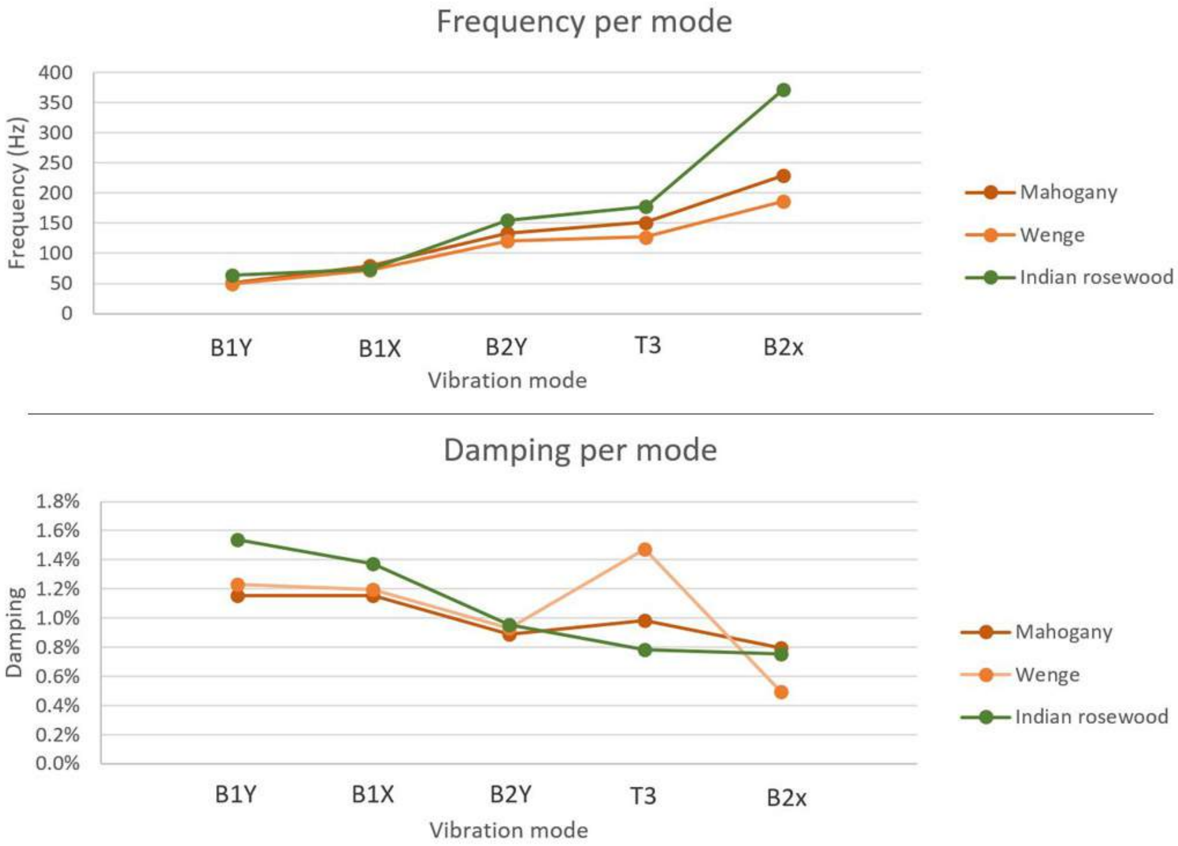


Figure 11.6: Top: frequencies of the 5 dominant modes investigated. Bottom: damping values of the 5 dominant modes investigated.

12

Development of polyethylene syntactic foam composite

The first composite option researched for the replacement of wood as main material in acoustic guitars is chosen to be the polyethylene syntactic foam composite. The reason for this is that the polyethylene has a better stiffness to density ratio than carbon used in two fibre reinforced blown foam options as discussed in chapter 14 and is therefore likely to more easily satisfy the sound radiation coefficient requirement A2 as presented in chapter 7. Additionally polyethylene has a lower internal damping according to material databases [99]. The main type of Polyethylene researched is the Ultra High Density Polyethylene (UHDPE) from Teijin Aramid which is marketed under the trade name Endumax. The product of the main competitor DSM is available under the name Dyneema but is not investigated. This is because at this moment Endumax is produced without solvents and therefore has a major benefit over Dyneema in terms of negative environmental impact. Considering the environmental scope of this thesis it is therefore decided to focus the investigation on Endumax.

12.1. Model for designing basic composite

A model is created to calculate the main material quantities within the composite. The initial model is designed to be basic and to only provide a rough first estimation on the stiffness and density. This is done to prevent a lot of effort to be placed in the model without knowing if the materials combined in the composite will provide the expected results.

From the datasheets the following data is obtained [119–121].

- Stiffness of fibre, Teijin Endumax, $E_{x_f} = 170\ GPa$
- Stiffness of resin, Epikote 04908, $E_{x_r} = E_{y_r} = 2.9 - 3.1\ GPa$
- Density of fibre, Teijin Endumax, $\rho_f = 980\ kg/m^3$
- Density of resin, Epikote 04908, $\rho_f = 1150\ kg/m^3$
- Density of additive, 3M K1 hollow glass spheres, $\rho_f = 125\ kg/m^3$
- Thickness of Endumax film $t_f = 55\ \mu m$

Additionally the following assumptions are made.

- The additive does not provide any stiffness and will be treated as a material with a stiffness of zero. Once the basic composite is able to provide a reasonable first estimate, additional research should be done

on the effect of adding hollow glass spheres on the stiffness of the resin/glass spheres combination in comparison with only resin.
- The Endumax tape has zero stiffness in the directions parallel to the fibre directions. The tape tears immediately when a load is applied parallel to the grain.

12.1.1. Modelling of stiffness

In order to obtain the required stiffness in the longitudinal direction E_{x_c}, the volume percentage of film v_{x_f} required can be calculated with the rule of mixtures as shown in Equation 12.1. As the stiffness of the resin E_{x_r} is much lower than the Endumax film E_{x_f} it assumed that the Endumax film is solely responsible for generating the stiffness. This results in that E_{x_r} can be set to zero. Additionally the stiffness of the additive E_{x_a} was already assumed to be zero resulting in the simplification shown in Equation 12.2.

$$E_{x_c} = E_{x_f} v_{x_f} + E_{x_r} v_{x_r} + E_{x_a} v_{x_a} \tag{12.1}$$

$$E_{x_c} = E_{x_f} v_{x_f} \tag{12.2}$$

For the transverse direction the relation will be as given inEquation 12.3 with E_{y_a} and E_{y_f} being zero.

$$E_{y_c} = E_{y_r} v_{y_r} = E_{x_r} v_{x_r} \tag{12.3}$$

The required stiffness in longitudinal direction of the composite is set to 14 GPa which is substituted in Equation 12.2 resulting in a volume percentage of Endumax film of 8.2%. The design of the composite is that it is build up in layers of Endumax film alternating with the mixture of resin and glass bubbles. This means that when considering a 3 mm thick composite a total number of 5 layers of 55 μm Endumax film should be added to arrive at the correct stiffness.

The required stiffness in transverse direction is to be provided by the resin material. Taking a transverse stiffness of the composite of 1 GPa the resulting volume fraction of the resin should be around 35% leaving a volume fraction of 57% for the glass bubbles.

12.1.2. Modelling of density

The density is modelled similar to the stiffness with the rule of mixtures. The relation to determine the composite density is provided in Equation 12.4. Here ρ_f, ρ_r and ρ_a are densities of the film, resin and additive respectively and v_f, v_r and v_a are the volume percentages of the film, resin and additive respectively.

$$\rho_{x_c} = \rho_f v_f + \rho_r v_r + \rho_a v_a \tag{12.4}$$

Substitution of the values for each of the densities and volume fractions as calculated before the resulting density is found to be 552 kg/m^3 which is considerably higher than the 450 kg/m^3 target as found in chapter 11. Even when the glass bubbles would have no weight the resulting density would not reach this target. The result is that with the current composite it is not possible to satisfy both requirement A1 as well as A2. As the sound radiation energy is considered more important the model is to be updated to find a composition with the correct relation of stiffness and density.

12.1.3. Modelling of sound radiation coefficient

As a first trial a simple Matlab model was programmed which increases the quantity of Endumax film in the composite until a sound radiation coefficient $\sqrt{E/\rho^3}$ of around 12.5 was obtained. For each iteration of the composite the resin and glass bubble mixture is varied to find the optimal point for the sound radiation coefficient.

The resulting output of the programme was a composite with 45% Endumax, 25% resin and 30% glass bubbles. The number of layers of Endumax at a volume percentage of 45% is found to be 24 to 25 which will be used for the first sample production. Using the equations from subsection 12.1.1 and subsection 12.1.2 the stiffness and density were found to be 76.5 GPa and 766 kg/m^3 respectively. This results in a sound radiation coefficient of 13 which is slightly higher than for wood. Once the production feasibility of the composite is proven the model will be updated using the empirical data obtained to provide a more accurate estimate.

12.2. Analysis and iterations on polyethylene syntactic foam composite

This section describes the development of the production method of the Polyethylene syntactic foam composite. First a test is conducted to find the limit on the amount of 3M K1 hollow glass bubbles which can be added to the resin while remaining processable. After this limit has been established the production iterations are described.

12.2.1. Initial tests with 3M K1 hollow glass bubbles

The first step is to verify if a high enough quantity of 3M K1 hollow glass bubbles can be added to the epoxy without severely increasing the viscosity making the mixture impossible to process with other constituents. The epoxy used is the Hexion Epikote 04908 infusion resin. Several samples were made with 10%, 25%, 40% and 60% glass bubbles in terms of volume. The viscosity of the first three mixtures up to 40% proved to be comparable in viscosity. When adding above 50% volume of glass bubbles a sharp increase in viscosity was noticed and above 58% the viscosity was considered too high to process the mixture further. Therefore it can be concluded that for bonding with another mixture, a maximum volume of 50% glass bubbles should added.

Looking back at the modelled composite, the resulting required volume percentage of glass bubbles is 55.5% which is slightly higher than the production limit found. Therefore it was decided to start the first sample production with a slightly lower glass bubble content to eliminate the risk of having not enough epoxy resin in the mixture to wet the surface of the Endumax film

Due tot the low viscosity of the resin and low weight of the glass bubbles it was found that most of the glass bubbles will float to the surface. The result is that for added quantities below 50% volume added glass bubbles the lower part of the cured resin consisted of only epoxy while the upper surface has a very high concentration of glass bubbles. This should therefore be considered when adding large quantities of mixture to a product.

12.2.2. First sample production and analysis

The first samples are produced in a aluminium mould which consisted of a top and bottom panel where a 3 mm aluminium boundary was placed. The inner length and width of the mould used are 120 mm and 60 mm respectively. The aluminium surfaces are treated with Marbocoat 227CEE release agent. The mould is sealed with tape around the edges. The resin and glass bubbles are mixed after which the 25 layers of Endumax and mixture are alternately stacked inside the mould. The mould is then closed with the top plate and positioned in a press where a force of 100kN is applied to completely close the mould and obtain a composite with a thickness of 3 mm.

The first sample was released from the mould and was bent by hand. Almost immediately after bending a soft crackling sound was heard and the composite did provide almost no resistance to bending at all. The composite was bent until failure to allow for visual inspection of the failure. It was found that there was practically no bonding between the epoxy and Endumax as the Endumax layers were relatively clean once peeled off. This is shown in Figure 12.1

Figure 12.1: Photo of the inner surface of the first failed sample. The clean surface of the Endumax indicates poor bonding between the materials.

12.2.3. Second sample production and analysis

The production of the second sample focused on the improvement of bonding between the epoxy resin and Endumax film. One method to improve the surface bonding of materials is the use of Corona treatment on the surface. This method uses a relatively cold flame with charged ions which increase the surface energy and therefore allows for bonding between the constituents. The process of Corona treatment is shown in Figure 12.2.

A water break test was conducted which is done by placing a droplet of water on the surface and looking at the water break angle which indicates the surface energy. Initially the Endumax film forces the water to pull together and form large droplets on the surface indicating poor bonding capabilities. After Corona treatment the water break test showed complete wetting of the Endumax surface indicating that bonding should improve significantly. A second sample was produced in the same mould and using the same method as for the first sample.

The resulting sample showed similar behaviour when bent and provided only a small amount of extra resistance. Upon visual inspection it was found that for this sample the interface between the Endumax film and epoxy resin mixture had not failed. The Endumax tape had sheared through its thickness due to the bending force and therefore hardly provided any resistance. The split Endumax tape is shown in Figure 12.3.

12.2.4. Third sample production and analysis

A final attempt to obtain a composite performing according to the calculations done in the model was done by splitting the tape in small strokes of material instead of having separate layers. The resulting sample however

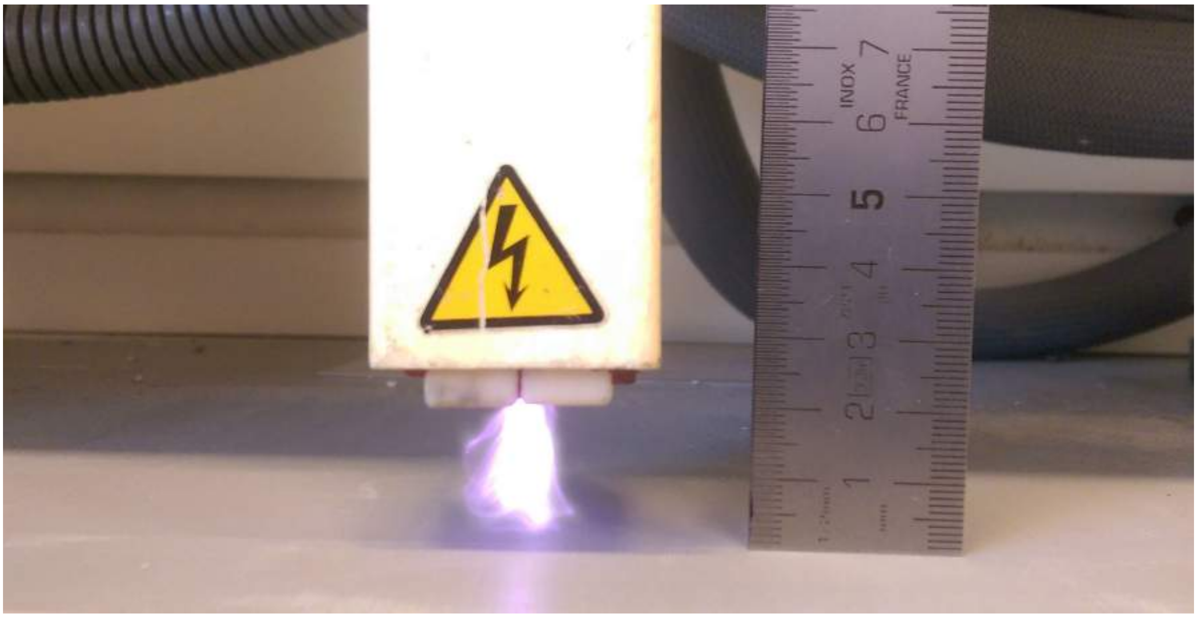


Figure 12.2: Process of Corona treatment of the Endumax film.

Figure 12.3: Photo of the inner surface of the second failed sample. The splitting of the Endumax tape through its thickness is clearly visible.

did not significantly improve the bending behaviour as observed with the first two samples.

12.3. Conclusion on composite option

From the samples produced it can be concluded that the combination of materials does not provide any feasible results towards the development of a composite with similar acoustic properties as wood. The bending stiffness of the samples was found to be extremely poor and the composite was easily torn apart by hand. Additionally the mixture ratio of epoxy and glass bubbles is not optimal in terms of processability. Finally the designed composite is not able to satisfy both requirements A1 and A2. Considering these downsides it was therefore decided to not focus on this type of composite and instead focus on the other options.

13

Development of polyethylene sandwich composite

An alternative method of using Endumax film is application of the material in a sandwich structure. As the damping of Endumax is higher than that of carbon fibre the risk of having too low damping due the ineffective damping of sandwich panels as shown in section 7.3 is lower.

The main materials of the sandwich panel are the Endumax film which is bonded on Rohacell 31HF foam using 3M EC-9323 B/A structural epoxy glue. The sandwich is build up from 3 layers of Endumax and 2 layers of Rohacell foam. The top, middle and bottom face each consists of 5 layers of Endumax film of which 4 are oriented in the longitudinal direction and one in the transverse direction.

13.1. Manufacturing method

The first step in the manufacturing of the sandwich panel is the consolidation of the Endumax layers. The panel was designed to be 450 mm in length and 300 mm in width. The Endumax tape has a width of 133 mm and therefore the layers were stacked on top of each other using the brick UD method. This means that the successive layer of tape is positioned over the small gap between two tapes in the layer below to form a layup such as a brick wall. The tape is stacked between two large plates of 500 mm by 500 mm and positioned in a press. The press first applies its maximum force of 1000kN resulting in a pressure of 40 bars. With the pressure applied the temperature of the top and bottom side of the press is increased up to 140 degrees Celsius. This causes the film layers to bond to each other without a large negative effect on the material properties. After one hour at 140 degrees Celsius the temperature of the press is brought back to room temperature after which the pressure is released. The resulting Endumax panels are just below 0.3 mm thick.

The second step is the plasma treatment of the layers to provide proper bonding with the epoxy glue. This is done in a similar fashion as for the samples discussed in chapter 12. An aluminium panel is prepared with wooden boundaries to support the stacking of the layers. First a layer of consolidated Endumax is positioned on the aluminium panel after which a thin layer of glue is applied on the Endumax using a plastic spatula. The Rohacell is positioned on top of the glue and the remaining layers are positioned where a thin layer of glues is applied to the Endumax surfaces. To provide proper pressure on the panel a vacuum bag was constructed around the product and a pressure of 500 mbar is applied. The final panel is shown in Figure 13.1.

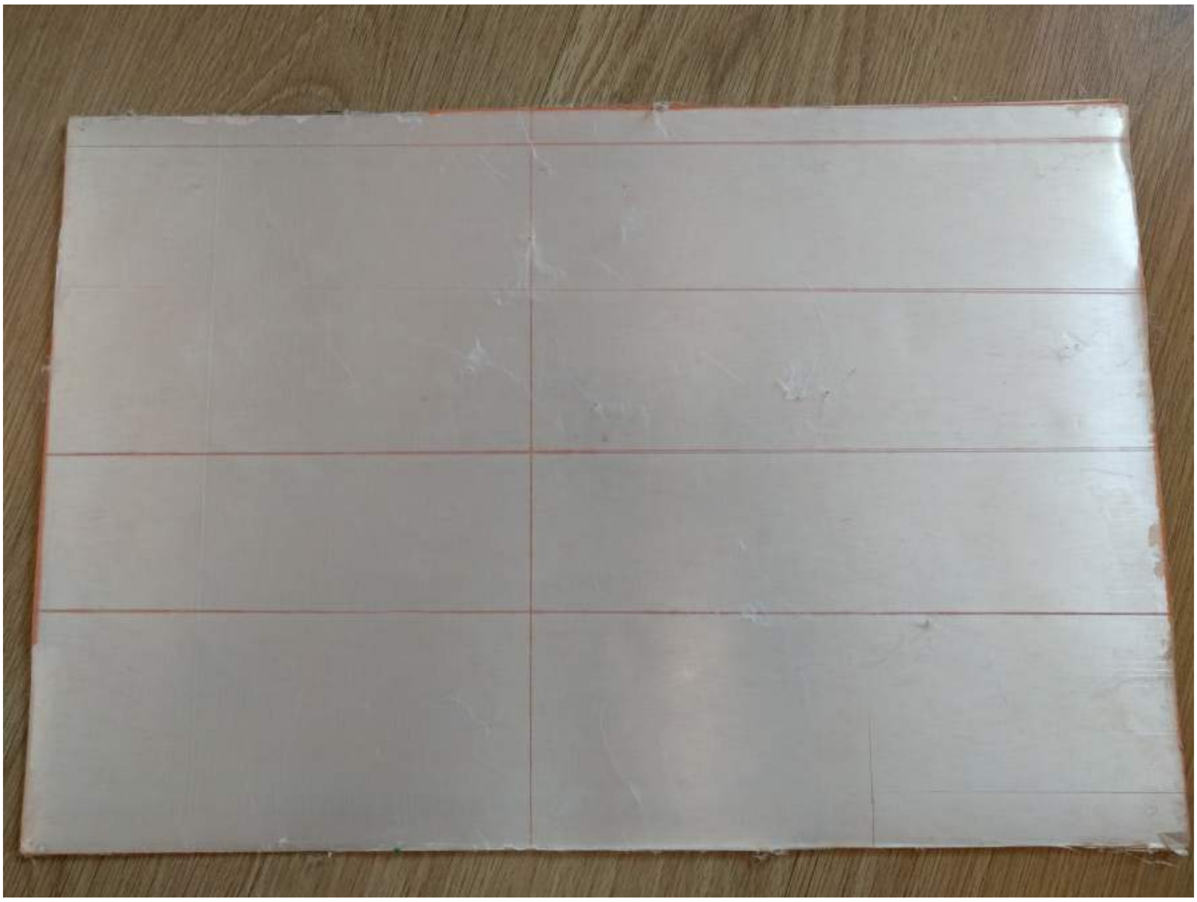


Figure 13.1: Endumax sandwich panel with Rohacell 31HF

13.2. Analysis of polyethylene sandwich composite

The stiffness of the panel in bending did not show the same problems as were found in the previous Endumax samples tested in combination with Epoxy resin and glass bubbles. Both the longitudinal direction as well as the transverse direction provided a large amount of resistance to bending making the panel almost impossible to bend by hand.

The obtained sandwich panel proved to have a much lower damping than expected. The sound of tapping the panel compared to tapping a wooden panel was very different. additionally the pitch was considerably higher which is likely to be caused by the relatively high amount of reinforcement in the transverse direction which causes the frequency of the first bending mode in the transverse direction to go up. A reduction in transverse stiffness would be possible by placing the transverse layers solely in the middle Endumax reinforcement layer. However no method was found to increase the damping of the panel.

Next to the problems with the damping, the panel proved to be much heavier than expected which is caused by the large amount of glue applied on the Endumax surfaces. The density of the panel obtained is 742 kg/m^3. The density could potentially be reduced by using a low viscosity glue which allows for a thinner layer and a significant reduction in weight.

Finally the panel proved to be very hard to machine to the desired shape. One of the requirements, C2 as expressed in chapter 7, is that guitar builders can work with the composite without having to use additional expensive equipment. The panel cannot be sawn using mechanical saws such as a belt saw or circular saw. Mechanical sawing results in the immediate delamination of the composite. Additionally the loose fibres on the edges will bulk up. Therefore a water cutting or a laser cutting machine should be used in order to create the correct dimensions. This is however considered a too large investment for a small shop guitar builder.

13.3. Conclusion on composite option

Considering the main downsides of the Endumax sandwich panel in terms of acoustics as well as processability into an instrument it was decided to not further investigate the composite option. No solution was found for the processability and therefore the analysis of the panel was stopped to allow more time for the exploration of other composite options.

14

Development of fibre reinforced blown foam composite

The third option that is to be investigated is the fibre reinforced blown foam. This option has greater potential than the other two options discussed before for two main reasons. First, the materials combined can form a composite capable of matching the stiffness as well as density of wood and on top of that, does not have the downside of sandwich structures in terms of lower effective damping due to incompatible stiffness of the stiff layer and the damping layer. Second, the concept of a fibre reinforced blown foam has already been investiged by T. Ono e.a. in their papers showing a high potential of this composite to match wood [75–77].

The basic concept of this composite is the placement of fibre strands in Polyurethane foam. This is achieved using the following production process. First the carbon fibre strands are attached to two aluminium plates (top and bottom) by stretching them over the panels and attaching them by pressing the strand ends into double sided tape. A second layer of carbon fibre strands is placed on top of the first layer of carbon fibre at an angle of 90 degrees. The amount of carbon in the longitudinal direction is considerably higher than in the transverse direction to mimic the anisotropy of wood.

After the carbon fibre strands are attached, a boundary with the same thickness of the desired composite thickness is placed around the carbon fibre strands on one of the plates to form a mould. Subsequently unfoamed Polyurethane foam is poured into the mould and closed off with the top plate. The Polyurethane starts to foam within a short period of time and fills the cavity of the mould. To ensure the mould stays closed, weights are placed on top of the mould. The process of foaming can build up considerable pressure inside of the mould. The mould and placement of carbon fibre strands is shown schematically in Figure 14.1.

The following sections will elaborate on the design iterations made on the fibre reinforced blown foam composites which are coded C1 through C9. Each of the composites is a renewed design on the previous one to solve certain downsides or negative aspects of the previous version. When considering the composite developed by T.Ono e.a. a number of problems were identified. These are listed below.

- Fibre lay-up was done by hand which results in a very poor uniformity of the composite. Expected is that especially the strength of the composite would be quite poor as the uneven distribution of carbon fibres in the composite causing the fibres to be unevenly loaded.
- Fibres are only placed on the outside of the composite similarly to a sandwich structure. As the fibres are not impregnated by the foam, the damping of the composite is much higher compared to the sandwich structure making the lower effective damping of the damping layer not an issue. The downside of this is that there is a thick layer of unsupported foam which can potentially quite easily buckle or compress due to relative low load.

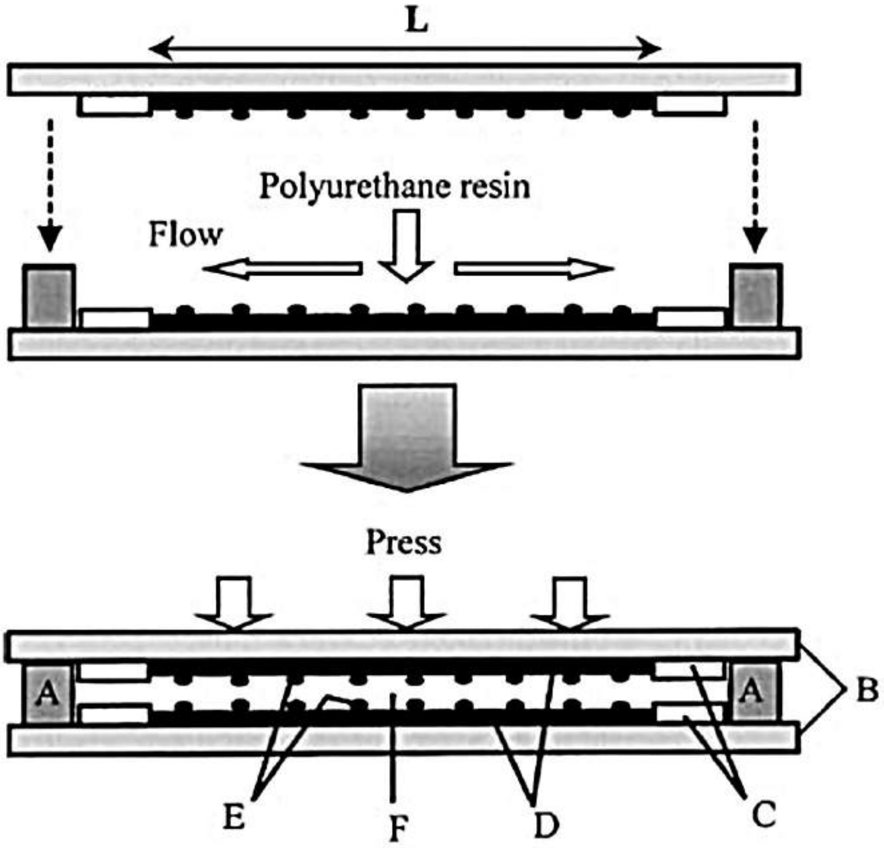


Figure 14.1: Schematic view of the mould used by T.ono e.a. to produce the carbon fibre reinforced Polyurethane composite [76]. A: boundary to ensure composite thickness. B: main top and bottom aluminium panels. C: double sided tape to secure fibres. D: longitudinal fibre strands. E: transverse fibre strands. F: cavity filled by polyurethane foam.

- The foaming material is positioned only in the center of the mould. This causes a density gradient of the foam throughout the composite making the acoustic properties very different in the center of the composite compared to the outer edges.

With these problems identified a strategy was set-up on how to tackle these problems in order to arrive at an improved version of this composite. These improvements are listed below.

- To have uniform spacing of the fibres, hand lay-up is unlikely to yield good results. Therefore it was decided to use a filament winding machine to perform the layup of fibres.
- Fibres are positioned in multiple layers and separated by layers of double sided tape in order to arrive at the proper spacing between layers and correct final thickness of the composite. This will be further elaborated in section 14.2.
- The foaming material should be applied as a layer and therefore distributed over a plate in order to obtain an even distribution of foam between the fibres.

Before going into the iterations of the composite designs, the following two sections introduce the basic model used to obtain the relative quantities of the constituents of the composite and describe the initial production method used for composite version C1.

14.1. Model for designing basic composite

The model to design the fibre reinforced foam composite is focused on matching the stiffness and density of wood. The damping parameters are considered later with the modal analysis method by laser scanning vibrometry as discussed in section 10.3

14.1.1. Modelling of stiffness

The first step in setting up the model is to obtain a high enough stiffness for the composite. Since the carbon fibres are much stiffer than the Polyurethane foam, it is assumed that only the carbon fibre provides the stiffness to the composite. A second assumption is made regarding the relation between in-plane and bending stiffness at this point. It is assumed that as long as the fibres are distributed evenly throughout the composite in a certain direction it has a similar in-plane stiffness to flexural stiffness ratio. Therefore the rule of mixtures holds and the in-plane stiffness can be calculated using Equation 14.1 where E_c is the stiffness of the composite, v the volume fraction of fibres in a certain direction and E_{carbon} the stiffness of the carbon fibres.

$$E_{c_x} = v_x E_{carbon} \tag{14.1}$$

In order to match the stiffness of wood, it is required that $E_{c_x} = E_{w_x}$ and $E_{c_y} = E_{w_y}$. From section 11.1 it was found that $E_{w_x} = 12to14.5GPa$ and $E_{w_x} = 1to1.5GPa$ and from the data sheet of the carbon fibre fillament E_{carbon} is $230Gpa$. Substitution of these numbers into Equation 14.1 results in the following maximum volume fractions in the x and y directions.

- $v_x = 0.0630$
- $v_y = 0.0065$

To have the composite perform around the average stiffness of wood, it was decided to use the following volume fractions of carbon fibre.

- $v_x = 0.0600$
- $v_y = 0.0055$

With the volume fractions known, it can be estimated how much weight of carbon should be added to the composite. The density of carbon fibre was given to be 1760 kg/m^3 which results in the following weights to be added to one square meter of the composite at a thickness of 3 mm.

- $w_x = 0.317kg$
- $w_y = 0.029kg$

At this stage the decision was made to use double sided tape between each of the layers in order to arrive at the correct thickness of the laminate. The 3M double sided tape has a thickness of around 0.2 mm varying between 0.19 and 0.21 mm at certain spots. Therefore if the carbon fibres are assumed to have a very small thickness as they are pressed into the tape, the total number of layers required can be set to 14-15 for a 3 mm composite. The layup used is presented below in Equation 14.2.

$$Layup = [0, T, 90, T, 0, T, 90, T, 0, T, 90, T, 0, T, \bar{90}]_s \tag{14.2}$$

To obtain a symmetric layup the total number of X-direction plies is set to 8 while the y-direction ply number is 7 with a y-direction layer in the center. This results in 14 layers of double sided tape.

With the number of layers known, the spacing between the layers can be determined. It is given in the data sheet of the carbon fibre filament that the weight per 1 km of filament is approximately 198 g. This is called the linear density indicated by symbol ρ_l. With this data and the weight of the carbon in each of the directions for the one square meter composite panels, the filament spacing (s_x and s_y)can be calculated using Equation 14.3 where w is the weight of the carbon oriented in either X- or Y-direction, n is the number of layers in either X- or Y-direction.

$$s = \frac{1}{\frac{w}{n\rho_l}} \tag{14.3}$$

This results in the following spacings for both directions.

- $s_x = 5.0mm$
- $s_y = 47.7mm$

As can be seen from these results the spacing in X-direction is relatively low while the Y-direction spacing is considerably larger. This is expected because of the anisotropy of the materials.

14.1.2. Modelling of density

The density of the composite should be matched to the density of wood as obtained in chapter 11. It was found that the density of high quality Moonspruce is around 450 kg/m^3.

The density of the composite can be regulated by varying the quantity of unfoamed resin material. The two options considered are Epoxy and Polyurethane foam. To obtain the quantity to be added to the plate, the weight is computed using Equation 14.4 after which the required film thickness $t_{unfoamed}$ can be determined using Equation 14.5. The dimensions of the composite plate are assumed to be the same as in subsection 14.1.1, one square meter area with a thickness t_c of $3mm$. In these equations below, w_c is the total weight of the composite panel, $\rho_{unfoamed}$ the density of the unfoamed resin material and ρ_c the density of the composite set to 450 kg/m^3.

$$w_{foam} = w_c - w_{carbon} = \rho_c t_c - w_x - w_y \tag{14.4}$$

$$t_{unfoamed} = \frac{w_{foam}}{\rho_{unfoamed}} \tag{14.5}$$

Both unfoamed Epoxy foam as well as Polyurethane foam have a density of around 1150 kg/m^3 according to their respective data sheets. Therefore with the values given the film thickness of the foam should be around 0.9 mm.

Foams are available in different densities. In order to choose the right product the foamed density inside the composite is to be calculated. This is done using Equation 14.6 where v_{foam}, v_{carbon}, v_c, are the total volumes of foam, carbon and composite respectively and a_c, b_c, t_c are the length, width and thickness of the composite.

$$\rho_{foam} = \frac{w_{foam}}{v_{foam}} = \frac{w_{foam}}{v_c - v_{carbon}} = \frac{w_{foam}}{a_c b_c t_c - w_{carbon}/\rho_{carbon}} \tag{14.6}$$

Since the length and width dimensions of the composite are still set to 1 square meter, the equation simplifies to Equation 14.7

$$\rho_{foam} = \frac{w_{foam}}{t_c - w_{carbon}/\rho_{carbon}} \tag{14.7}$$

Filling in the parameters results in a foamed density of around 360 kg/m^3. As the foam is to fill all cavities completely in the composite, a lower density foam under normal expansion should be selected, in this way pressure can build up in the system such that foam is compressed to the right density and at the same time fills all cavities.

14.2. Production method of carbon fibre reinforced blown foam

As this carbon fibre reinforced foam has not been produced before a number of concerns should first be addressed before starting to produce full scale samples. First, the foam materials should be tested to investigate if the required densities could actually be reached. Secondly the filament winding process has to be set-up. Finally the application of the thin film of foam is discussed.

14.2.1. Testing of foam samples

As stated before, two main types of foam have been investigated for the fibre reinforced blown foam composites. The first is Epoxy foam as Epoxy is known to properly bond with carbon fibres and therefore seems to be a suitable solution. The second option is Polyurethane foam which has been proven to be a good candidate by T. Ono e.a. [75]. Both options will be discussed in more detail below.

14.2.1.1. Epoxy foams

The foaming of Epoxy is achieved by addition of a blowing agent to the Epoxy component. After the hardener is added, the foaming reaction occurs together with the hardening process. Therefore the reaction speed of the foaming is very similar to the curing speed of the Epoxy chosen. As many types of epoxies are available, it is possible to choose the reaction speed ranging from a level of a few minutes up to many hours.

Next to Epoxy foams created by adding a blowing agent, off the shelf products such as the sicomin Epoxy foams are also available. These two-component epoxies have the blowing agent already in them in a certain quantity resulting in a range of densities from 170 kg/m^3 to 600 kg/m^3 [116].

The first tests were performed using the standard infusion Epoxy resin, Hexion Epikote Epikur 04908, in combination with the R&G EP Treibmittel. A number of small tests were performed by adding 1-5% in steps of 1% of foaming agent to the Epoxy. The result however was very disappointing as the foaming took a very long time due to the long pot-life of this Epoxy of 4 hours. At first, it appeared as if the blowing agent did not react enough with the Epoxy. However after close inspection, it appeared that the bubbles did form in the Epoxy but also easily escaped at the surface due to the very low viscosity of the Epoxy. Therefore it was decided to leave the Epoxy for several hours after mixing with the hardener to allow the viscosity to increase before adding the blowing agent. This resulted in a good quality epoxy foam of which the density could be manipulated according to the addition of blowing agent. Adding blowing agent in high quantities resulted in a density of lower than 250 kg/m^3 under free expansion in a mixing cup. However these foams were extremely brittle causing fracture and crushing even when taking the foam out of the mixing cup. This indicated that the limit of the epoxy foam would be around 250 kg/m^3 when adding a normal blowing agent. Potentially the foam could get to lower densities by addition of flexibilizers to decrease the brittleness, however this has not been verified.

For comparison the Sicomin PB250 Epoxy foam with a expanded density of 250 to 300 kg/m^3 was ordered and tested. The speed of foaming was considerably faster than the previous attempts with the infusion Epoxy and added blowing agent. The final product however was very comparable in terms of uniformity and quality.

14.2.1.2. Polyurethane foams

Polyurethane foams are available in many more types than Epoxy foams. Most commonly used are the soft or slab-stock foams which are used for packaging and car seats. These foams are extremely flexible and compressible. On the other side, there is a large range of closed cell structural foams which are commonly used for insulation purposes. The foam that is of interest for the fibre reinforced foam is the stiff structural foam. These foams have a density ranging from about 30 kg/m^3 to about 300 kg/m^3. Most foams are around 80 kg/m^3 while the heavier 180+ kg/m^3 foams are used in very specific applications.

Initial tests with Nestaan PN013/80-HM Polyurethane foam gives good quality uniform foams of the reported density in the data sheet of around 80 kg/m^3. The foaming process is extremely fast and starts within 50 seconds after start of mixing the two components and is fully expanded after about 150 seconds. These values are faster than reported in the data sheet of 70 seconds and 240 seconds respectively. Due to the limited time to process the Polyurethane foam, distribution of the foam over a larger panel might be difficult requiring a different solution.

14.2.1.3. Initial tests with glass fibre strands

In order to investigate the potential of both foams a test was performed by applying the unfoamed material in a small mould with two layers of glass fibre strands placed over double sided tape in a similar fashion as T. Ono e.a. created their composite. The mould was sized 240 mm in length, 180 mm in width and was closed by adding double sided tape between the boundaries of 2.5 mm and the mould bottom and top plates. As the double sided tape has a thickness of 0.2 mm this results in a spacing between the top and bottom plate of 2.9-3 mm The fibres were positioned predominantly in the longitudinal (length) direction to mimic the situation for the wood.

Each of the tests performed with the different foams will be discussed below.

Epoxy foam with blowing agent The first option tried was the epoxy foam with added blowing agent. Even though 50% extra foam was added to the mould than the quantity required to have the foam expand to 300 kg/m^3, the foam did not reach the upper surface of the mould in most places. This indicates that the foaming is blocked by the resistance of the mould and fibres and therefore cannot expand enough. The density of the leftover foam in the mixing cup was determined to be 265 kg/m^3 which shows that indeed the mould and fibres provide a large resistance.

Sicomin PB250 Epoxy foam A second test performed with the PB250 foam showed a very comparable result. At some positions the foam reached the upper side of the mould while in other places the foam did not reach all cavities.

Polyurethane foam The Polyurethane foam showed a very different result. The foam expands to a density of around 80 kg/m^3 when able to expand freely. Therefore to arrive at a density of around 300 kg/m^3, the foam should be compressed nearly four times. From literature it was found that the resulting overpressure inside the mould could potentially go up to 1.5-1.6 bar [122]. This is also the reason that the total of 25 kg of weights positioned on top of the mould did not prove to be enough to withstand the force exerted by the foam on the top of the mould. This indicates the high potential of the Polyurethane foam to reach all cavities of the mould. A second test with the Polyurethane foam was conducted with a number of parameters changed. Firstly the surfaces were covered with perforated Teflon film as the release agent Marbocoat 227CEE is not suitable with one of the Polyurethane components Polyol and therefore demoulding the system was more difficult than with the Epoxy system. Additionally the place where the foam was applied showed a slightly denser area at the surface of the mould which is resolved by having a open structure such as the Teflon film effectively taking away the contact with the smooth surface. The second parameter changed was the positioning of the mould in a press at several kilo Newtons of force to keep the mould closed and to withstand the pressure build-up by the foam inside the mould. The second sample proved to be of higher quality and indicated a high probability of similar results when switching to Carbon fibre on a larger scale.

From these tests it was concluded that the Epoxy foam did not prove to build-up enough pressure to fill all cavities between the fibre strands. Therefore it was decided to continue the development of the composite with only the Polyurethane foam.

14.2.2. Filament winding process

For the filament winding process a baseline winding set-up and programme was obtained and changed according to the required specifications of the model. First the set-up will be discussed after which the winding programme will be introduced. Finally the problems that occurred during initial testing of the set-up and winding will be addressed.

14.2.2.1. Filament winding set-up

The filament winding set-up as used is shown in Figure 14.2. A plate is suspended in the machine at two corners such that it is at an angle of 45 degrees. The machine has four main axes listed below.

Figure 14.2: Photo of the filament winding set-up on which each of the axes are indicated.

C-axis Main rotation axis of the plate.
A-axis Rotation of the feed eye.
Z-axis Movement axis along the direction of the plate arm suspension.
X-axis Movement axis perpendicular to the direction of the plate arm suspension.

The fibres in the longitudinal direction are placed first after which the fibre is detached from the panel. In order to start the fibres perpendicular to the first layer, the panel is rotated 180 degrees around the C-axis such that the bottom face now faces up. When starting the filament programme in this way, the fibres are positioned at 90 degrees of the first layer.

The driving axis that is controlled by the feed rate of the programme is the C-axis. Therefore the C-axis is spinning at a constant rate and the other axes' coordinates follow accordingly. The X-axis is only used to set the feed eye at a certain distance from the plate and does not get translated once the winding starts. The other two axes, Z and A, are accelerating in a near sinusoidal pattern to ensure that tension is kept on the filament and to prevent the filament from sliding out of the feed eye. A close-up photo of the feed eye is presented in Figure 14.3.

Figure 14.3: Photo of the feedeye used in the filament winding process

The filament tensioner is positioned at the back of the machine and therefore the filament requires to be redirected via a number of rings such that it does not touch the machine with a chance of damaging part of the fibres. First two vertical bars are placed to prevent too much lateral movement of the filament. Second the filament goes through a ring mounted on a plate on the machine arm. Third, the filament goes through a feed eye mounted in front of the main feed eye to properly direct the filament to the main feed-eye. Finally the filament moves through the main feed eye where it was decided to limit the number of cylinders it passes as the tension on the very thin 3K filament would otherwise become too high. This increases the risk of damage or even breakage of the filament.

14.2.2.2. Filament winding programme

The filament winding machine works by reading G-code out of a main programme file which directs to several sub-programme files. The G-code provides the main settings of the machine and indicates the start, pauses and end of the programme. As no software package was available for generating the correct G-code for the machine, it was decided to use a Matlab script written by fellow student Talha Dikici which generates the G-code files according to a number of input parameters below.

- The fibre filament spacing could be set by which the machine automatically shifts $\sqrt{2}s$ in the negative Z direction where s is the fibre spacing. As the plate is suspended at an angle of 45 degrees the $\sqrt{2}$ is required.

- The place dimensions are to be provided. As the programme is only capable of running on square panels, only one dimension is to be inserted into the programme.

- Due to a memory limitation on the machine, the programme could only run a small main programme file. Additionally the sub-programme files could only be run a limited number of times before the machine would give an error. This error cannot be explained by the memory shortage. A workaround was created by inserting positions after which the first sub-programme would switch to the next sub-programme allowing the programme to do the required 100+ windings per layer.

- The feed rate for the C-axis was to be provided.

- Finally the X-axis and Z-axis starting positions had to be defined such that the machine feed eye was aligned with the nearest corner. This was done by manually bringing the machine to the correct position and feeding the coordinates obtained back into the programme. In this way, the machine first moves to the correct starting position from its reference position before it start the winding process.

With the correct parameters inserted the programme was loaded on a floppy and copied to the machine where it was loaded into its memory for execution.

14.2.2.3. Filament winding problems addressed

The filament winding machine and programme had a number of problems that had to be addressed. Below a description of the problems and the method of solving them is provided.

When the filament tensioner looses tension on the fibre there is a chance that due to malfunctioning the tensioner locks the material roll in position not allowing it to rotate to feed material. After the machine reaches the furthest Z-axis position and starts to move back, there is a short period where fibres are to be feeded back on the roll before additional material is required again. Initial tests performed with 24K filament fibres of glass did not cause large problems as the roll would slip over the clamping system due to the high torsional forces applied. However for the 3K carbon filament this proved to be a force at which the filament would immediately snap. To solve this problem, the roll of material was mounted inversely on the machine and the tensioner was locked in position such that the tensioner was spinning backwards such that as long the roll of material is attached to the tensioner, it rolls backwards to place filament on the roll. On the inside of the material roll, smooth Teflon foil was placed such that the roll would slip in the machine if the force would become too high. In this way the fibres would always be able to roll back on the roll and when more material was needed the roll would slip over the tensioner clamps.

A second problem has to do with the geometry of the winding process. The original programme was written in such a way that the the step for the spacing between the filaments was distributed over both sides of the panel. The result is that on both sides of the panel the fibres are not wound parallel to the edge of the panel. As the programme was made to run with a spacing of 1 mm or lower, this effectively yielded almost no visible angular deviation. In the case of the 5 mm programme this angle difference was still very low, however in the case of 47.72 mm, the angular difference is significant over a panel length of 750 mm. Therefore the programme was rewritten such that the upper side of the panel would be wound parallel to the edge of the plate and thus at an angle of 90 degrees on top of the longitudinal layers. The bottom side of the panel would be used to translate the machine in the Z-direction to maintain the correct spacing. As this geometrical relation is different for each filament wound around the plate, it was not possible to create a sub-programme file that would be executed several times. Therefore all of the coordinates would be inserted into one sub-programme file. As this file is constrained in size due to the machine, it was decided to use a different step-size in the Matlab script generating the G-code files. This proved to be a workable solution with the machine.

14.2.2.4. Application of thin film of unfoamed Polyurethane

In order to apply the correct amount of Polyurethane in all positions, a rake was developed over several iterations. The rake consists of a Teflon cylinder over which a steel wire with a diameter of 0.8 or 1 mm is curved. This results in a device that, when stroked over the Polyurethane, creates a film of a thickness equal to the diameter of the steel wire.

For the initial manufacturing process, it was decided to leave the fibres on the panel and have the double sided tape function as the boundary. In this way no tension would be lost on the fibres making sure the separation of the fibres would not be distorted. On the wooden panel a flat aluminium plate of 1.5 mm thick was attached. Over this panel an open Teflon foil was applied to prevent bonding of the Polyurethane foam to the aluminium. Therefore first the Polyurethane was applied on a aluminium plate covered with open Teflon foil after which the panel with fibres was placed with fibres down on the Polyurethane foam and pressed into the unfoamed material once the press was closed. The panel used is shown in Figure 14.4

14.3. Analysis and iterations on carbon fibre reinforced Polyurethane panels

In the following sections each of the produced panels of carbon fibre reinforced Polyurethane foam will be discussed. The following steps were performed in the analysis of the panels in order specified below. When a

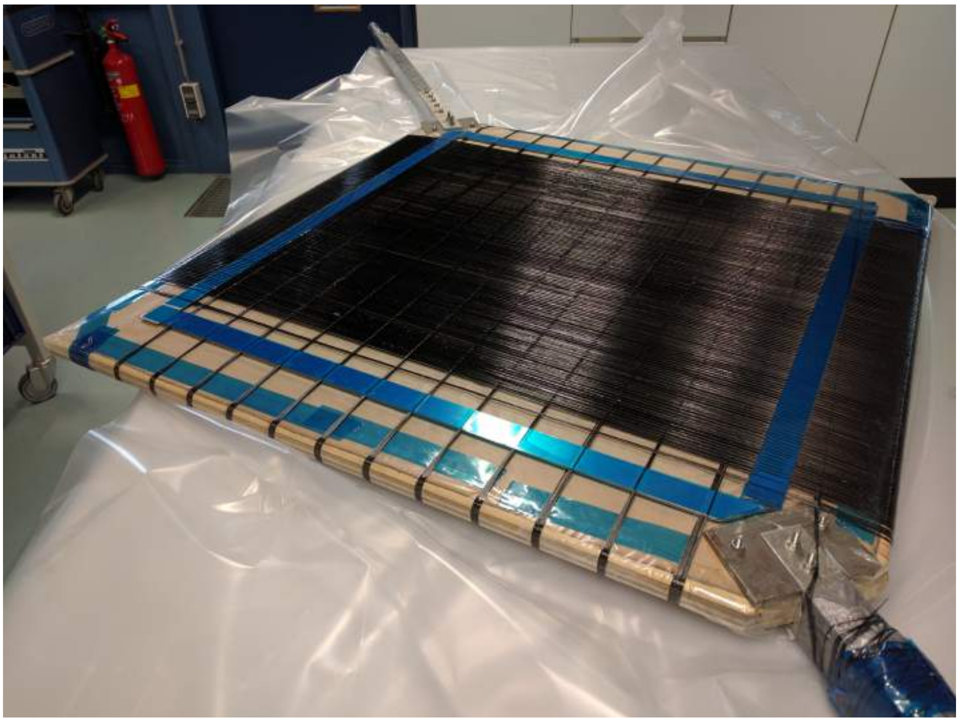


Figure 14.4: Wooden panel used in the filament winding process.

major drawback or problem was found in a specific version of the composite, it was decided to not perform all tests as set out in chapter 10 but rather focus on the next iteration of the composite to resolve the problems. Additionally it should be noted that no reference panel of Moonspruce was available until the production of composite C4 started. From C6 onwards the panels were tested using Laser Scanning Vibrometry as set-out in section 10.3 while for panels C1 through C5 the damping characteristics were estimated by ear.

The composite versions will be discussed in three parts. First the manufacturing process and specific deviations of the methods used above will be presented. After this the overall workability and feasibility independent of its characteristics will be discussed. Similar to the evaluation of the Endumax composites presented in chapter 12 and chapter 13, the most important characteristic is the potential to apply the composite in guitars. Therefore the minimum requirement before performing analysis is that the composite can be made to a guitar soundboard and provides stable characteristics to be used in a musical instrument over a long period of time. Once this condition is satisfied, the stiffness and acoustic properties will be discussed. Finally every discussion of the composite ends with a short summary of the main problems to be solved, if at all possible, for the next iteration of the composite.

14.3.1. C1 panel manufacturing and analysis

The C1 panel was manufactured according to the specifications as stated above. The main difference was the application of a higher amount of Polyurethane by using a steel wire of 1.6 mm instead of 1 mm to be certain the plate would be completely filled with foam for the first trial. The fibres were left on the wooden panel as described in subsubsection 14.2.2.4. In this way no mould was required as the boundary of double sided tape essentially formed a closed boundary.

A force of 100 kN was chosen to be applied on the 750 mm by 750 mm wooden panel which effectively results in a pressure of just above 1.75 Bar, enough to overcome the pressure build-up.

The Polyurethane foam solidifies in approximately 20-25 minutes. To be on the safe side, a pressing cycle of 1 hour was applied. After lifting up the press and removing the aluminium plate and Teflon foil, minor damages were present on the surface caused by slight bonding to the Teflon foil. The reason for this was later found to be the extremely brittleness of Polyurethane foam just after solidification. The toughness of the foam becomes factors higher when left to cure further for around 12 hours. The produced panel is shown in Figure 14.5

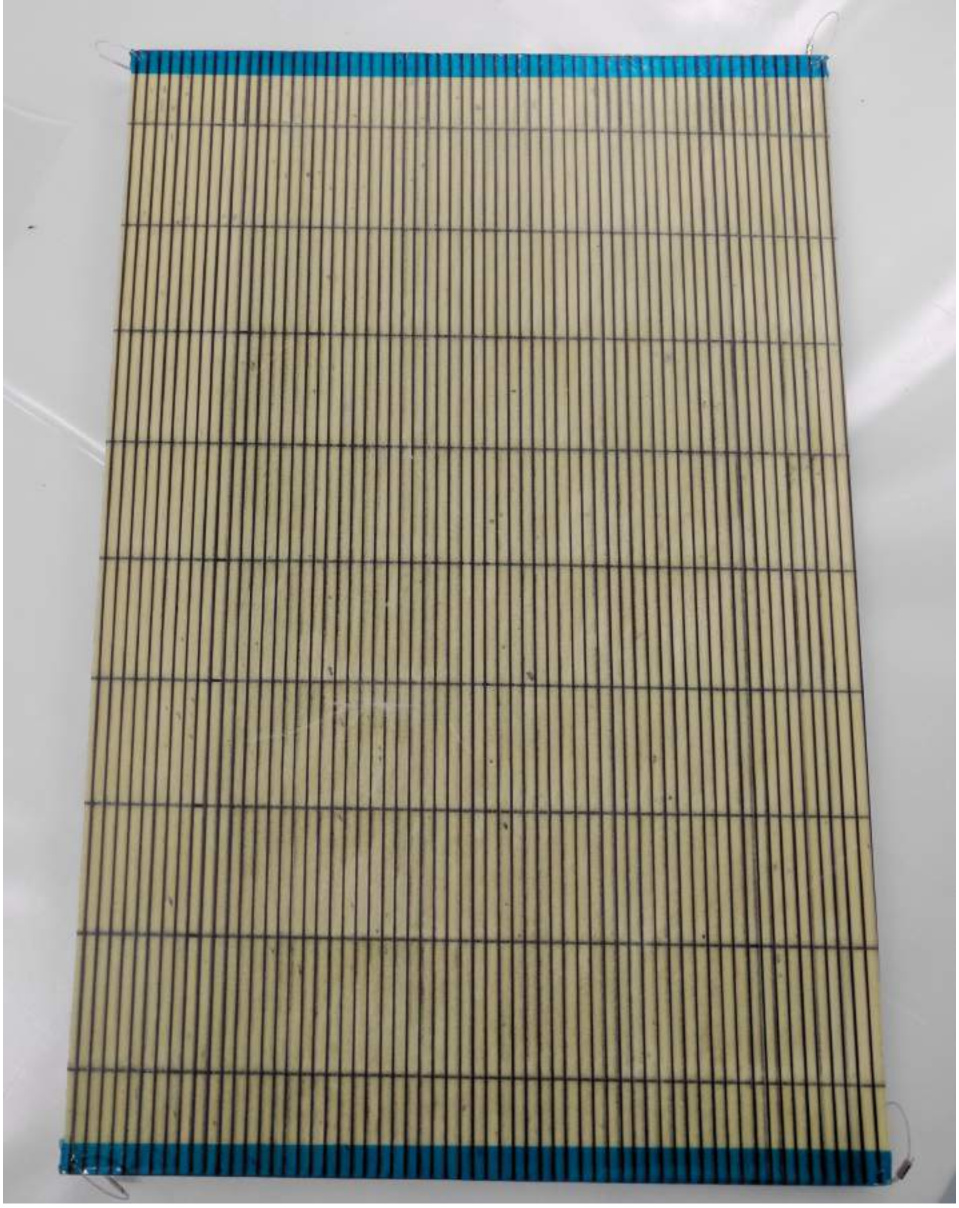


Figure 14.5: Panel C1 after being cut to 450 mm by 300 mm.

14.3.1.1. C1 - Feasibility for use in musical instruments

As discussed in chapter 10 the panels to be tested in the modal analysis set-up using laser scanning vibrometry are of dimension 450 mm by 300 mm. The panel produced was considerably larger at 580 mm by 580 mm. Therefore the panel was cut using a band saw. Due to the poor impregnation of the fibres, the fibres were partially pulled out in this process leaving very rough edges with loose fibres.

The thickness of the panel was highly varying from 2.45 mm to 3.32 mm which was unacceptable. This could be explained by the relatively low pressure applied on the wooden panel to prevent it from crushing and the fact that the panel is not perfectly flat. The density of the panel was found to be about 582 kg/m^3.

An abrasive belt was used in an attempt to flatten the panel. This resulted in a bundle of fibres at the edge to catch into the sanding paper pulling the plate towards the machine severely damaging it. Additionally it was not possible to flatten the edges where fibre bundles were sticking out as the Polyurethane foam would grind away easier leaving even longer pieces of fibres sticking out.

From these downsides it was concluded that the current composite, although an improvement over the composite produced by T. Ono e.a. in terms of uniformity, would not be suitable for production of guitars due to the bad workability and health dangers associated with loose fibres.

14.3.1.2. C1 - Acoustic and stiffness analysis

The remainder of the panel was cut in tensile samples and tested using the second stiffness testing method as described in chapter 10. The results of the tests are shown below in Table 14.1. Although both longitudinal as well as transverse samples were tested, the transverse samples did not provide any usable results. This can be explained by the fact that the sample width is only about half of the filament spacing in the transverse direction. Therefore half of the samples do not contain any fibres while the other half of the samples has one strand of fibres randomly positioned.

Table 14.1: Stiffness results for the C1 composite samples in longitudinal direction.

Sample	**t** $[mm]$	**w** $[mm]$	**area** $[mm^2]$	**strain1** $[V]$	**strain2** $[V]$	**Δstrain** [-]	**Force1** $[N]$	**Force2** $[N]$	**ΔStress** $[MPa]$	**Stiffness** $[GPa]$
C1L1	2.63	25.6	67.3	0.10	0.45	940	3970	0.00311	4.50	14.47
C1L2	2.49	23.8	59.2	0.10	0.40	984	3401	0.00267	4.08	15.31
C1L3	2.44	25.3	61.9	0.10	0.55	879	4519	0.00400	5.88	14.70
C1L4	2.68	23.5	63.1	0.10	0.50	813	3981	0.00356	5.02	14.12
C1L5	2.53	25.7	65.0	0.10	0.45	878	3865	0.00311	4.60	14.78
C1L6	2.54	25.8	65.7	0.10	0.55	842	4440	0.00400	5.48	13.69
C1L7	2.65	24.4	64.8	0.10	0.45	869	3666	0.00311	4.31	13.86
C1L8	2.43	25.3	61.4	0.10	0.35	990	3048	0.00222	3.35	15.08
C1L9	2.53	26.2	66.2	0.15	0.50	1281	4298	0.00311	4.56	14.64
C1L10	2.57	24.0	61.8	0.10	0.45	854	3618	0.00311	4.47	14.37

The average longitudinal stiffness was found to be 14.5 GPa which is very close to the target value of 14 GPa. The uniformity of the composite can be considered relatively good as the results of the tests are similar for all samples. It should however noted that some of the specimens have more fibres in them due to the wide spacing of fibre strands. This could theoretically lead up to differences of around 20% as the 25-25.5 mm wide samples would either contain 5 or 6 strands of fibres.

The samples that were tested until failure showed the poor impregnation of fibres. The failure mode was predominantly fibre pull-out after initial fracture of some of the fibres. Although the strength should preferably not be tested using straight samples but rather with dog-bone samples, the failure strength values obtained were considerably lower than expected. This can also be explained by the uneven loading of fibres and initial fracture of the samples after which fibre pull-out occurs.

Damping of the composite was extremely high when tapping the panel. This can be explained by the fact that the fibres are dry in the composite and therefore do not interact with each other as they would in a regular carbon epoxy composite. Further analysis on the acoustics was not performed as the workability problems are of considerable size that further analysing this iteration was not considered to be useful.

14.3.1.3. C1 - Summary of problems for next iterations

The production and testing of composite panel C1 indicated the following problems listed below.

- The dry fibres were not impregnated properly resulting in a almost unworkable composite. The loose fibres cause a risk for both machines as well as humans. Additionally the composite strength is considerably lower than expected due to failure by fibre pull-out.

- The thickness of the composite is not uniform enough with a variation of about 30% with respect to the target value of 3.0 mm.

14.3.2. C2 panel manufacturing and analysis

For the second iteration of the composite, version C2, two major changes were made. The filament winding process was expanded by adding a epoxy bath in front of the feed eyes to perform wet filament winding. The wetting bath as shown in Figure 14.6 features simple roll system where each roll is covered with smooth Teflon. Before leaving the bath the fibre passes a double roll where a narrow opening causes the fibre bundle to flatten. This allows for more contact with the resin material and squeezing out excess resin. Resin is caught in the red plastic Teflon foil which allows for easy replacement with a fresh one after the filament winding is done. The opening of the final two rolls is tweaked by adding layers of tape around the bundles by which the rolls as spaced a certain distance from each other. This was necessary as there is a trade-off between optimal wetting of the filament against the maximum tension and friction that can be applied before the filament is damaged.

Figure 14.6: Fibre wetting device which applies a small amount of epoxy resin to the filament. At the entrance point of the device a small amount of loose carbon fibre material builds up during the plate winding process.

The Epoxy used is the Hexion Epikur Epikote 04908 which is a low viscosity infusion resin. This makes it possible to apply a very small amount of resin to the system. The largest downside of performing wet filament winding is the added weight of the epoxy in the system. An estimate from a short wetted piece of filament showed that the total added weight could be as much as 60-80% of the weight of the carbon fibre itself causing the need to lower the density of the Polyurethane foam. As the same amount of Polyurethane was added as for the C1 composite, it is therefore expected that the composite density should be up to 40% higher.

The second major change was the cutting of fibres outside of the boundary of double sided tape. In this way the filament wound fibres could be handled independently from the wooden panel. To improve the uniformity of panel thickness an aluminium mould was created. This mould consists of a large aluminium bottom plate covered with open Teflon to aid in the foaming process. On the sides of the aluminium plate a boundary was created using 3 mm thick aluminium and two layers of 0.2 mm thick double sided tape to create a minimum panel thickness of 3.4 mm. To ensure proper closing of the mould, the pressure of the machine was increased to 1000 kN after an initial test indicated that there were no problems applying this force. Additionally the polyurethane foam was now applied directly in the mould panel after which the net of fibres is positioned on top of the unfoamed polyurethane film.

14.3.2.1. C2 - Feasibility for use in musical instruments

The added epoxy to the carbon fibre strands created a solid mesh. After infusion the C2 composite proved to be much easier to machine and no loose fibres were present at the edges. Additionally sanding on a sanding belt was now possible as the solid carbon fibre epoxy strands would grind away similar to how the Polyurethane grinds away.

The density of the panel was found to be 642 kg/m^3. This is only slightly higher than composite panel version C1 which is expected due to the addition of a small quantity of epoxy resin around the fibres.

14.3.2.2. C2 - Acoustic and stiffness analysis

The stiffness test results are shown below in Table 14.2. As can be seen, the results in terms of stiffness are very comparable. The largest difference is visible in the strength. As indicated before, the samples used are merely an indication of strength and cannot be used as a reliable result as the failure occurs mostly at the clamps due to additional clamping stresses. All of the C2 samples failed above a load of 8 kN resulting in a failure stresses between 0.95 and 1.5 GPa. For comparison two wood samples of similar dimensions were tested which both failed below a stress of 0.4 GPa. This indicates that the composite is considerably stronger in tension compared to the wood.

Table 14.2: Stiffness results for the C2 composite samples in longitudinal direction.

Sample	t [mm]	w [mm]	area [mm^2]	strain1 [V]	strain2 [V]	Δstrain [-]	Force1 [N]	Force2 [N]	ΔStress [MPa]	Stiffness [GPa]
C2L1	3.50	27.0	94.4	0.2	0.6	0.003596	2774	7555	5.07	14.09
C2L2	2.85	26.7	76.0	0.2	0.6	0.003596	2212	6318	5.40	15.02
C2L3	2.85	26.6	75.7	0.2	0.6	0.003596	2001	5837	5.07	14.09
C2L4	3.16	27.1	85.6	0.2	0.6	0.003598	2770	7205	5.18	14.40
C2L5	3.09	27.2	84.0	0.2	0.6	0.003599	2606	7081	5.32	14.79
C2L6	3.19	27.2	86.6	0.2	0.6	0.003599	2937	7306	5.04	14.01
C2L7	2.93	27.0	79.2	0.2	0.6	0.003599	2885	7232	5.49	15.24
C2L8	3.27	26.8	87.6	0.2	0.6	0.003600	2482	6605	4.71	13.08
C2L9	3.03	26.6	80.5	0.2	0.6	0.003601	2494	6472	4.94	13.72
C2L10	3.38	26.7	90.4	0.2	0.6	0.003601	2881	7357	4.95	13.75

Acoustically the C2 panel was on the other end of the spectrum than the C1 panel. Due to the low damping of the carbon fibre epoxy strands the overall plate damping decreased dramatically. Therefore an attempt should be made to increase the damping for the next iteration.

14.3.2.3. C2 - Summary of problems for next iterations

The production and testing of composite panel C2 indicated the following problems listed below.

- The wetted fibres caused the composite to have not enough damping with respect to wood. An attempt should be made to increase the damping.
- The density of the panel is too high and should be lowered.

At this point it was concluded that the stiffness in longitudinal direction was validated and would not be tested for the remaining samples. The stiffness in bending would be further investigated using the modal analysis as the frequency of the resonance peaks in the FRF data directly relate to the bending stiffness of the panel.

14.3.3. C3, C4 and C5 panels manufacturing and analysis

Composite versions C3 and C4 were manufactured in the same way as composite version C2. The main difference was the addition of flexibilizer in quantities of 20%, 33% and 40% respectively. The main goal of this is to increase the damping of the panels.

The density of the panels was lowered by slightly modifying the rake used to distribute the resin in the mould. As indicated in the manufacturing description of panel C1 the rake was wound with a steel wire of 1.6 mm. The original calculations indicated however that only a film of around 0.8 mm was required to obtain the correct density. Therefore a steel wire with diameter 0.8 mm was wound around the Teflon cylinder of the rake to reduce the amount of unfoamed polyurethane foam that would remain in the mould. Additionally due to the addition of epoxy to the fibres the weight increased by several grammes which is also visible in the increase in density of panel C2 with respect to panel C1. By wiping the fibres with a dry cotton cloth after the winding of one layer was completed excess resin was removed to reduce the weight and thus density of the panel. This process step was introduced for panel C5 which reduced the density to 525 kg/m^3 from 556 kg/m^3 and 566 kg/m^3 for panels C3 and C4 respectively.

14.3.3.1. C3 through C5 - Feasibility for use in musical instruments

The composite versions obtained are all suitable for the use in musical instruments. As no major design changes were made to the production process the composite is still easy to machine and workable.

14.3.3.2. C3 through C5 - Acoustic and stiffness analysis

The difference between C2 and C3 in terms of damping was relatively low. The method used to get a first indication of damping is still done by tapping the panel and listening to the response. Increasing the flexibilizer content to 40% increased the damping of the panels significantly making them sound very similar to a low quality spruce panel obtained from a local wood store in Amsterdam.

At this point both panels C4 and C5 were tested using the modal analysis test set-up and compared to a A-grade spruce panel obtained from the Amsterdamse Fijnhouthandel as an initial comparison panel. The modal analysis set-up was not optimized yet and therefore no damping analysis was performed in detail. However the main goal was to find if the mode shapes of the composite panel would match those of wood and if the frequencies at which they occur are comparable. It was found that both panels C4 and C5 provided enough stiffness in the transverse direction while the longitudinal stiffness fell short considerably.

14.3.3.3. C3 through C5 - Summary of problems for next iterations

The damping from an initial tapping method indication was found to be much closer. However the density did not yet reach the values aimed for and is still slightly too high. Therefore additional measures should be taken to reduce the density below the maximum threshold of 500 kg/m^3. It was noted that during the resin distribution the film thickness is likely to become slightly thicker as the working speed of distributing the unfoamed polyurethane has to be extremely high to be able to perform all required actions and close the press before foaming starts. Therefore to be able to work more securely and apply a uniform film thickness on the mould surface the start of the reaction should be retarded.

14.3.4. C6, C7 and C8 panels manufacturing and analysis

Two potential solutions to delay the start of the foaming reaction were investigated. First, a sample of a blocking agent by Airproducts was requested. Added in the specified quantities no measurable result was obtained in terms of reaction delay. Adding around 8 times the specified amount resulted in an additional 10 seconds before the reaction started on top of the 50 seconds previously mentioned to be the time from start of mixing until the foaming starts. This however greatly decreased the properties of the foam and was therefore not an option. Upon consultation with Airproducts the suggestion was made to add Acetic Acid to the mixture as the blocking agent was designed to work with the weaker slab-stock foams. Addition of 1% of Acetic Acid resulted in a similar delay of the reaction of 10 seconds. The foam properties were not affected noticeably however the reaction speed and thus foaming was more aggressive.

A second solution to delay the reaction was found by cooling the two components to 6 degrees Celsius. This resulted in a much larger delay of the reaction of about 25 seconds bringing the total time until reaction starts to 75 seconds which was considered workable for the larger panels to be produced. The time to properly mix the two components is about 20-25 seconds leaving effectively around 50 seconds for distribution of the foam, placement of the fibres and closing of the mould.

To improve the stiffness of the panels two solutions were investigated. Firstly for panels C6 and C7 the longitudinal layers were positioned more to the outside of the panel which, according to laminate theory as discussed in subsection 5.1.1, should result in considerably higher bending stiffness without affecting the longitudinal stiffness. An additional solution was investigated by decreasing the fibre spacing to 4 mm which effectively increases the fibre quantity by 25%.

The density of the panels was found to be 502 kg/m^3, 516 kg/m^3 and 535 kg/m^3 respectively. The increase in density due to panel C8 having a higher carbon quantity is in line with expectations as the 25% increase should account for an increase in density of around 32 kg/m^3 according to the model as described in subsection 14.1.2.

14.3.4.1. C6 through C8 - Feasibility for use in musical instruments

The composite versions obtained are all suitable for the use in musical instruments. As no major design changes were made to the production process the composite is still easy to machine and workable.

14.3.4.2. C6 through C8 - Acoustic and stiffness analysis

Similarly to panel C5 the acoustic characteristics when tapping panels C6 through C8 were comparable with the wooden panel. Additionally the Moonspruce panels as discussed in chapter 11 were now available for comparison and proved to have actually less damping than the initial spruce panel used for comparison.

The modal analysis conducted indicated that neither of the two methods did dramatically improve the bending stiffness of the panels. The shift in frequency by using a different lay-up only increased the resonance frequency of the first longitudinal mode by 6.6% while according to the updated model the bending stiffness should have increased by over 120%. Panel C7 and C8 with increased carbon content only showed an increase of 12-15% in the longitudinal stiffness while a increase of 25% was expected.

For panel C8 a small test was conducted towards the possible cause of the relatively bad stiffness performance of the panels in longitudinal directions. It was found that due to the releasing of the fibres from the wooden panel the tension in the fibres was loosened. This was caused by the application of the tape by stretching. Once the fibres and the tape boundary is released from the wooden panel the tape has a possibility to contract essentially compressing the fibres. The fibres therefore buckle and the fibre spacing in the thickness direction drops to only 1.8 mm at some positions at the center of the panel. Therefore to improve the stiffness performance a different solution should be created to keep the fibres in place after cutting them loose.

14.3.4.3. C6 through C8 - Summary of problems for next iterations

The production and testing of composite panel C6, C7 and C8 indicated the following problems listed below.

- The stiffness performance of the panels in longitudinal direction is not following the model due to compression forces by the double sided tape boundary causing the fibres to loose their position in the thickness direction and effectively lowering the bending stiffness of the panels. Therefore a solution should be created to prevent the fibres from buckling in.
- The density of the panel is slightly too high due to the increased carbon content.

14.3.5. C9 panel manufacturing and analysis

The main focus of the C9 composite iteration is the improvement of the bending stiffness. By using thin aluminium strips instead of double sided tape at some positions in the boundary the compression force of the remaining double side tape layers is applied to the aluminium strips which will be barely affected. In this way a much stiffer frame was obtained that did not compress the fibres after cutting them loose around the boundary. Performing the same test as for the previous iterations by measuring the fibre spacing at several points at the center resulted in fibre spacings of at least 3.12 mm which means that the position of the fibres is significantly more consistent compared to the previous iterations. The layup used is presented below where the 0 and 90 layers are indicated and T and A stands for tape and aluminium respectively. The filament spacing of 4 mm as used for panel C7 and C8 was also used for panel C9. The number of layers in Y-direction was lowered to 6 instead of 7 as previous tests showed a relatively high frequency for the vibration modes dependent on the transverse stiffness of the panel.

Layup: $[0,90,T,A,0,T,0,90,0,90,T,\bar{A}]_s$

Additionally, less polyurethane was mixed and distributed to slightly lower the density of the panel to match the density of the Moonspruce as discussed in chapter 11. The resulting panel had a density of 466 kg/m^3 which is very close to the density of the Moonspruce samples tested. The panel produced is presented in Figure 14.7.

Figure 14.7: Panel C9 after being removed from the mould and prepared for sawing.

For the final analysis the damping values were studied. Both panel C7 and C9 are included in the analysis. In Figure 14.8 the main frequency response curves are presented of the two composite panels and three grades of Moonspruce.

As can be seen from Figure 14.8 the composite panels show similar behaviour with two large peaks below 110 Hz corresponding to the first bending modes in Y and X directions. In order to illustrate the difference between the developed composite material and a carbon fibre epoxy, a carbon fibre panel of thickness 1.2 mm was produced using vacuum infusion. This panel is tested similar as the other composite panels and added to the analysis for better interpretation of the results.

From Figure 14.9 it can be observed that the carbon fibre epoxy panel has considerably different behaviour than the Master grade wood and composite panel. The peaks are significantly sharper indicating a much lower damping and additionally the output signal is much lower due to the lower sound radiation coefficient.

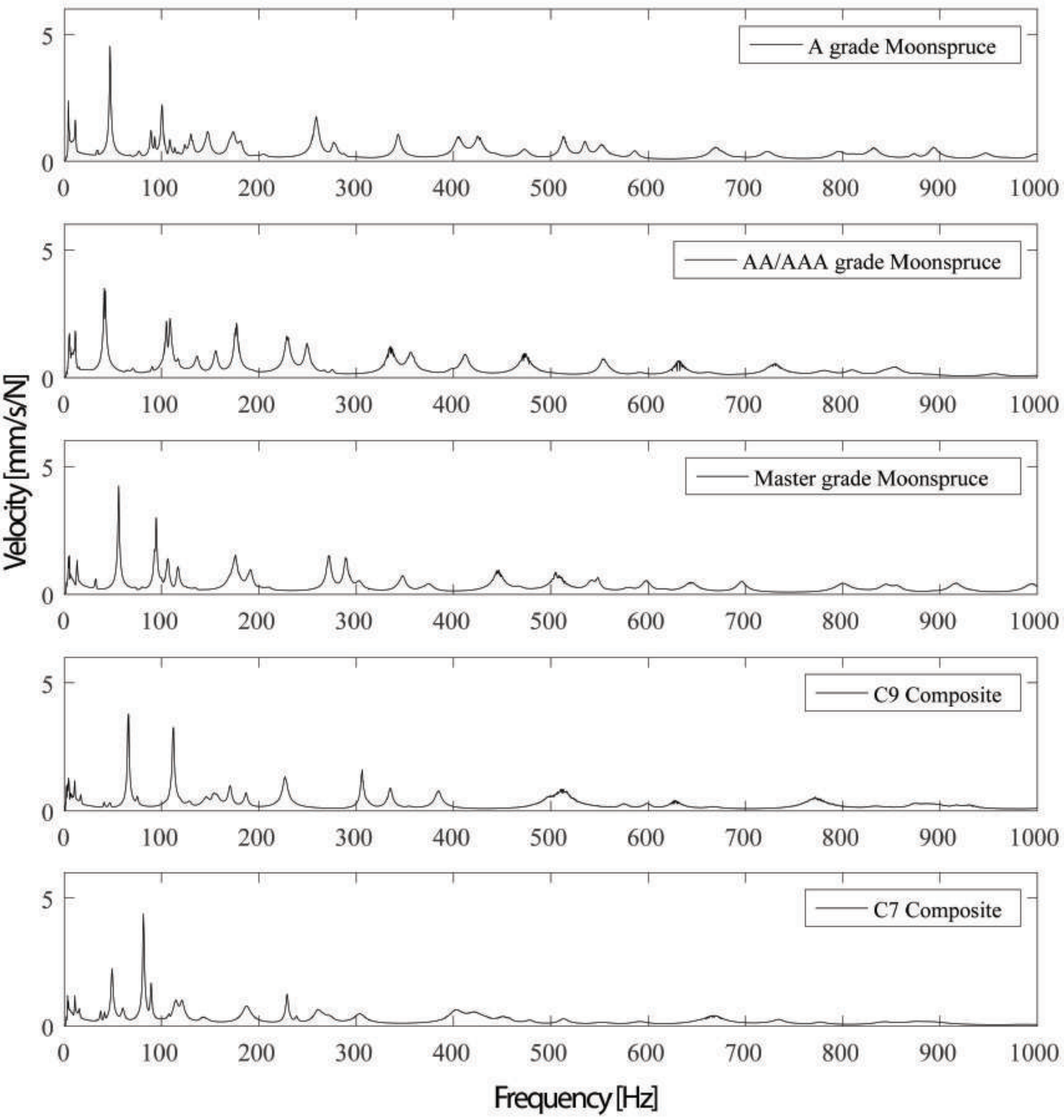


Figure 14.8: Frequency response data of three wooden and two composite panels tested from 0-1000 Hz.

As discussed in chapter 10 a more detailed analysis of the five most dominant modes for the composite and wooden panels is conducted. The mode shapes researched are shown in Figure 10.5. In Figure 14.10 and Figure 14.11 the frequency and the damping values of each of the modes for the panels researched is presented graphically. The mode names are restated below including their respective numbering as used in the graphs.

- First bending in X direction, **B1Y**
- First bending in X direction, **B1X**
- Second bending in Y direction, **B2Y**
- Third torsional mode, **T3**
- Second bending in X direction, **B2X**

From Figure 14.10 it can be seen that the frequency response of the composite panels largely follows the same behaviour as the wooden panels. The main difference can be observed for the torsion mode T3 which shows

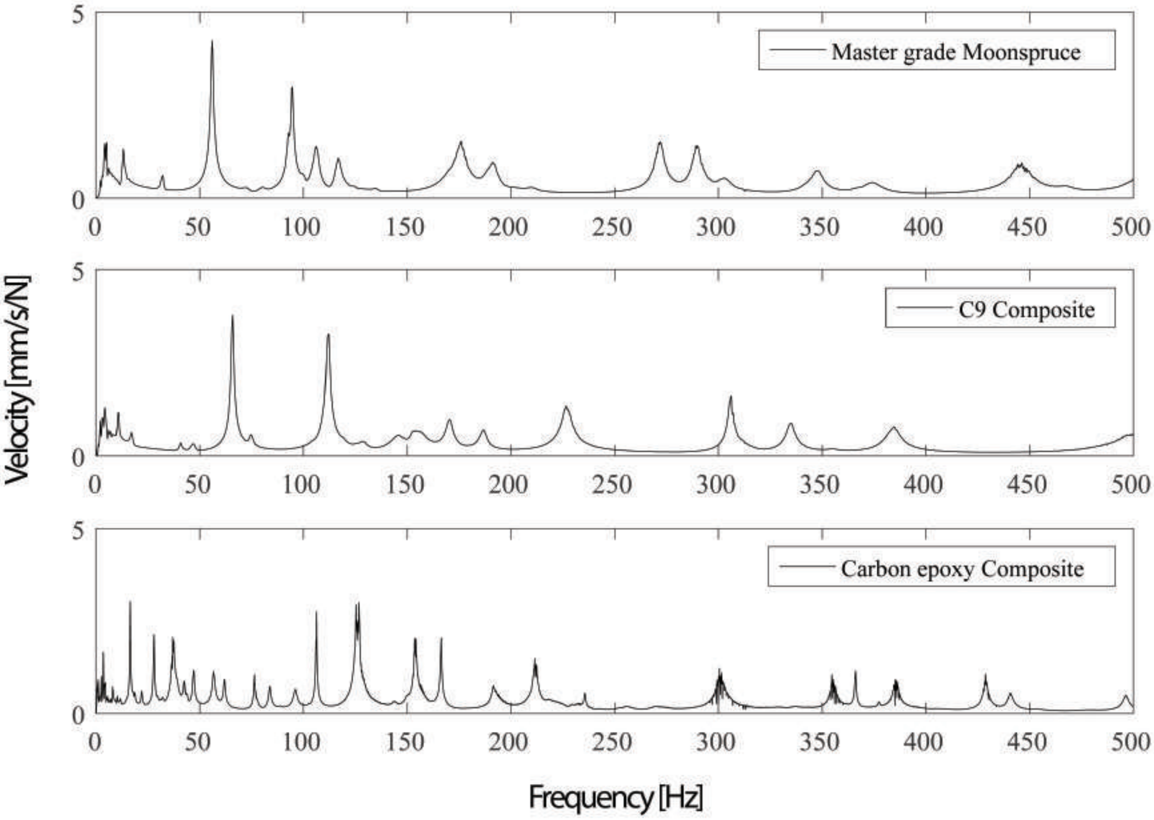


Figure 14.9: Frequency response data from a Master grade Moonspruce, composite C9 and carbon fibre epoxy panel from 0-500 Hz.

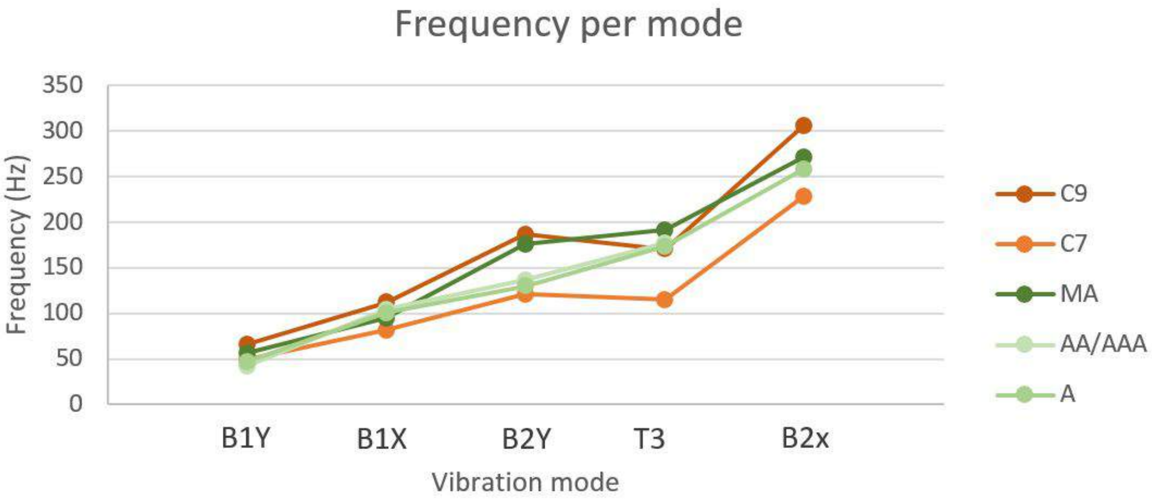


Figure 14.10: Frequencies of the five dominant resonance peaks.

a slightly lower frequency than the second bending in Y mode B2Y for the composite panels while for the wooden panels the B2Y mode is at a lower frequency than the T3 mode. This can be explained by the fact that the torsional stiffness of the composite panels is relatively low due to the absence of any reinforcement in the 45 and -45 degree directions. To obtain a perfect match with wood it can therefore be concluded that the composite should be designed with additional reinforcement in the 45 and -45 direction.

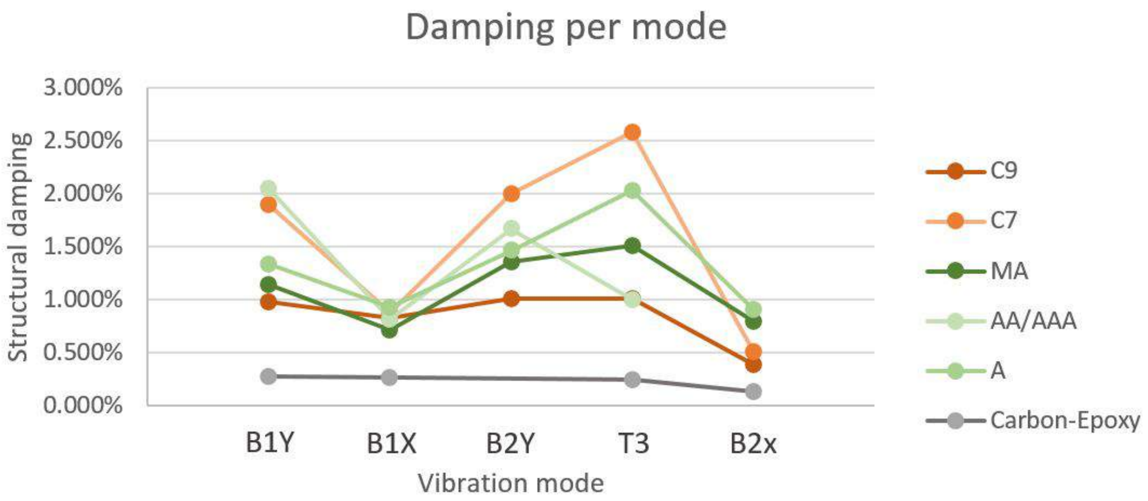


Figure 14.11: Damping values of the five dominant resonance peaks.

Overall it can be seen that the stiffness can be tweaked above and below the wooden panels to arrive at the same resonance response peaks. From this it can be concluded that almost perfect matching of the acoustic response is possible with respect to the frequencies.

On the damping side the story is very similar. The damping values of the wooden panels is between the values obtained from the C7 and C9 composites which shows that also tweaking of damping can potentially result in near exact matching. Additionally the carbon fibre epoxy panel is included in the damping analysis to illustrate the large difference between a normal carbon fibre epoxy and composite iteration C9. While the developed composites and wooden panels show damping values between around 1% and 2% the damping values of the carbon fibre epoxy panel are at least 4 times as low at around 0.25%

14.4. Conclusion on composite option

From the iterations performed it can be concluded that the composite has very high potential to replace wood in guitars. The stiffness can be matched almost perfectly in both longitudinal and transverse direction and the lay-up allows for active steering of the bending stiffness. The main differences observed are the dip in frequencies of the torsional modes. Although these modes are not as prominent as the main bending modes further iterations of the composite should include the torsional stiffness in the model to be able to further improve the acoustic response.

The density of the composite can be controlled reasonably well. Although the application of the polyurethane resin in the mould is not a convenient process small changes to the production process resulted in expected changes in density of the composite. Using more advanced equipment the composite density should be controllable even better making nearly exact matching possible.

The damping values show a similar story with values very close to those of the main woods tested. Using flexibilizer in the epoxy during the filament winding the damping can be steered to be both lower and higher than wood making also nearly exact matching possible.

The production process of the panels is very labour intensive. The process of filament winding after optimization takes at least 3.5 hours. The epoxy around the fibres has to be cured for either 30 hours or placed in an oven at 60 degrees Celsius for a minimum of 6 hours. Additionally the application of the polyurethane foam is currently a high risk operation as poor distribution of polyurethane foam potentially leaves dry spots in the composite making it unusable.

After production of the composite the post-processing towards a guitar can be very similar to the post processing of a wooden panel. The workability of the final composite panels is excellent with only one main downside compared to wood. This is the potential health risks associated with sawing and sanding of carbon fibres due to the fine dust released in the working environment. However this can be solved easily by taking the required safety measures by wearing a protective mask.

15

Validation of environmental performance

This chapter provides the results and a short discussion on the validation of environmental performance as performed according to the methodology explained in section 10.4. The goal of this analysis is to provide an initial indication if the composite would indeed perform better in terms of environmental sensitivity. A lower environmental sensitivity would result in a more stable guitar that does not loose its tuning and tone due to temperature or relative humidity changes and would additionally be less prone to structural damage.

15.1. Temperature sensitivity

The temperature sensitivity results indicated by the thermal expansion coefficients are presented below in Table 15.1. The samples are labelled according to the following specifications.

L1-L3 - Composite samples with carbon fibres running through the polyurethane foam in one direction.
K1-K3 - Composite samples with carbon fibres running through both the longitudinal and transverse direction of the the polyurethane foam. These samples contain roughly double the amount of carbon compared to samples L1 through L3.
W1-W3 - Wood samples tested.

Table 15.1: Thermal expansion coefficients of tested samples.

Sample	**Thermal expansion** $[10^{-6}K^{-1}]$
L1	74.5
L2	57.9
L3	64.6
K1	76.0
K2	80.8
K3	71.3
W1	51.9
W2	48.3
W3	71.0

During a number of the tests the probe appeared to slip away over the sample surface. Therefore a number of samples is tested twice as the linear portion of the curve was considered too short to calculate the thermal expansion coefficient. The second run of the TMA starts at the final conditions at the end of the previous test. Therefore the probe position at the start of the test is different for the second test as it is for the first test. During the second test the slip of the probe is much smaller yielding a linearly behaving curve up the maximum sample temperature for the respective tests. The test curves of the first and second test of sample L2 are shown in Figure 15.1.

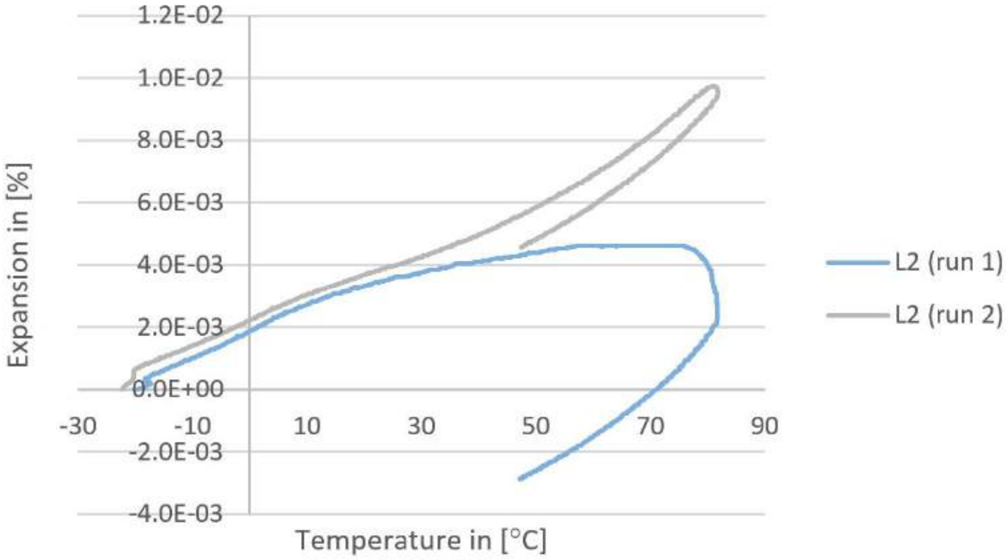


Figure 15.1: First and second TMA test of the L2 sample. The second run shows a linear behaviour up to the maximum test temperature while the first run shows probe slip from 20 degrees Celsius onwards.

From the results it can be observed that the thermal expansion coefficient of the composite is slightly higher than for the wood. Both the composite and wood samples show varying results. For the wood this is expected as the uniformity of this natural material is relatively low compared to high quality composites. For the composite the differences between samples is less than for the wood but higher than expected. There are two possible causes for this. First the overshoot during cooling of the testing chamber is different for every sample. Some samples have been cooled to below -40 degrees Celsius while after a number of samples a more consistent overshoot to around -20 degrees Celsius was realized. This was caused by the delay of effect of adding liquid nitrogen to cool the test chamber. At the point where the sample temperature reaches 10 degrees Celsius the addition of liquid nitrogen should stopped to reach a cooling of below -10 degrees Celsius without a large overshoot. The wood samples were all tested with roughly the same overshoot as the composite samples were tested first. A second explanation for the differences is the behaviour of the foaming process when the material comes in contact with the carbon fibres. The foaming process can be disturbed resulting in a different foam density around the carbon fibres. This in turn could potentially result in different thermal expansion behaviour.

From literature it was found that the typical thermal expansion coefficients of spruce and rigid polyurethane foam are 38 to 41 $10^{-6}K^{-1}$ and 50 to 80 $10^{-6}K^{-1}$ respectively [123, 124]. From this it can be seen that the wood samples tested show a slightly higher thermal expansion compared to literature. Additionally it is found that the composite thermal expansion coefficient is dominated by the Polyurethane foam. This is in-line with expectations as the Polyurethane foam is responsible for over 80% of the volume of the composite.

It can be concluded that the composite does not succeed in meeting requirement E2 on the thermal sensitivity. However to understand the complications of a complete composite guitar in terms of thermal sensitivity a test should be devised to analyse the behaviour of a composite guitar with respect to a wooden guitar. As the other components are made from more rigid composites with more carbon it is expected that these composites and thus the whole composite guitar will be significantly less sensitive to temperature changes.

15.2. Humidity sensitivity

The results of the humidity sensitivity study are presented in the following two sections. First the wet TMA test results are discussed after which the water absorption test results are presented.

15.2.1. Wet TMA results

The wet TMA results are presented in Table 15.2.

Table 15.2: Thermal expansion coefficients of tested wet samples.

Sample	**Thermal expansion** [$10^{-6}K^{-1}$]
LW1	72.6
LW2	71.1
LW3	88.5
WW1	533.9
WW2	221.3
WW3	102.9

From the results it can be seen that the composite samples do not behave significantly different after being soaked in water for 24 hours and left to dry for one hour. The wood samples however show a completely different response. All three samples are affected to a very different extent ranging from 2 to 12 times the original average thermal expansion coefficient of the dry wood samples. This does not only indicate the much higher humidity sensitivity of wood compared to the composite but also shows that a larger wood panel is potentially not uniformly affected by the change in humidity. This might result in additional stress concentrations and will also have a great effect on the sound of the wood. To analyse the extend of this nonuniformity behaviour to water or moisture additional samples should be tested.

15.2.2. Water absorption tests

In Table 15.3 the main water absorption test results are presented. The test samples follow the sets as presented in subsubsection 10.4.2.2. The A samples are the reference samples that have been in normal room temperature conditions at 54% relative humidity for 24 hours after being dried. The B samples are the samples being soaked in water for 1 hour and left to dry for 1 hour. The C samples are the samples being soaked in water for 24 hours and left to dry for 1 hour.

The water absorption tests show a comparable outcome to the wet TMA tests. The composite samples are hardly affected by the humid conditions and only show a 0 to 1.3% increase in weight for each each of the tests. The wood samples in comparison show a 4 to 5% weight increase for the A sample tests. This is a considerable weight increase as the sample have not been in direct contact with water. For the samples soaked in water for 24 hours the average weight increase is 65.83% while the composite samples show only a 1.01% weight increase after this time. From this analysis it can be concluded that the composite has very low sensitivity to a change in relative humidity while wood will be significantly affected.

In order to understand if the wood samples would return to their original conditions quickly the B samples were weighed again after being left to dry on a clean piece of plastic. Two additional measurements were done after 3 and 24 hours respectively. A can be seen from Figure 15.2 The weight decreases after longer periods of drying. After 24 hours of drying the wood samples still show an average weight increase of 20.48%.

Table 15.3: Results of the water absorption tests.

Sample	Initial dry weight [g]	Weight after process [g]	Relative weight increase
A-W1	0.9915	1.0387	+ 4.76%
A-W2	1.0153	1.0586	+ 4.26%
A-W3	1.0705	1.1167	+ 4.32%
A-C1	1.1633	1.165	+ 0.15%
A-C2	1.3852	1.3867	+ 0.11%
A-C3	1.3561	1.3592	+ 0.23%
B-W1	1.0087	1.4300	+ 41.77%
B-W2	1.0441	1.5499	+ 48.44%
B-W3	0.9654	1.3777	+ 42.71%
B-C1	1.4105	1.4138	+ 0.23%
B-C2	1.1319	1.1354	+ 0.31%
B-C3	1.2300	1.2319	+ 0.15%
C-W1	0.9801	1.6255	+ 65.85%
C-W2	1.0043	1.6785	+ 67.13%
C-W3	1.1135	1.8318	+ 64.51%
C-C1	1.4783	1.4905	+ 0.83%
C-C2	1.1625	1.1783	+ 1.36%
C-C3	1.2805	1.2912	+ 0.84%

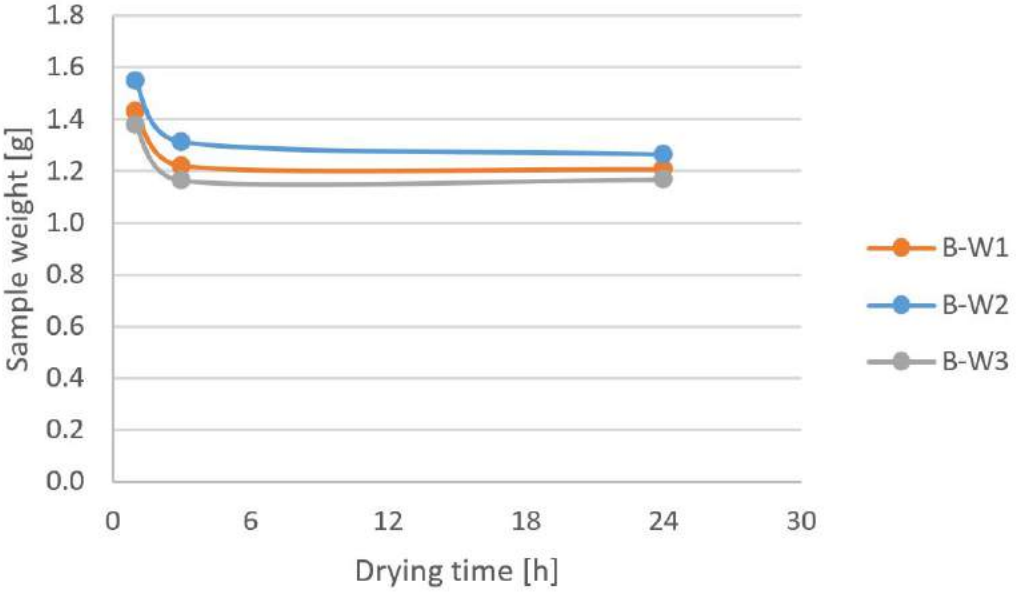


Figure 15.2: Graph of sample weight versus drying time. The samples decrease in weight rapidly during the first three hours of drying but stabilize afterwards.

15.3. Conclusion on environmental performance

From the analyses conducted it can be concluded that the composite does not meet requirement E2 on thermal sensitivity but does satisfy requirement E1 on humidity sensitivity. The thermal sensitivity of the composite is slightly higher while the humidity does not pose any problems for the composite. Considering that the other components of the composite guitar are constructed from different materials than the developed composite a full analysis on both a wooden and composite guitar should be conducted to find an accurate sensitivities of both instruments. It is expected that, due to the use of more carbon in other components, the composite guitar will perform significantly better in both thermal and humidity sensitivity compared to a wooden guitar.

16

Cost and market potential analysis

Requirement C1 as set-up in chapter 7 states that the composite should be at least as cost efficient as high quality wood. In order to verify if this requirement is met the total production costs of one panel of composite material is to be checked. The panel dimensions are chosen to match the dimensions of one soundboard set of moon harvested alpine spruce as sold by Florinett AG [125]. The dimensions are two separate panels of 560 mm by 210 mm. As the production process of the composite allows panels up to 650 mm by 650mm to be produced, the total costs of the wooden panels is multiplied by 3/2 to account for the difference in surface area and considering the minimum size panel should have to be usable.

16.1. Material costs

The material costs are taken up by four main components. These are the Carbon fibre 3K filament, the low viscosity Hexion 04908 infusion epoxy, R&G epoxy flexibilizer and finally the polyurethane foam. The costs and quantity required of each of the components is summarized in Table 16.1.

Table 16.1: Overview of material costs of composite panel.

	Price/unit	**Unit**	**Quantity**	**Unit**	**Total price**
Carbon fibre 3k fillament	76.8	€/kg	0.08	kg	€ 6.14
Epoxy	25	€/kg	0.2	kg	€ 5.00
Flexibilizer	45	€/kg	0.15	kg	€ 6.75
Polyurethane foam	8.5	€/kg	0.55	kg	€ 4.68
					€ 22.57

The total material costs are estimated to be around 23 Euro.

16.2. Production costs

As can be seen from Table 16.2 the production costs of the composite take up the bulk of the costs. This is mainly caused by the labour intensive process of filament winding which takes roughly 4-6 hours for one panel. This results in a total of 8 labour hours for one panel. Addition of the production material costs such as tape and Teflon sheets and including the machine and equipment use pushes the production costs to a total of 330 Euro. Combining the production and material costs it can be calculated that the production of the composite is around 350 Euro of which 280 Euro (80%) is taken up by the labour costs.

Table 16.2: Overview of composite production costs.

	Price/unit	Unit	Quantity	Unit	Total price
Production materials	15	€/unit	1	unit	€ 15.00
Tooling	35	€/unit	1	unit	€ 35.00
Labour	35	€/h	8	h	€ 280.00
					€ 330.00

16.3. Comparison with wood species

With the total price of the composite using the current production method found to be around 350 Euro, a comparison can be made with soundboard woods and back and sides woods. These comparisons will be presented below.

16.3.1. Soundboard wood comparison

The price of the master grade soundboard wood of similar size as the composite panel is found to be 265 Euro including shipping, import and taxes. This is 25% cheaper compared to the composite panel. Therefore it can be concluded that the composite is currently not competitive for the use in soundboards of guitars. When the price of high quality woods continues to grow as it historically has it can be expected that the costs of wood will become higher than the costs of the composite panel within 10-20 year.

16.3.2. Back and sides wood comparison

The price difference in woods used for the back and sides of acoustic guitars is relatively large. Common woods such as low grade Indian rosewood start from around 150 Euro while high quality sets of Brazilian rosewood can result in a 6,500+ Euro upcharge for high end guitars [126, 127]. From this is can be concluded that in case the acoustic properties of a high grade wood can be approached with a composite, the price advantage of the composite can be very large. It should however be considered that back and sides woods are also commonly chosen for their visual appearance rather than their acoustic properties. Therefore it is hard to determine how competitive the composite will prove to be when introduced in the market.

16.4. Potential optimization on production method

As can be seen from the cost analysis the labour costs take up the bulk of the composite costs. Therefore an investigation should be done in a more effective production method of the composite as the material costs are considerably lower than the wooden panels the composite matches.

One potential solution is to design and build a continues production machine which can reduce the labour costs dramatically. A machine capable of doing this could be an automatic braiding machine which creates the correct fibre pattern for the composite. On top of that the fibres are pulled through an epoxy bath and are cured under UV lighting in a short time span of several minutes. Finally the cured fibres are pulled through a mould where the polyurethane foam is sprayed between the fibres. At the end of the production line the composite is pushed out and cut in the required panel sizes.

It is expected that the labour costs, production material costs and tooling costs can be reduced to 10-15 Euro per panel. This drops the total costs of the composite to around 40 Euro per panel. The main considerations of this method are the investment costs for development and production of the machine of which currently no estimation is made. However when considering at least 2500 guitar tops to be produced per year at a sales price of 150 Euro and cost of 50 Euro including overhead and other business costs, the machine costs can be over 1 million Euro if a customary break even of 5 years is taken into account. Therefore it is realistic to state that there is a high potential that the developed composite can be very cost efficient when a different more efficient production method is considered. It can therefore be concluded that requirement C1 as presented in chapter 7 can be satisfied.

17

Potential applications of developed composite in aerospace

This thesis is done as part of the final examination of the Aerospace Masters programme at the Delft University of Technology. Therefore this chapter is presented to look back at the developments and advancements in the Aerospace sector and identify areas where the research performed in this thesis might add to the progress. The focus is the potential areas of application of the newly developed composite. The composite developed has unique properties in terms of damping and strength. In the following sections a brief reasoning will be presented for each of the options identified.

17.1. Structural components in drones or UAVs

Drones have become hugely popular in the past few years [128]. The market is flooded with relatively cheap, high quality drones for consumers. The material developed during this thesis could potentially be used for drones. Current drones are largely made out of foams and small structural components. This results in a relatively weak structure in terms of impact performance. Especially the consumer versions of drones will be used by inexperienced flyers making the likelihood of crashes very high. Therefore a more impact resistant material such as fibre reinforced foams can prevent denting and crushing of foam structures without adding a significant amount of extra weight.

Another benefit could be the damping characteristics. The material developed in this thesis has considerably lower damping than a common composite, especially at high frequencies. The propellers of a drone generate frequencies that can effectively be damped by the reinforced foam composite. This can result in more quiet drones.

17.2. Damping material for wing structures

Wing-mounted engines cause large vibrational loads on conventional passenger aircraft. Creating sandwich panels in wing structures using fibre reinforced foams cannot only add to the stiffness and structural performance of the wing, but can also help dampen the vibrations. Due to the high stiffness of fibre reinforce foams, the effective damping will be considerably higher compared to damping with a normal damping layer. This is because the stiffness difference between the face material and the fibre reinforced foam is much lower. Lower vibrational loads can help to reduce acoustic noise in the passenger cabin making the flight more comfortable. Next to that the vibrational stresses in the structures which cause fatigue damage might be lowered.

17.3. Damping material for satellites and rocket systems

Satellites and rocket systems could potentially benefit from the decrease in vibrational loads. Although the vibrational loads in space will be negligible, the vibrations in the rocket and satellite are extremely high during take-off. Having a material with which certain vibrational characteristics can be tuned could greatly reduce the stresses on the satellite and its systems. By using fibre reinforced foams the stiffness and thus resonance frequencies of certain components can be changed such that the components do not resonate with the thruster vibrations. This effectively creates a self-damping structure.

17.4. Floor structure in passenger aircraft

Another use case for passenger aircraft is the use of fibre reinforced foams in aircraft floors. One of the main design criteria is the high pressure of women's shoes with thin, stiletto type heels due to the small area on which the load is applied [129]. This requires the floor to be much stronger and heavier than would otherwise be the case. Using the fibre reinforced foam material in a sandwich structure can help transfer the load to a larger area of the material due to the coupling of the top face via the fibre reinforced foam underneath it. This can reduce the local stress in the material, making it possible to reduce the overall weight of the floor structure.

17.5. Windmill structures

Windmill structures are inducing their own vibrational loads due to the wing blades moving along the main pillar structure. These loads can be so severe that windmills have to be designed in such way that the resonance frequencies of the structure do not align with the wing blade induced frequencies.

The fibre reinforced foam developed allows for large flexibility in designing the resonance frequencies of a panel and the control of damping parameters. Although potentially hard to produce at the scale of a full wing blade or windmill tower structure, fibre reinforced foams can be used in certain parts to help satisfy the design criteria in terms of vibrational stability of the structure.

18

Conclusion and recommendations

The development of a composite that matches wood acoustically proved to be a difficult research goal. While it was expected that the modelling and data acquisition would take up the bulk of the development time, it was the production process optimization that required the most effort. Therefore the modelling part of the research was kept limited to an initial model and iterations were made almost solely on the production. This holds for all four composite options researched.

The two Endumax composite options did not yield any feasible results. Both the production method and the resulting composite performance did not meet the requirements as set-out in chapter 7. Additionally the processability of the samples was very poor. Because of these downsides it was decided at a relatively early stage of development to not further investigate these options and focus on the two other options.

The other two options, the fibre reinforced glass blown foams, were investigated in more detail as the initial results were more promising than for the Endumax composite options. Initial tests indicated that the epoxy foams did not build-up enough pressure to fill the moulds while the polyurethane foams required additional pressure to keep the mould closed. The basic model used for the computation of the volume percentages of each of the composite constituents worked well and was validated by density and stiffness tests of the first two production iterations of the composite. During the iterative process a number of changes were made to improve the acoustic performance in terms of damping, improve the uniformity of the panels produced and create a composite that is workable in a similar fashion as wood. The main requirements as set-out in chapter 7 are reviewed using the output of the analysis on composite iteration C9.

A1. Stiffness and density The longitudinal stiffness of the composite can be controlled accurately by the amount of fibre material in certain directions. The density of the material is 466 kg/m^3 which is within the range set-out. Therefore this requirement is satisfied.

A2. Sound radiation energy The resonance peaks of the composite C9 are slightly higher than of the woods used as a baseline. This indicates a higher stiffness in bending of the composite. Additionally the density is within the range set-out resulting in a sound radiation coefficient that is slightly higher than for wood. Tweaking the quantity of fibre material in the composite can lower the stiffness slightly and thus match the sound radiation coefficient of wood. Therefore this requirement is considered satisfied.

A3. Speed of sound As both the stiffness and density are matched to wood the speed of sound will be the same. While a test should be conducted to confirm this, at this stage the requirement can be considered satisfied.

A4. Damping The damping values of the composite are slightly lower than the woods used as a baseline. Previous iterations however show a slightly higher damping resulting in the conclusion that the damping can be matched almost exactly to wood after more iterations are done. Therefore the requirement is satisfied.

E1. Humidity sensitivity The wood samples tested showed a very large sensitivity to humidity in both the wet TMA and moisture absorption tests conducted. The composite C9 version however was not measurably affected by the wet TMA tests while the moisture absorption is factors lower than for wood. Therefore this requirement is satisfied.

E2. Temperature sensitivity The composite has a slightly higher thermal expansion coefficient than wood. Therefore it is expected that the risk of damage due to a temperature change is higher than for wood. To confirm this full scale tests with wooden and composite guitars should be conducted. Therefore this requirement is not satisfied.

C1. Composite cost efficiency The cost of the composite is slightly higher than high quality master grade Moonspruce. This is mainly due to the high labour costs. There are potential solutions to automate the composite production process which might result in a very large decrease in price. Additionally the wood prices are increasing at a relatively fast rate. Therefore it can be concluded that the composite is likely to be more cost efficient after further development or once the prices of wood surpasses the production costs of the composite. This is expected to be within 20 years at the current price development of high quality woods. Therefore the requirement is considered satisfied.

C2. Design and production efficiency The processability of the composite is very similar to wood and therefore does not affect the production efficiency. The only major difference is the requirement of protective equipment as the post processing of carbon fibre poses a health risk.

From the requirements it can be concluded that the main thesis goal of developing a composite with similar acoustic properties as wood is accomplished.

Next the application in guitars, the concept of fibre reinforced foams might have interesting applications in other fields. A short study in the field of Aerospace engineering shows numerous applications areas. In these areas the two major benefits of a fibre reinforced foam are the increased crush strength of the foam core in sandwich structures and the modifications of vibrational characteristics of structures.

III

Development of a carbon fibre guitar with acoustics comparable to wooden guitars

19

Introduction to the design and production of a composite guitar

The newly developed carbon fibre reinforced polyurethane foam composite proved to be acoustically very similar to high quality woods as used in acoustic guitars. This part of the research thesis focuses on the development of a full scale acoustic guitar made predominantly out of composite materials. This is done to validate if the developed composite material applied in a full composite guitar would bring the sound of the instrument significantly close to high quality acoustic guitars.

This part of the thesis report is structured in a number of chapters covering both the production of the instrument as well as the psychoacoustic analysis conducted towards the perceptive testing of the instrument. The first chapter details the design of all components required including the main materials used. Second, as some of the components were designed to be made out of moulds, the mould design and production of the moulds will be discussed in detail. Third, the production of the components will be discussed. As some materials used in other components of the guitar were not tested in the previous part of the thesis, the development of these materials will be discussed in the respective sections for each component. Fourth, the assembly of the guitar is covered which also includes the finishing of the guitar in order to present a near market ready product.

After the production of the guitar is explained, the set-up and results of the psychoacoustic analysis will be discussed. This chapter will also be used to reflect on the main research objective as introduced in section 4.1 of designing a composite guitar with similar acoustics as a wooden guitar. Additionally the cost analysis of the full instrument will be conducted to demonstrate the market potential of the design. Finally a conclusion will be presented with regards to all thesis work conducted which will review the main research objective in a wider perspective.

The design of the composite guitar is created using a number of assumptions and considering the specific goal of matching the instrument to a wooden guitar. Therefore, although the composite guitar may prove to be a good quality instrument, the aim is not the optimization of the instrument as this would require many more iterations. The main assumptions are stated below which are applicable to all chapters.

- The general design philosophy for the composite guitar comes from the books by Erwin Somogyi [9]. These books are regarded by many guitar builders as the most valuable tools for both novices and experienced guitar builders. This is because they provide not only the main method of constructing and designing a guitar but also the main reasoning why a guitar and its components are designed in a certain way.
- While composites allow for many new guitar designs it has been decided to stay as close as possible

to traditional guitar designs including for example the Martin guitars style X-bracing pattern and the general shape of the body. This is done to limit the number of changes made on the structural level of the instrument as discussed in chapter 6

20

Design of composite components

This chapter will cover the main component designs and material selection. The design follows largely the dimensioning of a Greenfield G4 guitar [28]. This guitar is a large jumbo sized model guitar. The main dimensions and design characteristics are presented below.

- Scale length of 660 mm
- Lowe body length $20^{3/4}$" = 52.71 cm
- Lower bout width 17" = 43.18 cm
- Upper bout width $12^{3/4}$" = 32.39 cm
- Depth of body $4^{5/8}$" = 11.75 cm which is decreasing from the top of the guitar to the bottom of the guitar.
- Arm rest and rib rest. These features will be discussed below
- 14 frets to the body of the guitar.
- Near elliptical neck shape
- Pin-less bridge design

The full design and assembly of all components is done using Dassault Systems CATIA V5R21. For each of the components one or more 3D renderings will be provided. These renderings are made using Keyshot V5 Pro edition.

The guitar design focuses heavily on the function of the components in a structural sense instead of analysing the acoustics of each of the components. As the largest portion of the sound is generated by the soundboard and back, the other components such as the sides and neck are free to be manufactured from other composite materials as long as they will be capable of performing their function properly.

20.1. Soundboard

The soundboard of the guitar follows the shape of the main body dimensions as specified above. Additionally a part of the left side of the lower bout is removed to allow the sides to be curved with a larger radius. This is called an arm rest which prevents the blood flow in the arm of the guitar player to be partially cut off by the sharp edge of the body. This will be discussed in more detail insection 20.3.

On the inside of the soundboard bracing is attached. The design renderings are shown in Figure 20.1.

Most guitar soundboards are produced with a slight curvature. This is done by taking a flat top and applying

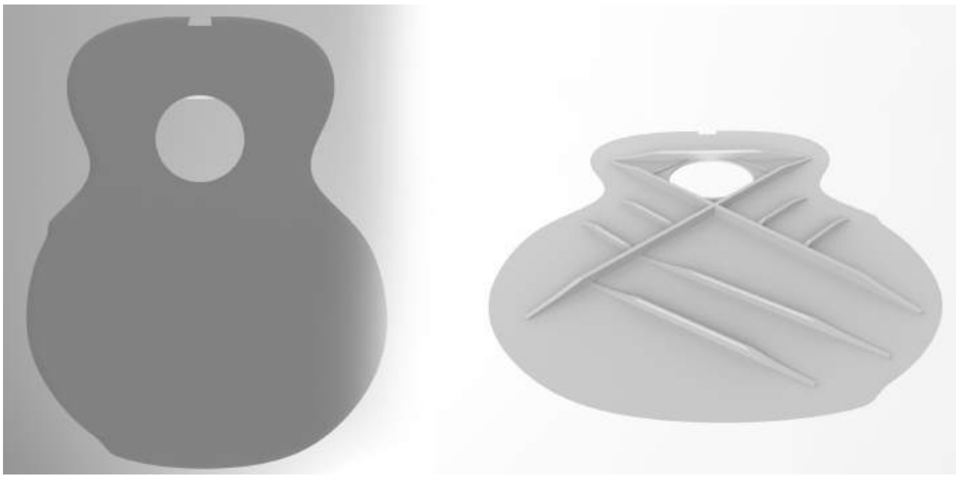


Figure 20.1: Left: front view of the soundboard. Right: angled view of the back side of the soundboard including the martin style bracing pattern.

the braces on it while the top and braces are pressed into a table with a specific radius. This is shown in Figure 20.2. The main reason for this is that the slight curvature provides additional stiffness to the top without adding any weight. Additionally the braces and top are pre-tensioned to prevent the top from buckling down near the lower bout and up near the lower bout due to the high string tension.

The material used for the soundboard will be a slightly modified version of the C9 version composite as presented in section 14.3. The spacing of the mould boundaries is reduced from 3.4 mm to 3 mm. This causes an increment in density which can be countered by adding a slightly lower amount of polyurethane foam. The reason for decreasing the top thickness is that a thick top might cause the guitar to become overbuild and sound brittle. The increase of 0.4 mm would theoretically provide a 46% higher bending stiffness compared to the 3 mm top according to subsection 5.1.1. The longitudinal stiffness of the material is unchanged by maintaining the same amount of carbon. This was done as the amount of carbon has a significant effect on the damping of the composite. An increase in damping caused by the reduction of carbon fibres would at this point be unwanted for validation of the designed composite in a full scale acoustic guitar. The braces on the top will be cut from the same panel as from which the soundboard is extracted. The classic Martin guitars style bracing pattern will be used as shown previously in Figure 2.3.

20.2. Back

The design of the back of the guitar is similar to that of the top. The filament winding layers are chosen to be the same as for the soundboard while the bracing pattern is designed differently. Michael Greenfield's custom guitars feature a radial bracing pattern with a connection ring. This system is patented under the name Tone Halo and will therefore not be used [28]. A custom radial bracing pattern is therefore designed which would structurally perform similar to the Tone Halo bracing pattern. The back plate is also pressed into a slight curvature when applying the braces similarly to the soundboard.

The main difference of the production of the back compared with the production of the soundboard is the amount of flexibilizer added to the epoxy. While for the soundboard the ratio of epoxy to flexibilizer is 60 to 40, for the back it was chosen to use a ratio of 80 to 20. This reduces the damping of the panel significantly providing a clearer ringing sound of the material. The main reason for this is that the typical woods used for the back and sides of high quality guitars, such as Brazilian rosewood or Macassar Ebony, have this typical ring sound. According to Somogyi this allows for a well balanced instrument with a clear and defined bass [9].

The design rendering is presented in Figure 20.3

Figure 20.2: Table with a specific radius used to create a slightly double curved and pre-tensioned soundboard [34]

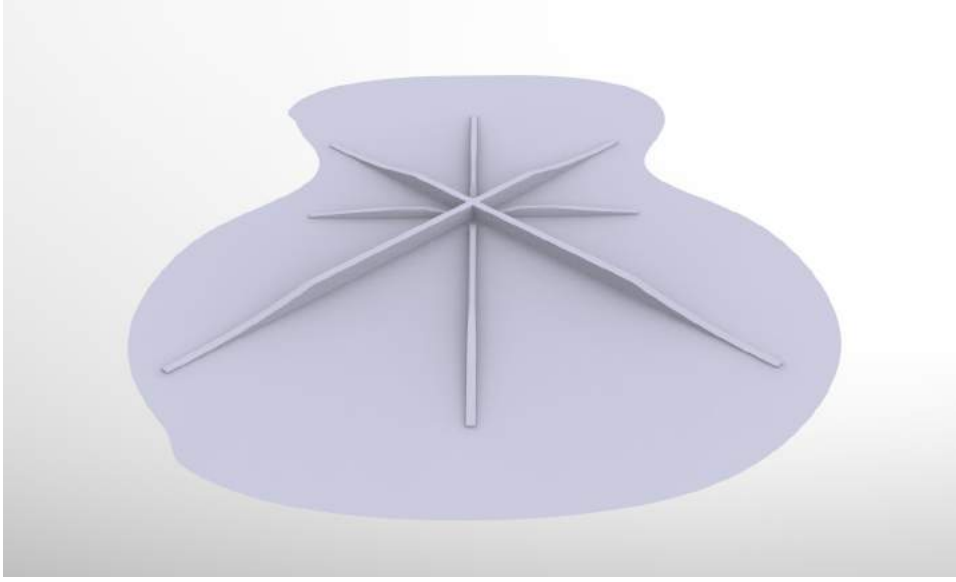


Figure 20.3: Rendering of the inner side of the back showing the radial bracing pattern to mimic the structural properties of the Michael Greenfield Tone Halo bracing.

20.3. Sides

The sides of the guitar create the stiff frame which supports the interaction between the top and back with minimum involvement in terms of damping or sound colouration. In some high quality guitars, the sides are laminated with a less expensive wood to allow for more thickness and thus rigidity on the sides without increasing the price of the instrument significantly. Therefore the material chosen for the sides is a regular carbon fibre epoxy as this material can be produced in the required shape with high quality. It also provides more than enough stiffness for the frame and has low damping. The lay-up will consist of 14 layers of carbon fibre twill weave of 200 g/m^2 provided by Ten Cate Composites. This results in a thickness of the laminate of 2.5-3 mm depending on the quality of the draping work and pressure applied to the uncured laminate. Each of the layers is placed in the 0/90 orientation as small scale tests on flat aluminium plates showed that other orientations might cause deformation once the product is removed from the mould. After production the stiffness as well as the shape of the sides has to be checked. It is however expected that the stiffness is much higher compared to the normal guitar as the thickness is similar or just slightly lower than the thickness of the sides in wooden guitars. As demonstrated in chapter 7 the stiffness of carbon fibres is significantly higher and will therefore likely provide much more rigid sides compared to a wooden guitar. As the shape of the sides is quite complex, moulds are required to be made which will be discussed further in chapter 21.

The sides feature a double flange which allows the soundboard and back to be glued directly to the sides. In regular guitars additional material is needed in the corner between the soundboard and sides or back and sides to create a strong glue bond. The design as presented in Figure 20.4 will provide enough strength and stiffness for this connection as the fibres will run into the flange. The radius of the flange is designed to be 3 mm as a smaller radius could potentially increase the difficulty of draping the fabric into the corner. A larger radius would require the flange to be longer decreasing the effective size of the soundboard that is vibrating. If a larger portion of the soundboard is restricted by the bonding to the larger flange a negative effect on the acoustics of the instrument is expected.

The design of the sides involves both an arm rest as well as a rib rest. By increasing the radius of the sides corner to the flange connecting to the soundboard and back to 15 mm, the sharp edge pressing in the upper right arm and ribcage of the guitar player is dulled significantly increasing the comfort when playing the instrument.

In the upper part of the sides a v-shaped gap is visible which is needed for the dovetail connection to the neck of the instrument. This will be further discussed in section 20.7

20.4. Neck

The neck and headstock of the guitar is created as one piece. For cheaper factory guitars, the headstock and neck often made separately and assembled later while for high-end guitars the neck and headstock are carved from one piece of wood. The downside of this is the orientation of the fibres which is not straight after the 15 degree bend of the headstock. This creates a more flexible headstock to neck connection. For this reason guitar builders take great care in selecting high quality and very stiff woods such as mahogany for their necks to prevent the stiffness drop to become a problem. For composite guitars the fibres can run through the entire neck and headstock causing it not to have any of the issues mentioned above. The neck features a near elliptical profile which is considered a common and comfortable profile. The headstock has a unique design shape and is comparably sized to common headstock designs. At the start of the neck a dovetail connection is featured which will slide in the neck block to prevent the neck from detaching after the strings are tensioned.

The design renderings are shown in Figure 20.5

The outer skin of the neck is a 12 layer thick carbon epoxy while the inner neck is filled with epoxy through which 40% volume fraction of 3M K1 glass bubbles are mixed. This is done to reduce the density of the material and therefore make the neck considerably lighter compared to a full carbon neck. As most wooden guitar necks are constructed with high quality and high density mahogany with a density of around 750 kg/m^3, the

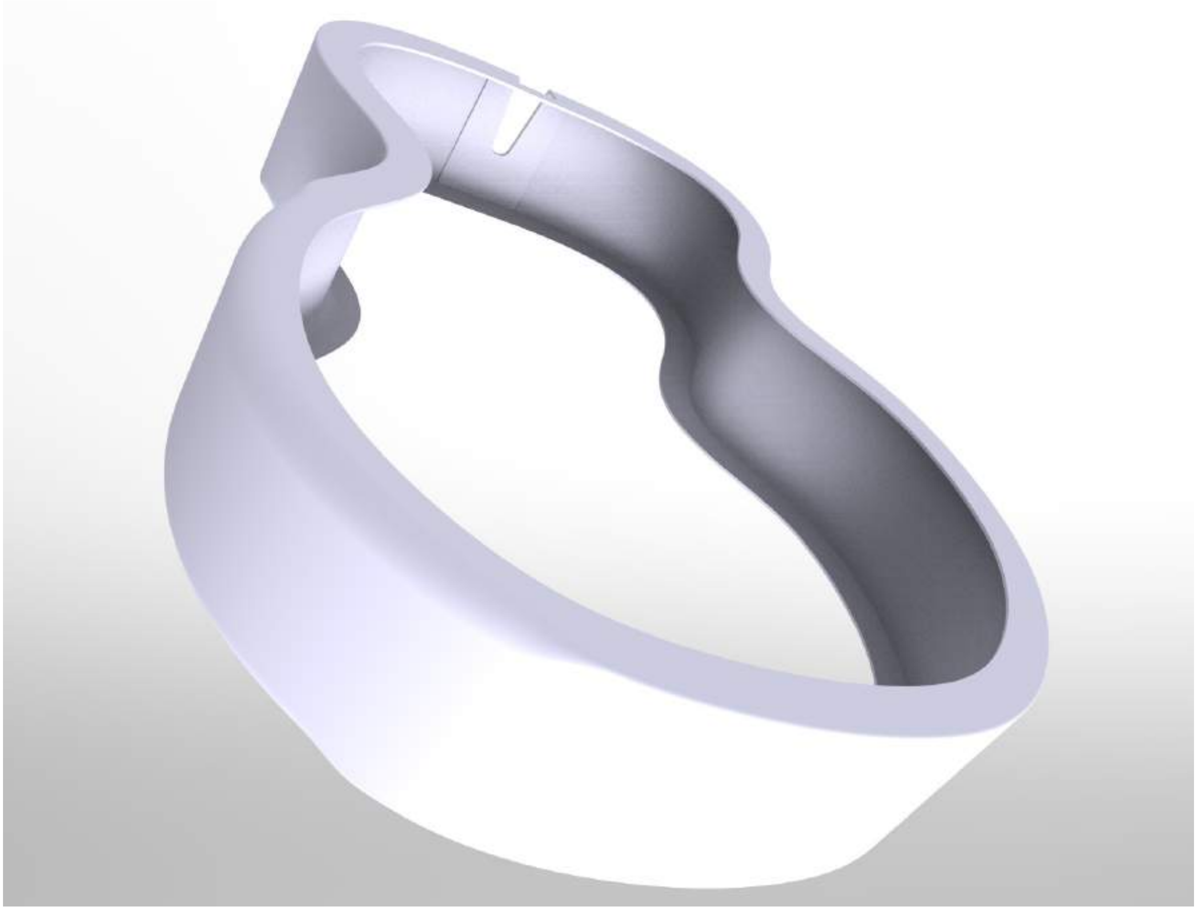


Figure 20.4: Rendering of the sides of the guitar.

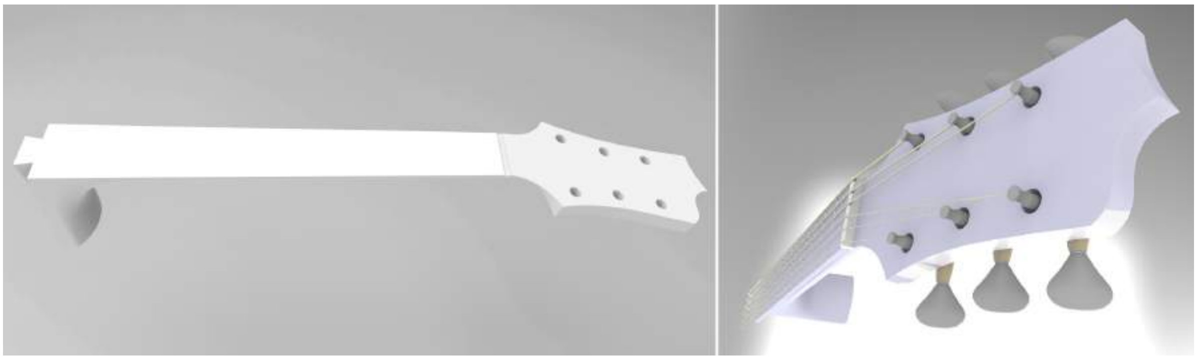


Figure 20.5: Left: rendering of the neck design featuring a unique headstock design, straight heel and dovetail connection. Right: rendering of the neck, fretboard, tuning mechanisms and strings assembled.

glass bubbles in the epoxy allow the density of the complete neck to reduce to around 800-850 kg/m^3. The 12 layer thick carbon epoxy provides more than enough stiffness such that a truss rod becomes obsolete. On the other side, with this specific amount of carbon, the neck should be flexible enough to become slightly curved due to the string tension. This is required for proper playability of the instrument. The estimation for the required quantity of carbon is obtained by taking the stiffness of mahogany and using the stiffness and volume percentage ratios to allow for a 50% stiffer neck. As the stiffness of carbon is roughly 20 times higher than mahogany, only 5% carbon is needed in the longitudinal direction. A 0/90 weave is used thus requiring 10% carbon. To account for absence of a truss rod it was decided to use 15% carbon in the neck which results in 12 layers. The stiffness in transverse direction is considerably higher than for a mahogany neck. This is done to prevent twisting and warping of the neck under the string tension which could affect playability of the instrument significantly.

20.5. Fretboard

The fretboard is designed using the same dimensions as the Greenfield G4 guitar [28]. It features a compound radius fretboard with a radius of 16" (406 mm) at the nut and 20" (508 mm) at the sound hole. The design is shown in Figure 20.6

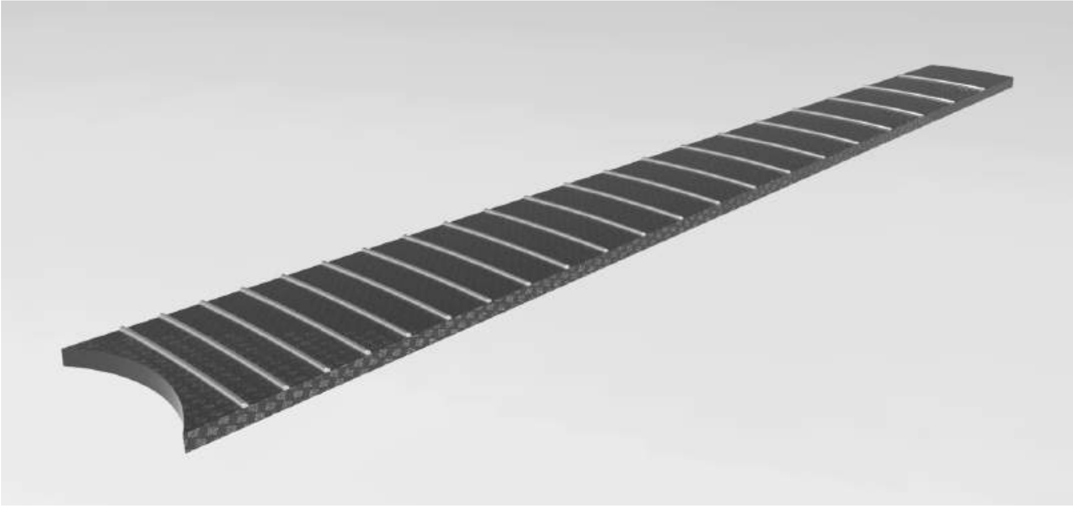


Figure 20.6: Rendering of the fretboard including the frets. The materials are rendered to give a visual representation close to the final product.

The fretboard will be created in a mould and made of several layers of carbon fibre epoxy twill fabric oriented in the 0-90 degrees direction. To obtain the required thickness of the fretboard, additional layers of UD fabric and a mix of 3M K1 glass bubbles with epoxy are placed inside the carbon fibre layers. This results in a reduction of the weight of the fretboard while remaining relatively stiff.

To accommodate for the frets, small slots are to be milled into the fretboard. These slots do not run through the whole width of the fretboard. This ensures that the heel of the fret is not visible from the side which is considered a nice visual feature of high quality guitars. The downside of this is the increase in time spent installing the frets as part of the heel of the fret is to be sanded or ground away. The end of the fretboard runs into the sound hole and does not have an extension over the sound hole as some guitars have as shown in Figure 2.10.

20.6. Bridge

The pinless bridge design for the composite guitar is inspired by the designs of Michael Greenfield [98]. The bridge is styled slightly more aggressive but has similar proportions. This is done to prevent the bridge design to have a significantly different effect on the sound of the guitar. The design is shown in Figure 20.7.

As introduced in subsection 2.2.1, the material normally used for high quality bridges is ebony wood. This black coloured wood has a much higher density compared to for example spruce. Some samples have been found with densities higher than water. Additionally ebony is chosen for the bridge as it has low damping which allows it to effectively transfer the vibration energy from the strings to the soundboard. Considering these specifications, it was decided to create a new composite by using a combination of unidirectional carbon fibre combined with epoxy and 3M K1 hollow glass bubbles. The production iterations to create a suitable

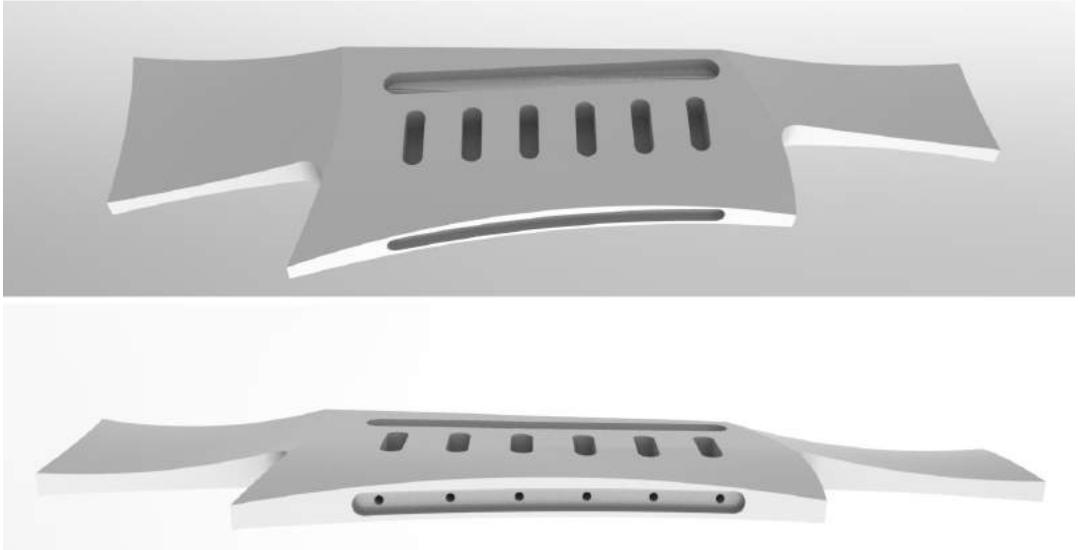


Figure 20.7: Two renderings of the bridge design inspired by the designs of Michael Greenfield.

material will be further elaborated in chapter 22. The desired shape of the bridge would be CNC milled out of bulk material.

20.7. Neck block

The neck block is to be installed in the sides of the guitar to allow for a dovetail shaped cut-out. The neck dovetail extension can therefore slide into the connection and can only move up and down. After the fretboard is installed over both the neck and body of the guitar, this degree of freedom is also removed resulting in a rigid connection between the neck and body of the guitar. The design of the neck block as well as its location in the body is shown in Figure 20.8.

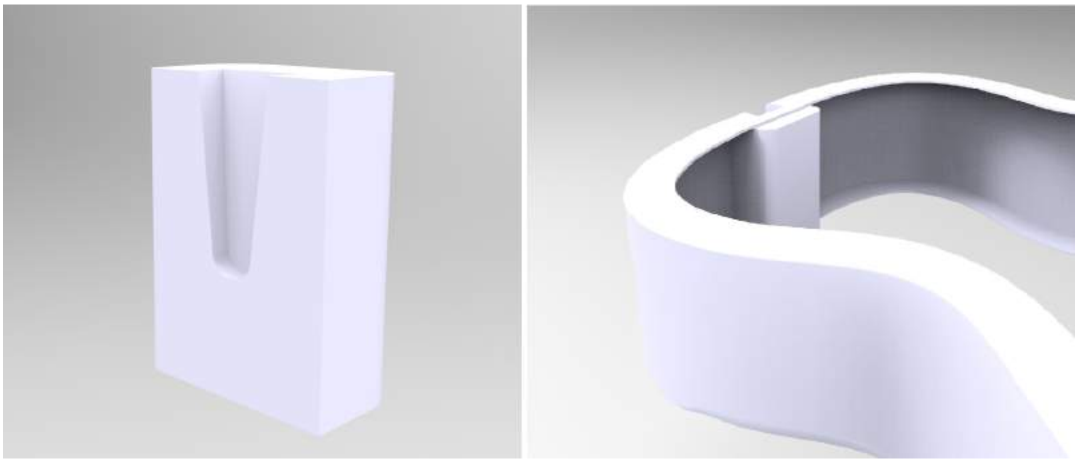


Figure 20.8: Left: rendering of the design of the neck block. Right: rendering of the positioning of the neck block in the sides of the guitar.

The material for the neck block will be similar to the material for the bridge. As this component has almost no effect on the acoustics of the instrument a combination of unidirectional carbon fibre and a mix of 3M K1 glass bubbles with epoxy is considered suitable. The production iterations to create a suitable material will be further elaborated in chapter 22.

20.8. Nut and saddle

The nut and saddle design follows from the approximate dimensions as found on the G4 model guitar by Michael Greenfield. The material used is full carbon fibre epoxy. This is chosen to obtain minimal sound energy loss between the strings and bridge. The designs of the saddle and nut are shown in Figure 20.9 and Figure 20.10 respectively.

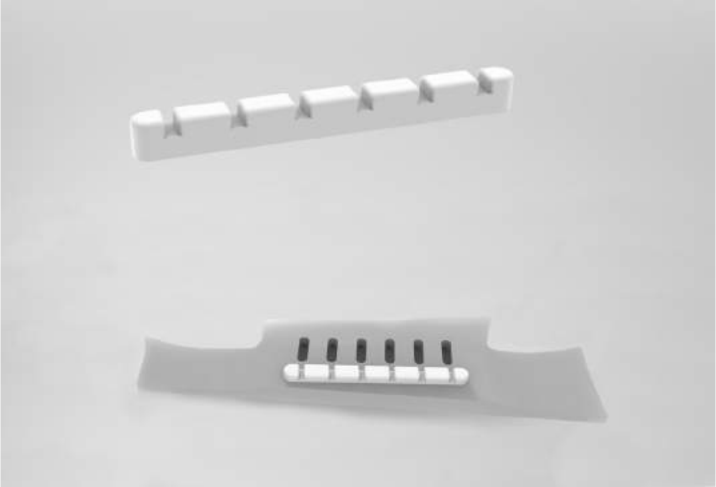


Figure 20.9: Top: rendering of the saddle. Bottom: rendering of the position of the saddle in the bridge.

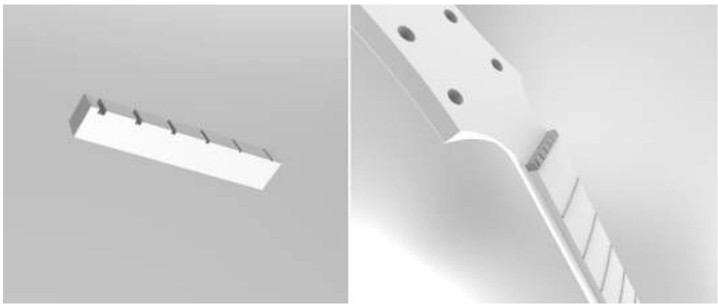


Figure 20.10: Top: rendering of the nut. Bottom: rendering of the nut positioned on the neck.

20.9. Additional components

Two sets of components will not be created using composites but will be bought from suppliers. These are the strings and the tuning mechanisms. The strings that will be used on the guitar are the medium gauge 13-56 Elixir 80/20 bronze Nanoweb strings. These strings are also used on the wooden guitars with which the developed composite guitar will be compared.The selected tuning mechanisms are the Wilkinson 191-BLR tunings mechanisms 3L+3R with a low gearing ratio of 19:1. These tunings mechanisms are black of colour and will therefore match the guitar styling. Alternatively Gotoh 510 tuning mechanisms were considered as these are often used on high quality guitars, however these are much more expensive and do not add additional benefit to the prototype guitar.

21

Mould design and production

Due to the complex shapes of several of the components moulds have to be created in which the parts can be laminated. The parts that require moulds are the fretboard, sides and neck. Each of the mould designs will be discussed below.

The manufacturing of the moulds is done in collaboration with Jules Dock in Rotterdam, the Netherlands. After a number of potential production partners for the moulds were investigated, Jules Dock proved to be the most suitable candidate. The reason for this was the possibility to design and make a trial mould out of a cheaper material for each of the designs. This would make a design error in the first version of the moulds less troublesome as a second version would have an updated design and could be used for the production of the instruments.

The first version of the moulds is CNC milled out of MDF. After a rough shape is milled out of the material the mould is covered with a number of layers of epoxy to impregnate the surface of the mould and make it hard. The harder surface is then CNC milled again with a much more refined programme resulting in nearly the exact shape of the mould design. The programme is set-up such that about 0.3-0.4 mm extra material is removed to allow a Doublecoat laquer coat to be applied. This coat is then sanded and polished until the required shape and surface quality are obtained.

The second version of the moulds is produced from green Sikablock M945 tooling block. This material is a cast polyurethane type resin with a high density of 1300 kg/m^3. Due to its high density it has very low porosity making the moulds suitable for vacuum infusion. The decision to create the moulds from of this material is based on the required stability and accuracy of the mould. Aluminium proved to be much more expensive and time intensive to machine considering the complex shapes of the moulds. Therefore the Sikablock M945 was though to be the best candidate for the second version of the moulds. All surfaces of the moulds were intensively sanded using 240 up to 2000 grid sand paper after which a final buffing step was conducted using a 6000 grit car polish. After the polishing step the surfaces were checked using a water break test as the water will not attach to the smooth surface.

Both the first version and second version of the moulds were treated with a three step release system by Chemtrend. First the moulds are cleaned using Chemlease cleaning agent after which three layers of sealer compound are wiped on the surface with 15 minutes drying time between each successive layer. The sealer closes the last porosities in the mould surface and provides a good layer on which the release agent can be applied. The release agent used is the Chemlease PMR EZ. While on the first version of the moulds only 3 coats were required for proper releasing of the products, initial tests with the Sikablock showed that many more coats had to be applied for good releasing of the products. Each of the mould surfaces is treated with 12 layers of release agent before the production is started. Additionally between every production step or new product when the unfinished or finished product is removed from the mould, the surfaces are treated again with 3 layers of release agent.

21.1. Fretboard mould

As the fretboard has a compound radius a mould is required to allow this curvature to be accurately present in the final product. The main design is shown in Figure 21.1. A flange at an angle of 45 degrees was made above the surface where the product would be in contact with the mould. This flange was made to create a clear line such that the carbon layers could be trimmed. Additionally two pockets on either side were made as a sharp corner was required at the end of the fretboard. Therefore the CNC mill needs room to run along the edge and will therefore have a slight run-out. To accommodate for this the pockets were created larger and made slightly deeper. In this way a thin line is visible in the product which can be used for trimming.

Figure 21.1: Rendering of the first version of the fretboard mould. Isometric view (left) and top view (right)

21.1.1. First version

The first version of the mould produced was of sufficiently high quality. The main downside is that the sharp corner along both sides of the fretboard was slightly dulled after the application of the Doublecoat lacquer. This proved to be a limited problem as the carbon fabric cannot be draped in the sharp edge anyway and will always take at least a radius greater than 1 mm.

A set of pictures of the first version of the fretboard mould is shown in Figure 21.2.

The mould surface quality was close to optimal but is expected to improve for the second version of the moulds.

21.1.2. Second version

As will be discussed in chapter 22 the main method of production of components out of the moulds would be done using vacuum infusion as this provides the best surface quality. Therefore the second version of the respective fretboard moulds were designed slightly different to allow easy installation of tubes. The final mould produced is shown inFigure 21.3.

Figure 21.2: Left: CNC milling of fretboard mould out of MDF. Right: first fretboard mould version after application of Doublecoat lacquer.

Figure 21.3: Second version of the fretboard mould milled from Sikablock M945 tooling block. The infusion inlet is created on the left side. The exit towards the vacuum pump is on the right side.

The mould in its final shape has no vertical edge. This change was made to the mould after releasing of the first product from the mould proved to be more difficult than expected. The vertical edge was removed and both pockets were smoothed using a Dremel multi tool. After this the required sanding steps, polishing and application of the release system was performed. The second test proved that the removal of the edges helped with releasing of the product.

The surface quality obtained from the Sikablock fretboard mould was higher when compared to the first version of the mould created out of MDF. However the shine of the trial samples created using the first version of the moulds was higher. This is due to the better releasing surface of the Doublecoat lacquer compared to the Sikablock.

21.2. Sides mould

The sides mould is designed to be a two components mould. The resulting products are to be connected in a later stage when additional layers of carbon fibre are added to cover the gap between the two products.

Similarly to the fretboard two considerably different versions of moulds are made. These will both be discussed below.

21.2.1. First version

The first version of the mould was designed such that inner part of the mould would be milled from MDF and covered with epoxy and Doublecoat lacquer after which aluminium panels would be mounted against each of the sides of the mould to allow for the creation of the flange required in the sides to mount the soundboard and back. The design rendering of the inner side and a photo of the final mould are provided in Figure 21.4.

Figure 21.4: Upper component of the produced sides mould including the aluminium panels.

The radius in the sides towards the flange proved to be too sharp to be properly milled out of MDF. Therefore the connection with the aluminium was not smooth and a very low quality edge was obtained. Additionally the lack of space for infusion tubes made the mould not very suitable for high quality vacuum infusion production. Therefore it was decided in an early stage to focus on the redesign of the moulds rather than spending time in improving the produced first version of the moulds.

21.2.2. Second version

As the products were quite easily released from the first version of the moulds, it was decided to include the flanges of the product in the mould and remove the need for aluminium panels connected to the side of the moulds. Similarly to the fretboard moulds a flange at an angle of 45 degrees was created to obtain a trimming edge for the flange. The radius was slightly increased to 2.5 mm to allow the use of a long enough CNC mill.

The second major design change was the addition of two channels for the infusion tubes which run in a large curvature with a radius of 50 mm towards the sides of he mould. This prevents the tubes from bending around a sharp corner which would limit the flow and therefore effectiveness and potentially the quality of the infusion. The design and photo of the moulds are shown in Figure 21.5

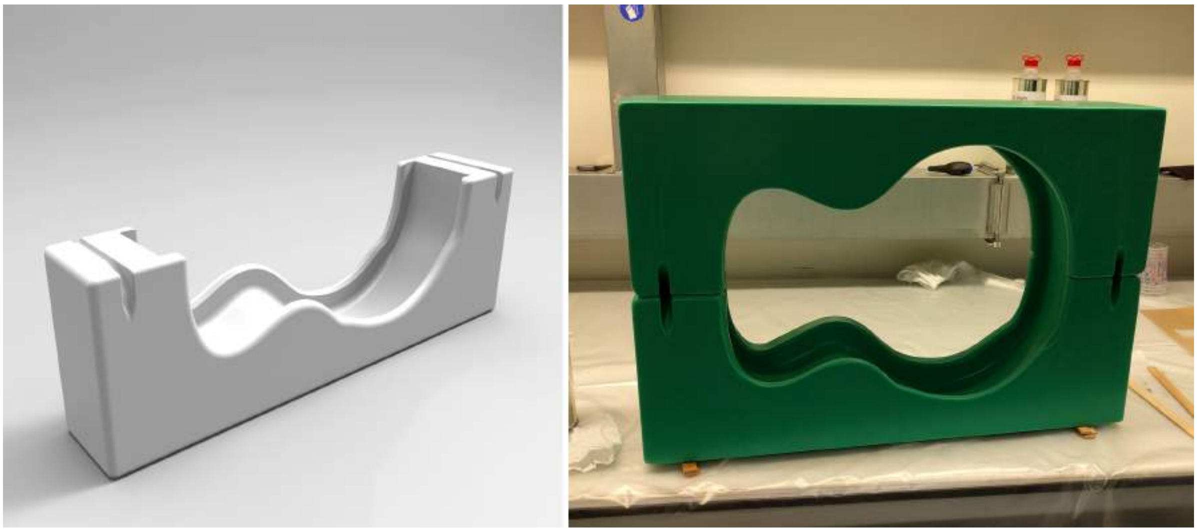


Figure 21.5: Left: design rendering of the one of the components of version 2 of the sides mould. Right: both components of version 2 of the sides mould positioned on top of each other.

CNC milling of the moulds was a time intensive process due to the large quantity of material to be milled away. The first step involved the contour milling of the moulds out of bulk Sikablock M945. This block of material weighs 100 kg and consists of two panels of Sikablock of thickness 100 mm and 50 mm to obtain the required thickness of 150 mm. After the initial shapes were milled out, the three remaining components together weighed 91 kg which means that 9 kg of material was milled away. The contour milling process is shown in Figure 21.6.

Figure 21.6: Contour milling of the sides mould out of bulk Sikablock M945

The second step was the pre-milling of the inner mould surface to obtain the flanges of the sides as shown in Figure 21.7. This again was a time intensive process as several kilogrammes of material had to be milled away.

Figure 21.7: Pre-milling of the sides mould with an elongated CNC mill.

After the pre-milling of the rough shape was completed the moulds were post-milled to obtain a nice surface. The main problem was that the depth of the mould did not allow the mill to reach a part of the edge of the mould even though a mill of 18 cm was used. Therefore during the final stage of the mould production, which was the sanding and polishing, the leftover material in the corners was removed by sanding using a Dremel multi tool.

21.3. Neck mould

The neck mould design was also updated considerably between version 1 and version 2 of the moulds. The original design consisted of 4 parts to be able to easily release the product while the second mould was designed with only 3 separate components. The design specifics will be discussed below.

21.3.1. First version

As the neck design required the addition of a dovetail connection piece, the first version of the mould was designed in four parts as shown in Figure 21.8. This was done as the headstock part was expected to release rather difficultly. Additionally the dovetail piece requires a split mould as it would otherwise be impossible to release the product.

Similarly to the fretboard mould and second version of the sides mould, a flange at an angle of 45 degrees was created to indicate the trim line for the product. The moulds were again made out of MDF coated with epoxy and Doublecoat lacquer. Finally a gap was created between the mould components such that pressure

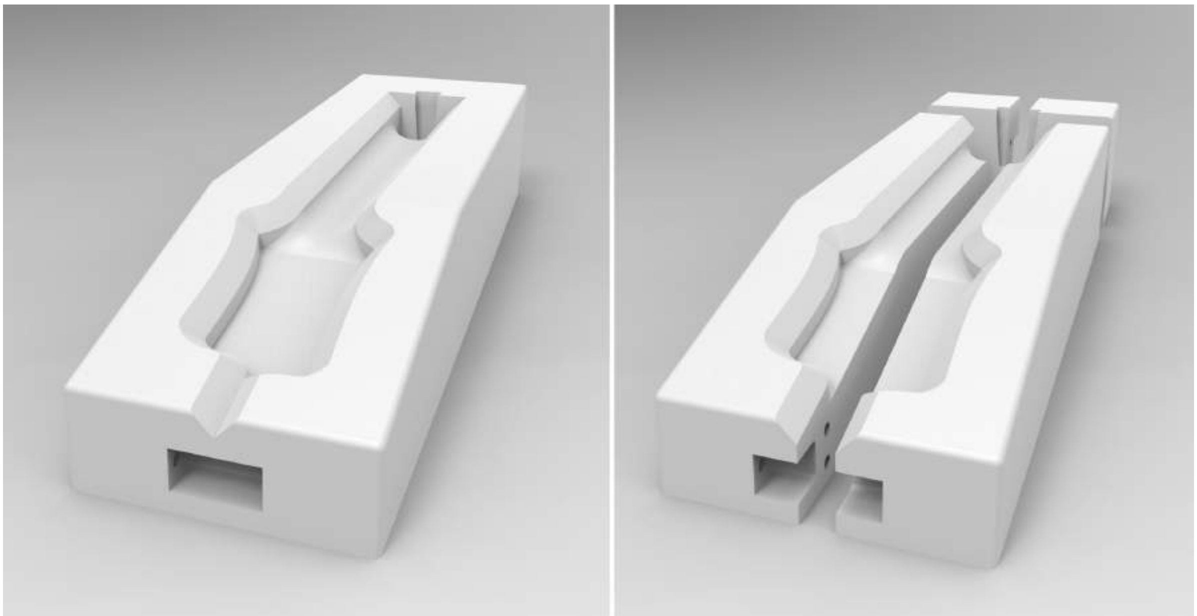


Figure 21.8: Renderings of the neck mould design. Left: neck mould assembly. Right: exploded view of the neck mould components.

could be applied between the moulds to release them from the product. The produced moulds are shown in Figure 21.9.

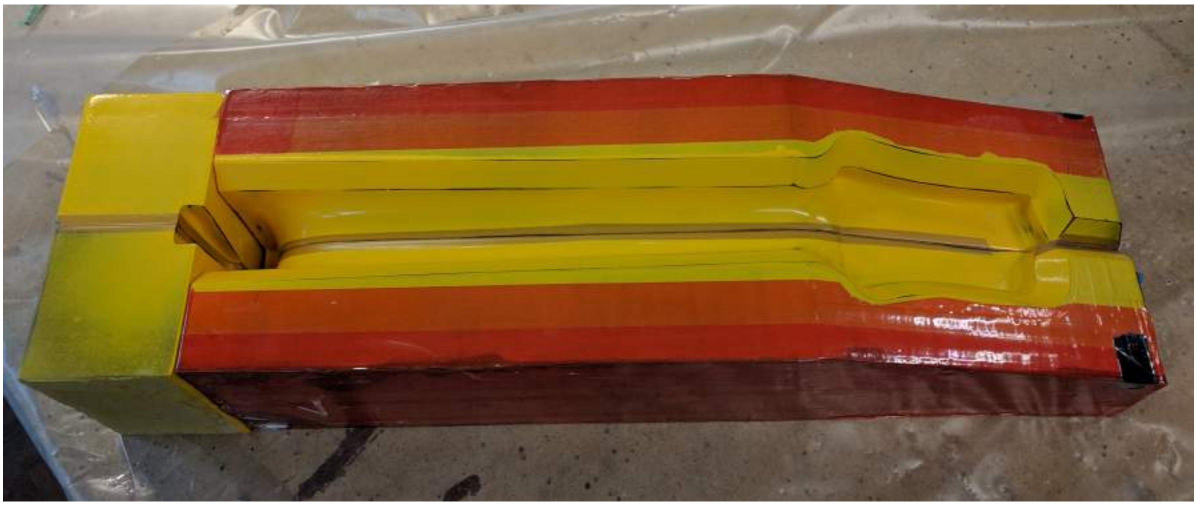


Figure 21.9: Photo of the first version of the neck mould.

The split in the main part of the mould where the neck and headstock is located proved to be unnecessary as the product was released from the mould even before the two mould components were disconnected. Additionally the split resulted in a resin line in the product which has to be sanded away before finishing with a clear coat could be done.

21.3.2. Second version

The second version of the neck mould was made out of three parts considering the easy release of the system noticed in the trial conducted with the first version of the neck mould. Similarly as with the updated fretboard mould and updated sides mould an infusion channel was created on the top side of the mould. During production it was decided that at the bottom side near the heel of the neck an infusion channel was not necessary. The tube could easily be attached in the corner between the mould and vacuum bag on the table. This saves an additional CNC milling step as it would require the mould to be repositioned on the table before the slot could be milled. The design rendering and final mould produced are shown in Figure 21.10.

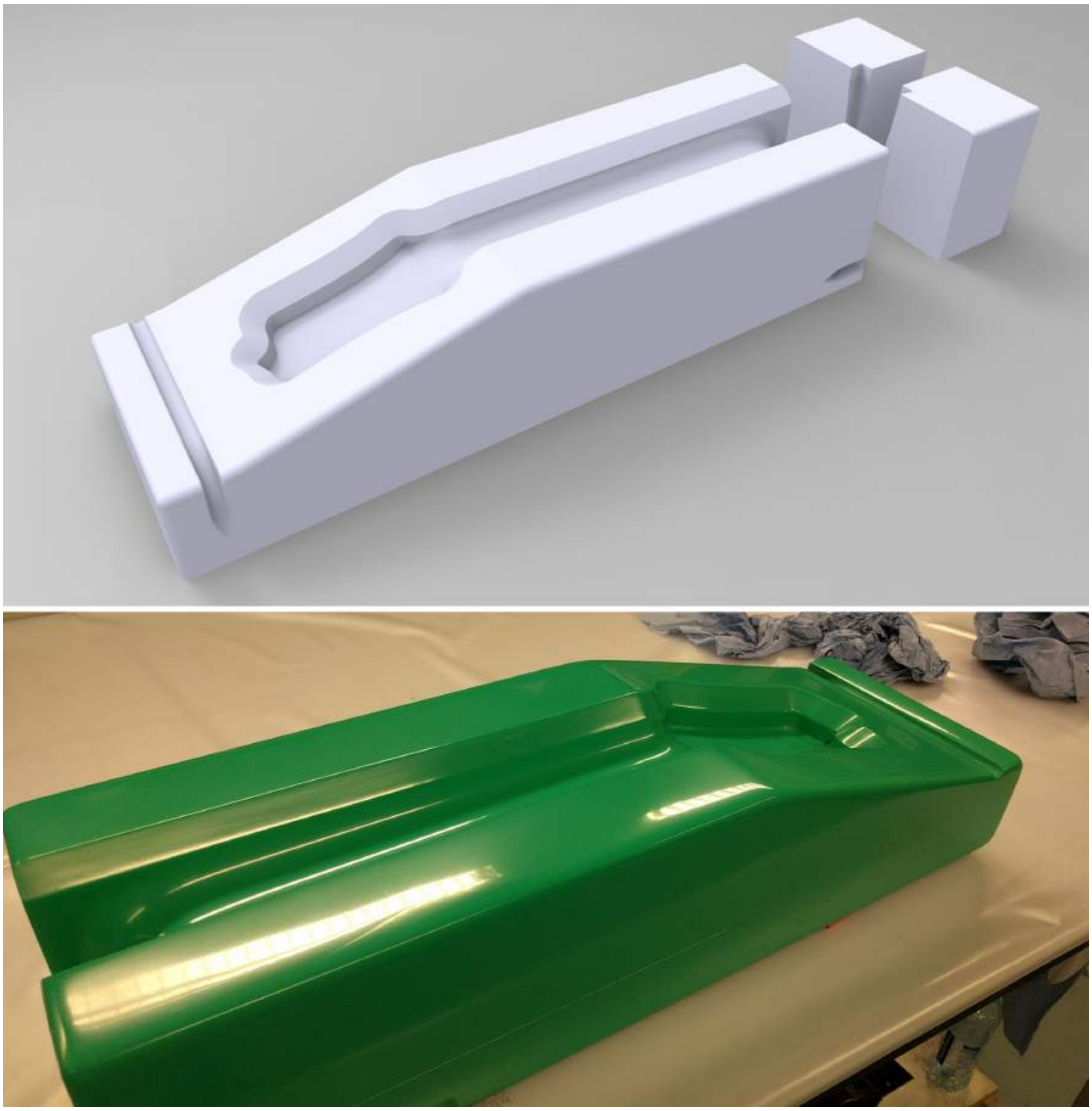


Figure 21.10: Top: design rendering of the second version of the neck mould. Bottom: photo of the produced second version of the main piece of the neck mould.

The pre-milling of the neck mould was done in a slightly different way when compared to the fretboard and sides moulds. As a similar height of 150 mm of the mould was required, two blocks of Sikablock M945 of 100 mm and 50 mm were pre-milled separately and glued afterwards. The pre-milling of the 100 mm block is shown in Figure 21.11 Once the blocks were glued the post-milling step was started. After the post-milling was completed the moulds were sanded similarly to the fretboard and sides moulds and polished afterwards.

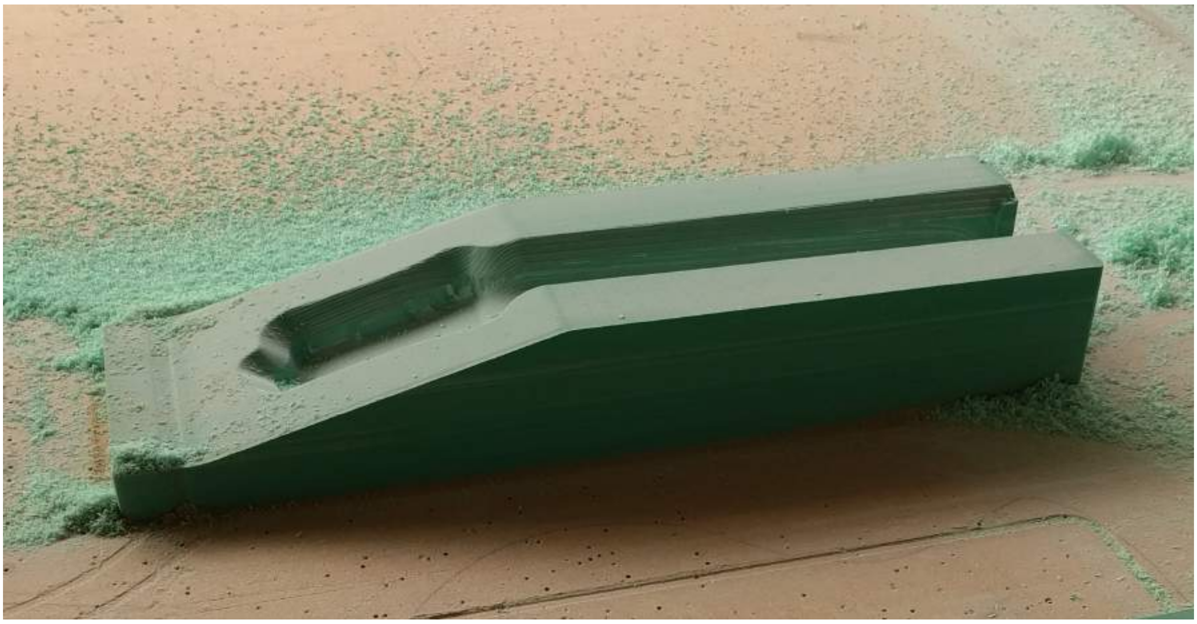


Figure 21.11: Pre-milling of the 100 mm block which would later be glued on top of the 50 mm block.

22

Production of components

In this chapter the production of the separate components of the composite guitar will be described. Additionally some of the design and production challenges will be reviewed as these have had significant influence on the mould design and overall quality of the guitar.

It should be noted that, while the main production steps are described in a linear fashion, most components have seen many production iterations at several stages. The most important information from these iterations will be shortly discussed. As the fretboard mould was used to perform trials in different production methods such as hand lay-up and vacuum infusion, the fretboard production will be described first before going into the sides and neck production.

22.1. Soundboard

The most important component for the acoustics of the soundboard was produced starting with a large panel of the C9 version of the composite. The first step was cutting out the basic shape of the soundboard on the band saw as shown in Figure 22.1. A projected shape of the soundboard was used to cut a template from packaging paper on a Gerber automatic cutting table. The paper template was taped to the panel to make easy sawing of the contour possible.

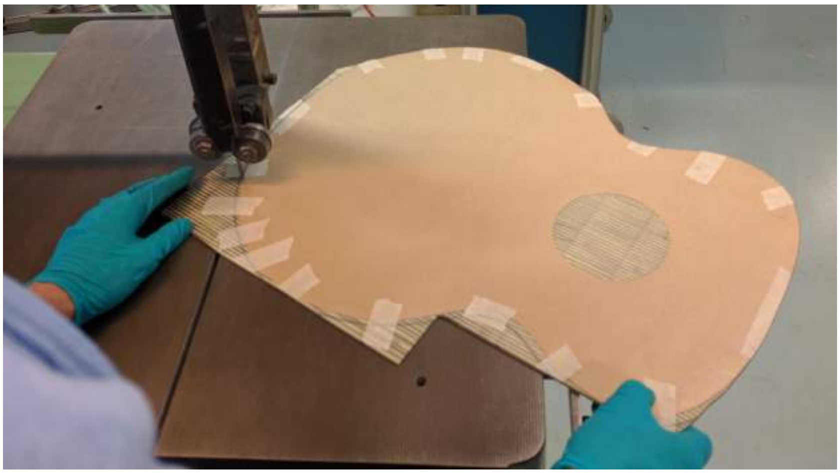


Figure 22.1: Sawing of the soundboard shape on the band saw.

With the main contour sawn out of the panel, the remainder of the material was sawn in long strips of approximately 25 mm wide for the construction of the braces. Similarly as with the shape of the soundboard, a piece of paper was cut using the automatic Gerber cutter to a template to identify the positions of the braces. This paper template was also placed on top of the sawn soundboard after which the brace positions, which were cut and removed from the paper, could easily be marked.

To obtain a slight radius and pre-tension for the soundboard a radius table was constructed. This was done by applying a under pressure of 50-100 millibars on a thin aluminium plate under which several elevations were positioned. The pressure pulls the plate against the plate underneath but is restricted at the edges causing it to become curved slightly. The elevations were positioned such that the spacing between the flat soundboard and curved panel at the center of the soundboard was about 3-4 mm. The radius table and the soundboard with the weights applied is shown in Figure 22.2.

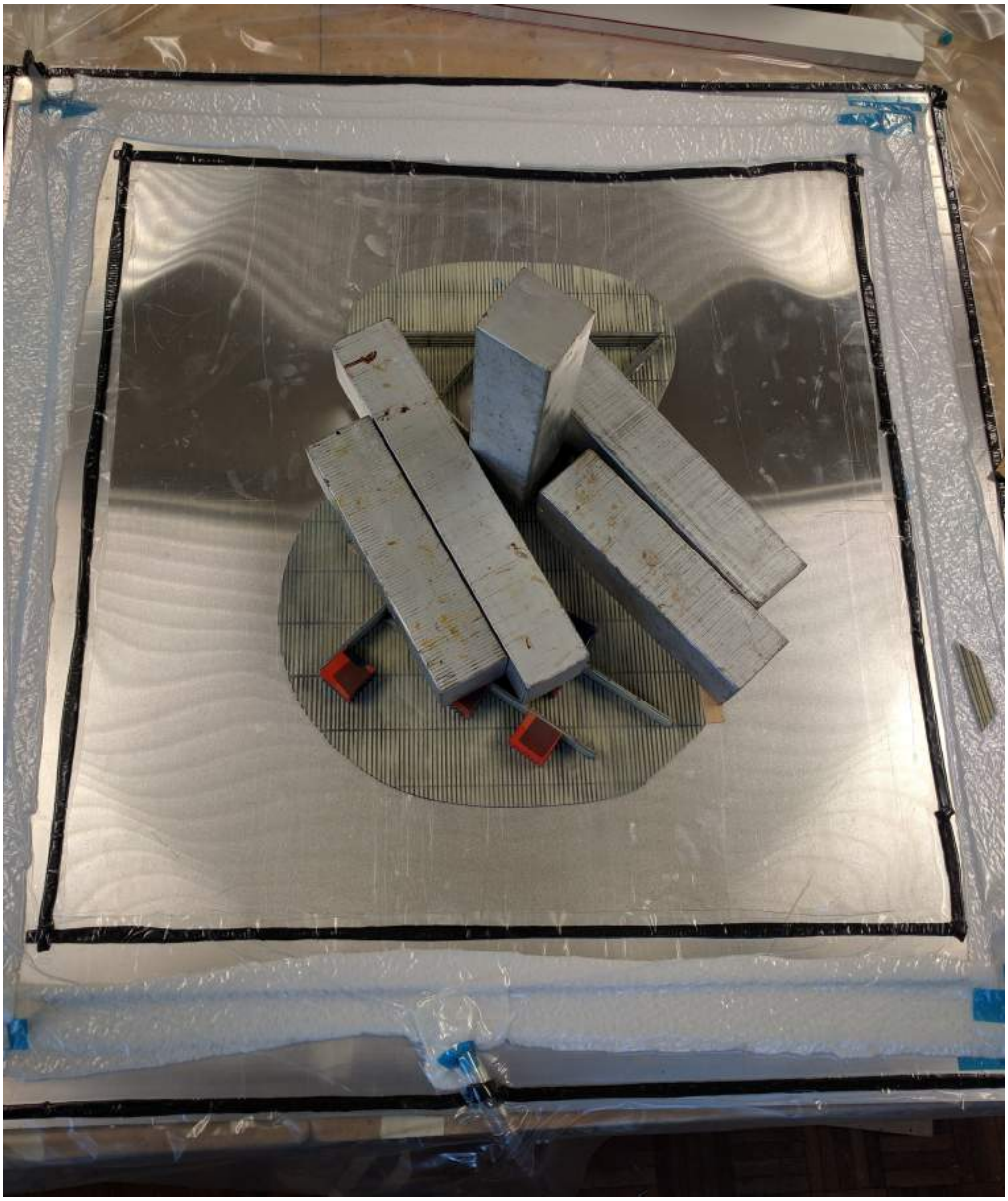


Figure 22.2: Soundboard and braces pressed into the constructed radius table using steel weights.

The braces were sawn into the correct dimensions and glued with Henkel Loctite EA 3430 fast curing two component epoxy. The braces were applied in several phases starting with the main X-brace after which the secondary braces were applied. Pressure was applied using large steel weights of 10 and 15 kg. These weights were not removed when the next set of braces were applied to prevent the curvature of the panel to spring back before all braces were positioned and fixed correctly.

With all braces attached, the soundboard proved to be extremely stiff. Tapping the soundboard yielded a very low sound output and limited amplification. Therefore the height of several braces was reduced in a number of positions and the ends of the braces were shaped to reduce their height towards the start and end of the brace. In between the removal of material the soundboard was checked acoustically by tapping it multiple times. The sound output increased dramatically as the braces were thinned in the lower bout. The final shape of the braces is shown in Figure 22.3.

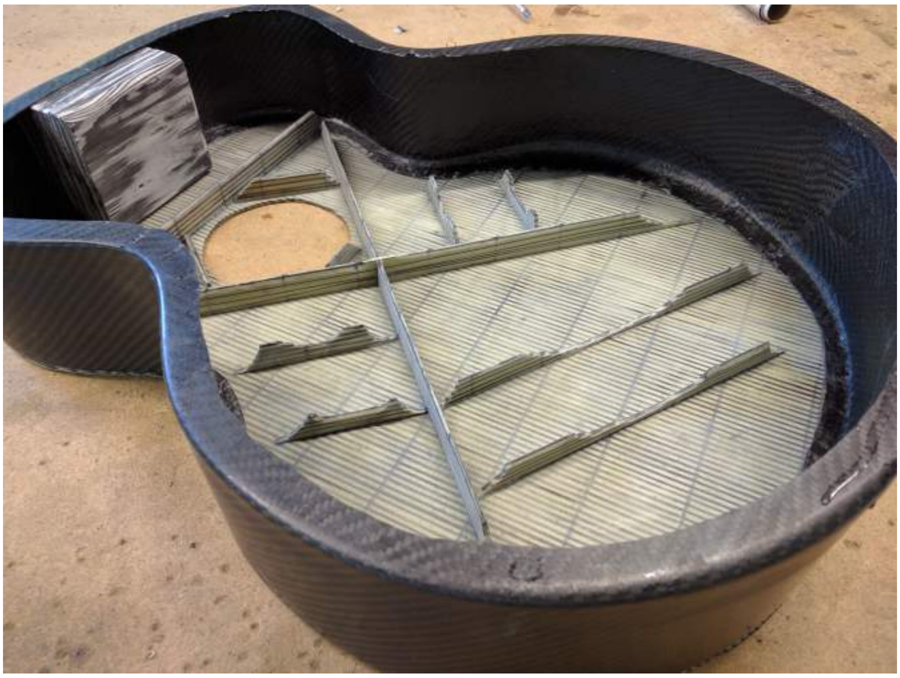


Figure 22.3: Final shape of the braces after material was removed in several iterations to improve acoustic response.

22.2. Back

The back is produced like the soundboard. The main difference is that the C9 composite material was slightly modified to have only 20% of added flexibilizer instead of the 40% for the soundboard. This reduces the damping dramatically giving the back of the guitar a strong ring.

The bracing pattern, although completely different, is applied using the same method as was done for the soundboard using the paper template, radius table and weights. The final result of the back and soundboard, which was at this stage already attached to the sides, is shown in Figure 22.4.

22.3. Fretboard

As the fretboard is the smallest product to be created using the moulds as described in chapter 21, it was decided to use the mould for the main trials before starting with the more complex shaped moulds of the sides and neck. The original plan for the production of the components was to use wet lay-up of fabric. After the mould has been readied a layer of epoxy is applied into the mould using a brush after which layers of carbon fabric are placed in the mould and wetted with epoxy. The wet lay-up method did not prove to be a viable method even when using only two layers of fabric. This is due to the following three reasons.

Figure 22.4: Left: Back with braces attached and finalized to desired shape. Right: Soundboard assembled to the sides.

- The fabric does not stay in the sharp corners of the fretboard as the carbon fibres are too stiff and the resin is not sticky enough. Even when applying full vacuum the corners are not full wetted.
- Pressing the wetted fabric into the corners as good as possible distorts the fabric pattern by which the visual qualities of the carbon are lost. Due to the wetting with epoxy, the fibres can more freely move relative to each other. Additionally the wetted bundles tend to stick together after minimal distortion resulting in gaps in the weave when only two layers of fabric are applied. The application of the additional layers closes these gaps however the visual defects are not reduced.
- Applying full vacuum resulted in dry spots on the surface. This is expected to be caused by the release agent as full wetting of the surface with only epoxy proved to be impossible without applying over 4-5 mm of resin. Therefore it is likely that resin would rather flow away from the surface than to stay against it causing the dry spots at fibre bundle crossings.

Due to the limitations of wet lay-up it was decided to perform a vacuum infusion. In total 4 different lay-ups of infusion materials were used. The most successful appeared to be a double layer of carbon fabric on which a layer of peel ply, perforated foil and flow mesh is applied.

As the infusion proved to be a viable method for the production of the first layers of the fretboard, the second version of the moulds were all updated to include infusion channels to allow for easy installation of the tubes. With a proper surface quality guaranteed by the infusion process 10 additional layers of fabric were applied using hand lay-up to obtain enough thickness to mill in the fret channels in which the frets are secured. After the secondary layers of fabric were cured under vacuum three layers of wetted unidirectional carbon fabric were placed in the mould alternating with a mix of epoxy and 3M K1 hollow glass bubbles. In this way the density of the product was reduced while the carbon provides some additional stiffness in the longitudinal direction.

The edges of the product are trimmed with a Dremel hand tool after which the fretboard was placed against a belt sanding machine until the desired thickness of the fretboard was obtained. In order to have a full flat surface on the bottom side for connection to the neck the fretboard was taped with double sided tape to a 10 cm thick block of aluminium.

With the fretboard sanded to its final dimensions a surface finish was applied. First the surface was sanded with 600 grit sand paper in order to remove any release agent that had been stuck to the surface of the fretboard. The full surface was tested using a water break test. Before sanding the water flows off the surface immediately leaving it completely dry while the surface stays completely wetted after sanding. This indicates that proper bonding of the top coat to the surface is possible. A trial was performed using the infusion epoxy however this epoxy proved to be of too low viscosity and tackiness to create a thin coat. Therefore Sicomin 1544 top clear was tried which provides a very shiny top coat and additionally has additives to provide the surface with UV protection to prevent fast de-colouration of the surface. The downside of this top coat is that it leaves a very uneven surface although it is very shiny. The margin of error for the fretboard is very small as a slightly elevated fret can yield the instrument unplayable due to fret buzz. Therefore the topcoat was sanded flat using 600 to 2000 grit sand paper after which polishing was done using 6000 grit equivalent polishing agent applied on a polishing brush.

The polished fretboard is then brought to the CNC mill where the fret slots are milled using a small CNC mill with a diameter of 0.5 mm. As the carbon is less flexible as wood, it was unknown how wide the fret slots were to be such that the frets would get in and stay in the fretboard. Therefore several slots of different dimensions were made in a trial fretboard after which it was found that a width of 0.7 mm was most suitable. This is 0.05 mm wider than is normally advised for a wooden fretboard [130].

Each of the frets was cut to the right dimension after which a Dremel hand tool was used to remove a part of the underside on the edges to have no fret wire sticking out on the sides. Additionally the ends of the fret are sanded to an angle as is a common visual feature in wooden guitars. The final preparation step involved taking away the sharp edges of the fret using 800 grit sand paper. The finished frets are glued into the fretboard and clamps are used to press it in the right position. The final fretboard is shown in Figure 22.5.

Figure 22.5: The finished fretboard after insertion of the frets.

22.4. Sides

The sides were produced using the two part Sikablock mould as described in section 21.2. Using the CAD files of the mould an unfold was created from the inner surface to obtain the required template for cutting out the first two layers of carbon fibre fabric which were to be vacuum infused. The Gerber automatic cutting table was used to cut out the fabric. After the first cut had been made a layer of paper tape was applied over the cut line and an additional cut was made such that the edges of the fabric were covered by a small piece of tape. In this way the fabric could be handled much easier without damaging the pattern and pull-out of fibres. Additionally several small cuts were made in the sides of the fabric to allow the fabric to be draped around the corner towards the flange. As the double curvature in the mould is quite sharp, it was not possible to drape the fibres without the cuts. The main pattern of the fabric is shown in Figure 22.6

Two layers of carbon fibre weave were draped into the moulds and carefully secured in position with small pieces of tape on the flanges of the moulds as shown in Figure 22.7. The paper tape used for easily handling was not removed as it can be infused together with the fabric. Although for structural applications this is not suitable, the sides are highly over designed and therefore the weak spots caused by the inclusion of the

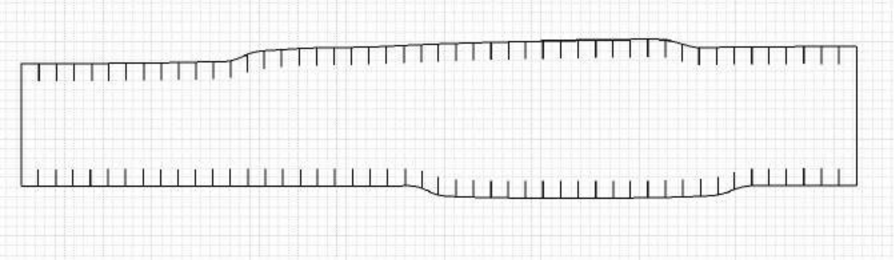


Figure 22.6: Template used for the automatic cutting of fabric for the first two layers of the sides.

tape are less important than the proper draping of the fabric in the mould and the visual qualities of the final product. On top of the fabric a double layer of peel ply is positioned to form a rough surface on which the additional layers can be bonded. On top of the peel ply a perforated foil is applied and finally the flow mesh, which covers about 60-70% of the width of the mould, is positioned. The perforated foil ensures that the peel ply and flow mesh do not bond. Bonding of these layers makes them very thick, stiff and hard to release and results in the need for the application of high forces when unpacking the product. These high forces potentially damage the product and are therefore highly unwanted. On both sides of the mould a tube with a piece of infusion spiral is positioned in the infusion slot and secured using tape.

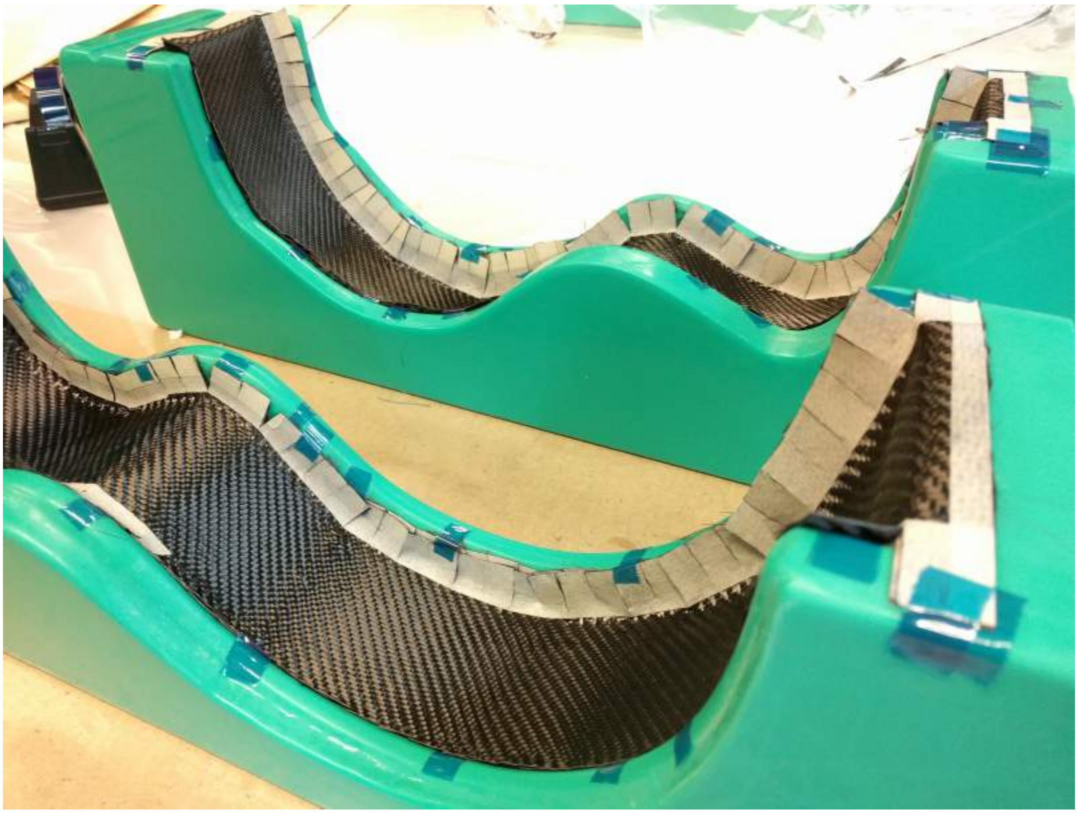


Figure 22.7: Lay-up of layers before the vacuum bag is applied around the mould.

A vacuum bag is created around each of the sides moulds. To improve the surface quality of the product several trials were conducted. An important find was that excess tension in either the carbon fibre fabric or vacuum bag could potentially result in small dry spots or places where fibres did not make contact with the moulds surface resulting in large resin rich areas. To improve the product quality two important actions were taken. First the vacuum bag was made a lot bigger than necessary to allow for enough material around and inside the mould. Second, the vacuum was applied in several steps making sure that after each pressure increase the fabric did not build up any tension in the corners towards to flange. Additionally it was found that a reduction in points where the carbon fibre fabric was attached to the mould with tape would allow for easier draping of the fabric during the pressure increments.

With the vacuum applied and checks performed to identify any leakage the two component infusion epoxy resin is mixed and degassed. The resin pot is positioned and the vacuum tube inserted. After opening of the valve the resins starts to flow through the tube and flow mesh. Due to the complex shape the resin flow was relatively slow. Using a heat gun, set to a temperature of 150 degrees Celsius to prevent the vacuum bag from getting damaged, the resin is heated slightly in some areas to reduce the viscosity and improve the overall flow of the resin through the carbon fibre. The full infusion takes approximately 15 minutes for one of the pieces of the sides mould.

After 24 hours the sides are carefully released from the moulds. The next step is the attachment of the two sides to each other using a small patch of wet carbon fibre as shown in Figure 22.8. This is done by carefully positioning the the two pieces to ensure that they fit together and form a smooth curve.

Figure 22.8: Application of a small patch of wetted carbon fibre fabric to bond the two side pieces.

After the patches are cured the position of the pieces of the sides relative to each other is checked before another 12 layers of carbon are applied using hand lay-up. The process of wetting the carbon fibre is done by positioning the carbon fabric between a layer of plastic foil such as vacuum bagging foil, pouring the degassed epoxy resin on top and finally distributing and pressing out the excess resin over the fabric. The resin distribution and pressing out is done until complete wetting of the fabric is obtained and all excess resin is removed while ensuring that no air bubbles are introduced. This is realised by building a dam of resin around the fabric such that air cannot flow back into the carbon fibre fabric. The wetted fabric pieces are cut out of the larger vacuum foil and one side of the vacuum foil is removed to expose the wet and sticky surface. This surface is ideal to drape and carefully secure the fabric in the correct position in the mould after which the second piece of vacuum foil can be removed. This second piece of vacuum foil prevents major distortions of the fabric during the draping process.

The main benefit of this wetting method is that exactly enough resin is present in the product and fabric pieces are sticky enough to stick into difficult corners and are not falling down when applied against the upper side of the mould. After all additional layers are applied a layer of perforated foil is used to cover all the carbon fabric after which breather fabric is applied all around the mould to be able to transport the air out. A very large vacuum bag is constructed around the complete mould as shown in Figure 22.9 and full vacuum is applied to the product. After 24 hours the product is ready to be de-moulded and trimmed using a hand tool as shown in Figure 22.10.

Figure 22.9: Construction of a large vacuum bag around the product. Left: the vacuum bag before vacuum is applied. Right: the vacuum bag after application of vacuum

Figure 22.10: Left: de-moulding of the sides. Right: the sides after trimming with a dremel hand tool.

After cleaning and trimming the sides are ready for the assembly of the body with the neck block, soundboard and back.

22.5. Neck

The production process of the neck is largely the same as the process used for the sides production. Again an infusion is conducted using only two layers of carbon fibre fabric in the 0-90 direction to allow for easy draping and to obtain a high surface quality. Due to the very complex shape it was not possible to obtain a undistorted lay-up in the mould. To make sure that the carbon touches the complete mould surface the fabric templates were designed iteratively to obtain a pattern that allows for enough draping such that distortion was kept to a minimum without using more than two separate pieces. The pattern used is shown in Figure 22.11. The fabric was cut with the Gerber automatic fabric cutter and the separate pieces were loosely secured in the mould using tape. The bell shape was used for the heel of the neck and additional cuts were made in the fabric to help the draping process.

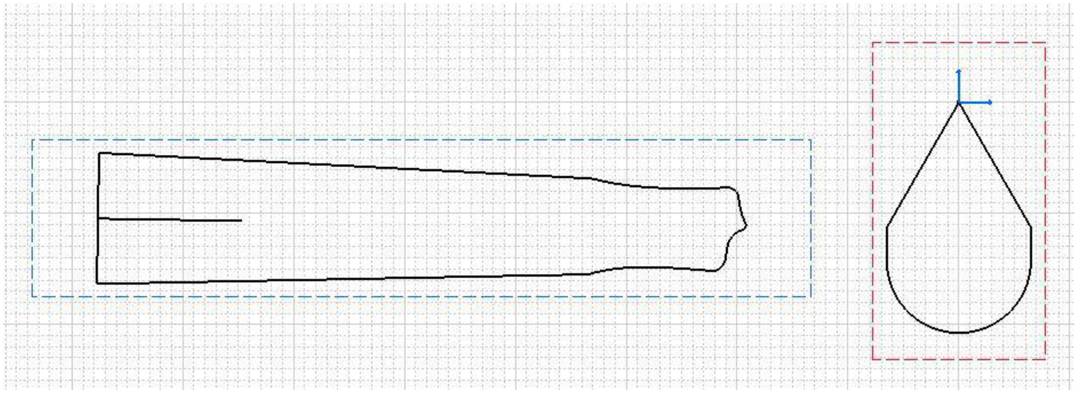


Figure 22.11: Pattern used for the lay-up of carbon fibre fabric in the neck mould to limit distortion during draping.

The same lay-up of infusion materials as for the sides was used for the neck infusion. The two mould pieces required for the dovetail extension were not used at this stage. After application of the fabric peel ply, perforated foil and flow mesh were added and secured in position using tape as shown in Figure 22.12

After de-moulding and checking of the two layer carbon fibre neck the product was placed back into the mould and the other two components of the mould with the dovetail cut-out were attached. 10 additional layers of carbon fibre fabric were added in the 0-90 direction using the same method as used for the sides and are also draped into the dovetail cut-out. As described before in chapter 20 no layers were applied in the 45 degree direction as this might cause twisting of the neck after de-moulding which is to be avoided.

A vacuum bag was applied after the hand lay-up was completed and perforated foil and breather fabric were applied. The carbon neck with 12 layers was released from the mould and checked again. Before putting it back into the mould for the final steps the edges were trimmed off to prevent too much material to be removed after the mould was filled. This filling step was done using a mix of the infusion epoxy and 40% 3M K1 hollow glass bubbles. As the headstock is angled at 15 degrees, the filling of the neck had to be done in two steps. The filling of the main neck is shown in Figure 22.13.

With the neck filled, the next step is to sand off the excess filling and flatten the neck to enable the attachment of the fretboard. Finally the position of the nut is marked after which the headstock is covered with a thin carbon fibre composite to improve the visual appearance of the headstock. This thin composite was manufactured using two layers of carbon fibre fabric infused with epoxy resin containing 30% flexibilizer. As the part has to be shaped on the headstock and partially on the neck, the flexibilizer allowed the composite to easily cover the shape.

Figure 22.12: Lay-up of infusion materials before the vacuum bag is closed and vacuum is applied.

22.6. Neck block

Before the final version of the neck block could be produced a composite with high quantities of carbon and 3M K1 hollow glass bubbles mixed with epoxy had to be developed. This was done using several iterations which will be described below and are shown in Figure 22.14. The moulds used are created by making a MDF box and covering the bottom and side surfaces with aluminium and closing the gaps with Teflon tape. The boundaries of the moulds were attached using double sided tape to limit potential resin flow into the MDF in case a leakage in the mould would be present. The inner surface of the moulds is cleaned and wiped with Chemlease release agent.

1. The first version of the composite was made using short fibres cut from unidirectional carbon fabric which were mixed with epoxy and glass bubbles. The viscosity of the mix increased dramatically resulting in a limit on the addition of carbon of only a few percent which was considered as being too low. Therefore a different solution had to be found.
2. The second version involved the build up of several layers of epoxy mixed with 3M K1 hollow glass bubbles and carbon fibre UD fabric. This allowed for more addition of carbon fibre without running into the problem of increased viscosity. The layers are between 0.9 and 1.2 mm thick which means that at least 32 layers are required to build up the neck block to a height of 35 mm. The second version of the composite was severely damaged due to the exothermic reaction of the Epoxy and the lack of cooling inside the mould. This resulted in large air bubbles inside the product.
3. The main focus of the third version of the neck block material was to reduce the exothermic reaction. This was accomplished by making the bottom part of the mould larger and using 3 mm thick aluminium instead of 0.8 mm thick aluminium to increase the heat capacity and to enable faster heat transfer away from the product. The better cooling makes it possible for each of the layers to be treated shortly with a heat gun to take out the largest bubbles before applying the next layer. The obtained

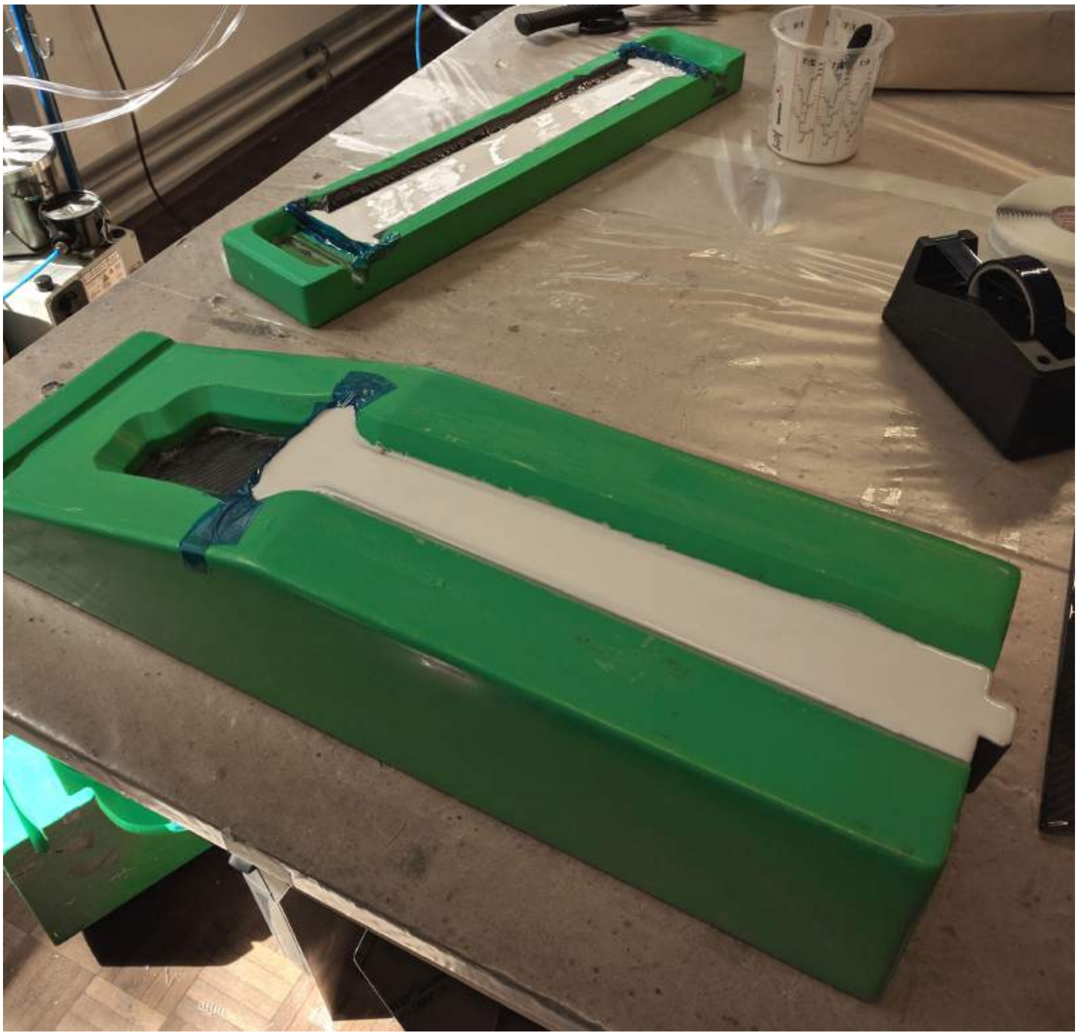


Figure 22.13: Filling of the neck with a mix of epoxy and 3M K1 holow glass bubbles. In the background the filling of the fretboard mould as described in section 22.3 is visible.

composite proved to be of high quality with almost no air bubbles and a relatively even distribution of layers. Additionally the density was found to be slightly lower than the density of water at 955 kg/m^3 which was near the target density of 950 kg/m^3 with the relative contents of epoxy, carbon fibre and 3M K1 hollow glass bubbles. The neck block was sawn through the center on a belt saw to assess the quality of the inside of the neck block. The air bubble content was found to be very low and therefore the neck block iterations was found to be of sufficient quality.

The final neck block was produced using the method described in the third iteration above. During the curing of the composite the temperature of the mould was monitored at several points in time to ensure the heat was transported away from the product effectively. In Figure 22.15 a photo of the neck block is presented.

22.7. Bridge

The bridge is constructed from the same material as the neckblock. A large blank of the material was created out of which 5 bridges could be CNC milled. The process of CNC milling consisted of four main steps which will be described below.

Figure 22.14: From left to right: neck block iterations 1 through 3

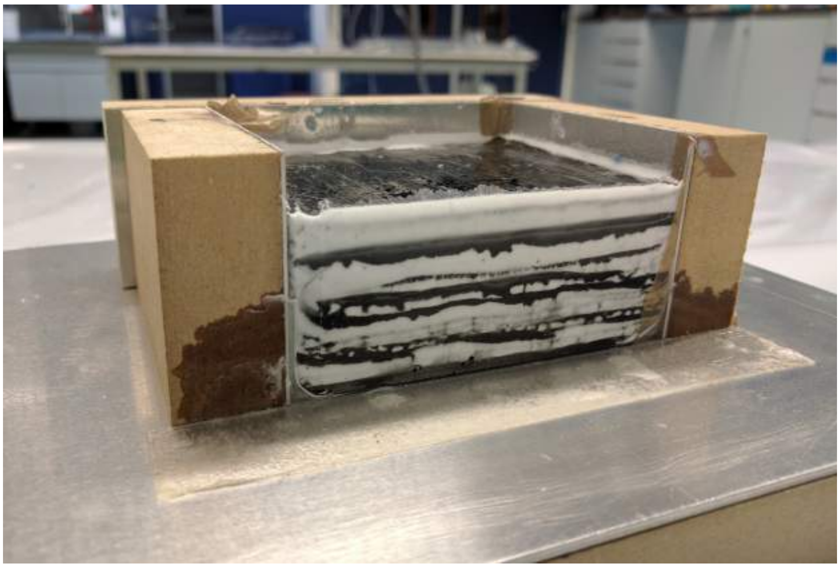


Figure 22.15: Final neck block as used in the production of the composite guitar

The first step involved the flattening of the blank with a large CNC mill with radius 8 *mm* to reduce the height of the blank to approximately 1 *mm* higher than the bridge products are to be made. Doing this as a first step saves time as the more complex shape with a finer CNC mill would otherwise take considerably more time.

The second step was the milling of the outer shapes of the bridges out of the blank. The contour was milled up to 1 *mm* above the bottom surface. In this way the bridge would stay in the blank in a stable position as the glue might not be strong enough to withstand the milling forces of the third step. The contour milling step is shown in Figure 22.16.

Figure 22.16: Milling of the contour of the bridges up to 1 mm above the bottom surface of the blank.

The third step created the general shape of the bridge by milling with a more refined programme and smaller CNC mill. This was done in two directions using two separate programmes to create a smooth surface. The slots and holes for the strings on top of the bridges were created and finally the contour of the bridges was further milled to be able to release the bridges from the blank.

The fourth and final step was the milling of the slot on the bottom of the bridge and the small holes which end up in the small slots on the top of the bridge. The bridges were constrained at their sides one by one after which the slot was milled using a mill with a radius of 2 mm after which the holes were drilled using a mill of 0.8 mm. The constrained bridge during the milling of the small holes as well as the final bridges are shown in Figure 22.17

Figure 22.17: Left: bridge constrained at its side for the milling of small holes on the back side of the bridge. Right: completed bridge.

22.8. Nut and saddle

As discussed in chapter 20 the nut and saddle are produced from carbon fibre epoxy. The blank was created using wet lay-up of 42 layers of carbon fibre 0/90 fabric in a mould similar to the mould used for the neck blocks. The fabric was wetted using the same method as was done for the additional 12 layers of fabric in the sides using vacuum foil to pre-impregnate the fabric. The complete mould was placed in a vacuum bag to create a compact composite and to transport away any excess resin.

The blank was sawn into small pieces which were shaped to the right dimensions using the belt sanding machine. in Figure 22.18 the sawing of the blank as well as one of the saddles in the bridge are shown. The slots for the strings in both the saddle and nut were milled using a manual milling machine to identify the string positions accurately. In a later stage, which will be described in chapter 24, the slots will be shaped to the right dimensions to optimize the intonation of the guitar.

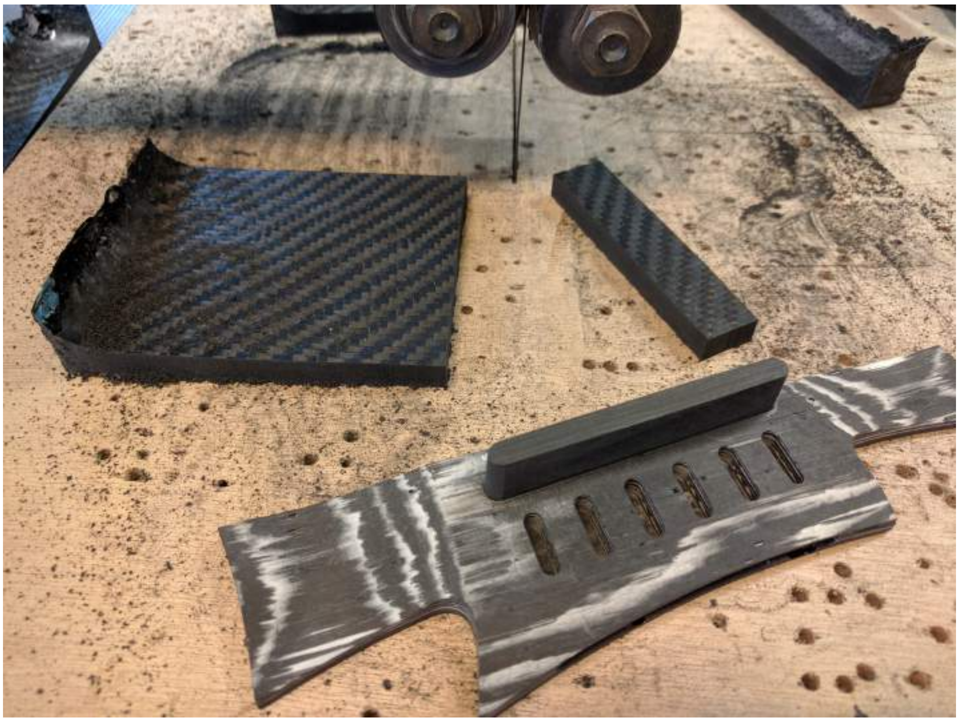


Figure 22.18: Sawing of the carbon fibre epoxy blank to obtain nut and saddle pieces.

23

Assembly of guitar components

After the production of the components the next phase is the assembly. This chapter will focus on the decisions with respect to the connection mechanisms of the larger components. The bridge, nut and saddle system will be discussed in chapter 24 as part of the main intonation system.

23.1. Body components

The first part of the assembly is positioning and glueing of the neck block to the sides. This was done with 3M 2216 high strength glue. This glue is more flexible which in theory should help to improve the distribution of the stresses from the neck applied to the body. This is to prevent the soundboard and back of the body to carry additional loads or be subject to stress concentrations due to a too rigid glue connection.

With the neck block in position the soundboard was glued on the sides which was again done using Loctite 3430 two component fast curing epoxy. This type of epoxy has a much higher stiffness compared to the 3M 2216 glue. This epoxy is used because it provides a more rigid connection between the soundboard and sides which will result in less structural damping. The back is connected in the same way as the soundboard which makes the guitar body complete.

The full body is coated with two layers Sicomin 1044 top clear to fill the pores in the polyurethane foam and to create a shiny finish. This finish will be sanded and polished on the sides to an even gloss after assembly and intonation is done. Polyester putty is used to fill tiny gaps between the soundboard and back after which the top clear and the putty is sanded smooth. On this smooth surface two coats with high gloss black lacquer spray are applied as a base coat for the final finishing.

23.2. Neck to body

To be able to install the neck a dovetail shape, as is present at the heel of the neck, is CNC milled from the body. The fit of the neck is checked after which the neck connection at the dovetail is bonded together using 3M 2216 high strength glue. Similarly to the neck block, this component has no major acoustic importance and therefore high strength is the dominant requirement.

The neck is positioned by placing a stiff and straight profile over the length of the neck and the guitar body. This ensures a proper surface to which the fretboard can be bonded. This is shown in Figure 23.1

Figure 23.1: Installation of neck to the body using a straight rectangular profile clamped to the neck and body.

23.3. Fretboard installation and final neck steps

The installation of the fretboard is fairly simple. After marking the correct position at the top of the neck, the fretboard is glued with 3M 2216 high strength glue in the correct position. With the fretboard attached two layers of Sicomin 1044 top clear are applied to the neck and sides of the fretboard up to the headstock.

On top of the neck a piece of carbon fibre epoxy is glued using 3M 2216 high strength glue to cover the white epoxy and 3M K1 hollow glass bubble fill material. After trimming and sanding down the edges of the carbon piece the headstock is signed with a paint marker over which a layer of Sicomin 1044 top clear is applied.

At this stage the holes for the tuning mechanisms are drilled in the headstock after the hole locations have been marked with the aid of a paper template. First a 3.5 mm drill is used after which a 9.5 mm drill is used to create the required space for the tuning mechanisms.

With all systems apart from the bridge, nut and saddle installed the main assembly is done. A photo of the resulting assembly is provided in Figure 23.2. The final steps of intonation and finishing are discussed in chapter 24.

Figure 23.2: Assembly of the guitar components before installation of the bridge, nut and saddle.

24

Intonation set-up and finishing

In this chapter the finalization of the guitar is discussed. First the intonation set-up is explained after which the final finishing steps are discussed.

24.1. Intonation set-up

With the main guitar components assembled the most difficult part of the guitar building process can be started which is the positioning of the bridge and correct intonation set-up of the instrument. Intonation refers to the principle that an instrument is able to produce the correct frequencies of each of the tones in relation to each other. If for example an A tone at 440Hz can be produced while the B tone, which normally is at a frequency of 493.88Hz, is produced at a frequency of 495Hz the tones sound out of tune. Especially on the guitar this is a complex process as the relative position of the frets does not allow for perfect intonation. This is caused by two main properties of the strings. First, each the strings has a different thickness and tension which causes different amounts of distortion of the frequencies when the strings are pressed against the fretboard. Second, straight fret positions are not optimal for intonation. To account for all intonation problems one would have to create a different fret position for each string which would result in a fairly complex fretboard as shown in Figure 24.1 [131].

A partial solution to the intonation problems is to compensate by positioning and orientation of bridge and saddle. This is achieved by rotating the saddle position in the bridge such that the bass strings are slightly longer. Additionally the saddles compensates the intonation by having the strings run over a certain position on the saddle. The contact between string and saddle can be tuned to about the saddle width.

The first step in setting-up the guitar with proper intonation is to find the correct bridge position. This was achieved in the following way. An aluminium plate of 3 mm thickness is placed against the fretboard after which the loose bridge is placed against the aluminium plate. By applying to clamps on the bridge enough downwards force is applied to prevent the bridge from sliding over the aluminium plate. Both the first and sixth string are tensioned to the correct pitch (E4, 329.63 Hz and E2, 82.41 Hz respectively). The tone of the first harmonic and the string pressed at the 12th fret should then match up perfectly. The harmonic is produced by positioning the finger above the 12th fret and removing the finger quickly after the string is plugged. This gives exactly the half wave length frequency of the string.

The aluminium plate intentionally produced slightly longer than the expected position of the bridge relative to the soundboard. This makes it possible to reduce the length of the aluminium plate and thus modify the bridge location in several iterations until close to proper intonation is achieved. This is shown in Figure 24.2. Once the first two strings have proper intonation, the other strings are checked one by one. Due to the limiting

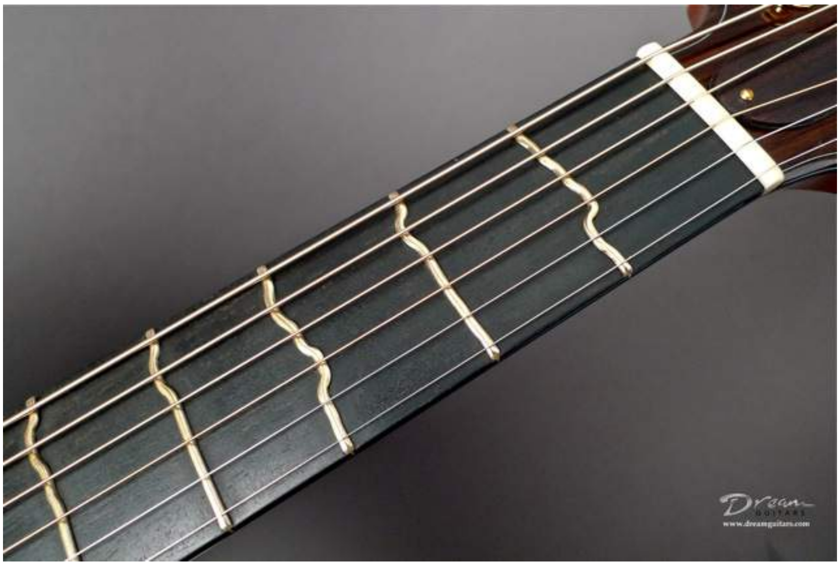


Figure 24.1: True temperament fretboard compensating for intonation issues of the guitar [131]. Guitar by Bamburg sold via Dream Guitars in the USA.

clamping force it is not possible to check all strings at the same time as the tension of the bridge and clamps would become too high.

Figure 24.2: Process of finding the optimal bridge position for intonation using an aluminium plate and two large clamps.

With the bridge location found, the bridge is glued to the soundboard after the layers of lacquer are removed. On the underside of the bridge and in the top side of the soundboard several small channels are made using a Dremel hand tool. This is done to obtain a mechanical bond between the bridge and the soundboard to prevent it from shearing off. The glue used for the bond is the 3M 2623 two component epoxy glue as this glue has limited flexibility and will therefore help to reduced vibration energy loss between the bridge and soundboard.

After curing of the glue layer between the soundboard and bridge the saddle and the nut are repositioned and intonation is optimized by carving in the slots using a small triangular file. The strings are loosened several times to adjust the slot dimensions until a good fit and proper intonation is obtained. Finally both the saddle and nut height are reduced to optimize playability of the instrument.

24.2. Finishing of guitar

The final finishing of the guitar is a very time intensive process. The top clear coat on all bare carbon fibre epoxy parts is sanded flat after which sandpaper up to 2000 grit is used to obtain a smooth and shiny surface. To improve the shine the surfaces are polished with 6000 grit equivalent polishing compound and finally wiped with Commandant 5 fine car polish.

The front and back panels are flattened and sanded to 1000 grit after which one layer of high gloss black lacquer is applied followed by a final layer of metallic lacquer. The complete guitar is polished again with Commandant 5 car polish to arrive at the end result as shown in Figure 24.3

Figure 24.3: The composite guitar with strings attached and final finishing and set-up completed.

25

Psychoacoustic analysis of the developed guitar

Psychoacoustics is the science of sound perception by humans. In this chapter the psychoacoustic analysis of the composite guitar will be discussed to validate if the composite guitar does indeed have more wood-like acoustics in comparison to existing carbon fibre guitars on the market. First the methodology of the analysis is explained after which the results are presented and discussed.

25.1. Methodology

The psychoacoustic analysis has two main goals. First and most important is to determine if the composite guitar is recognized as a wooden or composite guitar in a set of four tested guitars. These guitars are a high-end wooden guitar built by Michael Greenfield, a medium range wooden guitar built by Taylor guitars, a full carbon fibre guitar built by Rainsong guitars and the newly developed composite guitar. The four guitars are shown in Figure 25.1.

The results of this analysis will either validate the findings from Part II of this thesis or will provide a set of recommendations for further research. The second goal of the analysis is to identify if the tonal qualities of the composite guitar are scaled high or low in comparison to the three other guitars in the test.

The test set-up of the psychoacoustic analysis consists of four parts. Part I presents a short introduction about the survey and research after which the main research parts (part II and part III) provide the actual main questions and data. In part IV the survey is finalised and an opportunity to provide comments about the survey is presented. For both part II and part III a number of sound clips is recorded in an anechoic room. The distinction between the parts is that part II focuses on the identification of sound clips without a reference from other clips while part III places the four guitars in direct comparison with identical clips played on each guitar after each other. A questionnaire is presented to both guitar experts and untrained listeners. The detailed structure of the questionnaire is presented below.

25.1.1. Questionnaire part I: Introduction and relation to guitar music

The first part of the questionnaire provides a short introduction to the research conducted as well as an explanation of the questionnaire. Additionally two questions are asked to identify the expertise of the participant. By knowing if the participant has a strong expertise in the field of guitar music a split can be made in the analysis of results between people with or without a trained ear with respect to identifying guitar sounds. It is

Figure 25.1: From left to right: Michael Greenfield G4.2, Taylor guitars 214CE, Rainsong Smokey, Newly developed composite guitar.

expected that guitar buildiers and guitarists will do significantly better in matching the sound clips to certain guitars. The two questions presented to the participants are listed below.

- *"What is your relationship with guitars?"* with possible answers: not involved, hobbyist, Performing artist or guitar builder/luthier.
- *"How long have you played/built guitars?"* with possible answers: not involved, 0-2 years, 2-5 years, 5-10 years or over 10 years.

25.1.2. Questionnaire part II: Identifications of sound clips without a reference

The second part of the questionnaire consists of 12 questions. In each question a unique clip is presented to the participant after which four questions are to be answered.

- *"Which guitar is played in this sound clip?"* - The purpose of this question is to find out if participants are able to identify the sound of each of the guitars without a reference.
- *"How do you rate the overall quality of the tone of this guitar?"* - This question provides a scale from 1 to 10 on the tonal quality of the instrument. Using this information, it can be found which guitar sound is considered to have the best overall quality of tone.
- *"Do you consider the sound of the guitar to be brittle or warm?"* - This question provides a scale from 1 to 10 where participants can choose between a brittle and warm sound. Using this information it is verified whether the participants are in agreement with each other or interpret the sound very different. A well trained ear should identify the carbon fibre guitar as more brittle while the wooden guitars should be identified as warmer.
- *"Do you consider the tone of the guitar to be well-defined or fuzzy?"* - Similarly to the question above, a scale is provided from 1 to 10 where people can rate the definition of the guitar tone. A well trained ear should be able to identify the medium range wooden guitar as more fuzzy in comparison to the other instruments.

Analysis of the results is done using Microsoft Excel where the percentages of correct and wrong interpretations are positioned next to each other. The results will then be discussed and provide a conclusion if people untrained and/or well-trained in listening to guitar music can identify the composite guitar.

25.1.3. Questionnaire part III: Matching of sound clips to guitars

In the third part of the questionnaire the participant has to answer four questions in which four identical sound clips are presented which are played on each of the guitars as described in section 25.1. The goal is to match each of the sound clips to the correct guitar. In this way it can be determined if the participants can distinguish the composite and carbon fibre guitars from the wooden guitars.

Analysis of the results is done using Microsoft Excel where the percentages of correct and wrong interpretations are positioned next to each other. The results will then be discussed and provide a conclusion if people untrained and/or well-trained in listening to guitar music can identify the composite guitar when directly placed in comparison with other guitars.

25.1.4. Questionnaire part IV: Thank you and follow up

The final section of the questionnaire presents the participant with a thank you note and the possibility to leave their name and contact email address for communication of test results as well as a summary of the thesis work.

25.2. Results

The questionnaire has been completed by a total of 70 participants. Over 70% of these participants have either no experience with guitars or over 10 years of experience. The detailed distribution of the participants and their relation to guitars is presented below:

- 23 (32.9%) of the participants have no experience with guitars.
- 21 (30.0%) of the participants are guitar hobbyists.
- 21 (30.0%) of the participants are professional performing guitarists.
- 5 (7.1%) of the participants are professional guitar builders.

25.2.1. Validity of survey results

In order to assess the validity of the survey an analysis is conducted on the average score and the score per group. An average score identifying the correct guitar of less than 25% would indicate that the survey is too hard and no sensible conclusions can be drawn from the survey. As all main questions have only 4 options it is theoretically expected that, even when every question is filled in randomly, an average score of 25% is achieved.

The average score by all 70 participants is 29.5% which is considerably higher than the theoretical gambling chance of 25%. Additionally this low score is expected due to the difficulty of the test. Upon consulting with several participants a number of comments can be made about the survey.

- Due to the compression of the audio files when uploading to YouTube a lot of the detail in the sound clips is lost. Sadly this was not preventable as only YouTube clips can be used in the survey system used.
- Many participants are likely to not use studio grade equipment to playback the clips which can potentially result in a completely different projection of the sound. Similarly the room acoustics when played back on a set of speakers can have a large influence on the perceived sound.
- A comment by luthier Nick Benjamin indicates that an experienced guitar player will be able to counteract the inferior tonal qualities of worse guitars. This is largely considered true as mostly the last

attempt played of a certain clip was chosen for the survey as these last attempts were by far the best possible representation of the guitars. This results in that negative tonal effects such as brittleness of the carbon fibre guitar can be partially counteracted and the differences between the four guitars will become smaller.

25.2.2. Results per user group

The second analysis performed on the results is the average score of each of the groups as presented in section 25.2. These are shown in Figure 25.2

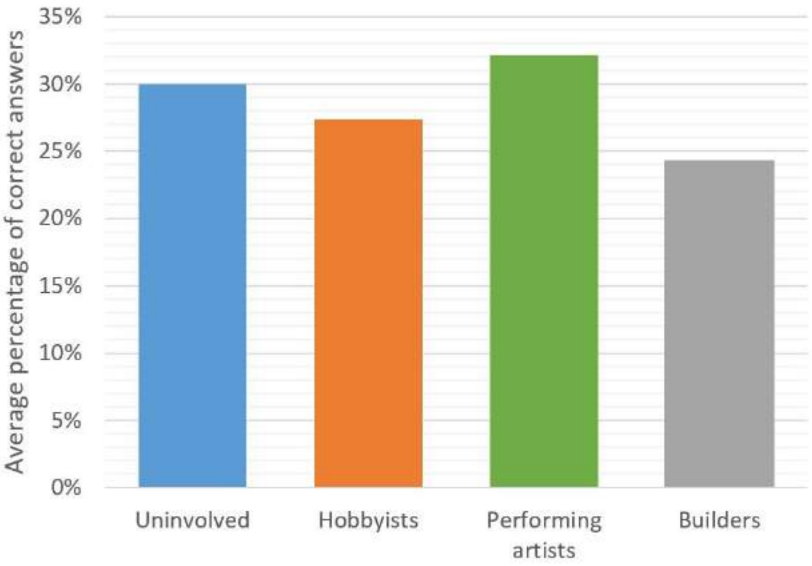


Figure 25.2: Average percentage of correct answers split by group.

The results obtained show a very different outcome than expected. The guitar builders, which were expected to score highest of all groups actually scored below average. The performing artists did score as expected slightly higher than average. Additional analysis did show that the participants with over 10 years of experience with guitars scored 32.1% which is higher than average as expected

25.2.3. Results per guitar

The results per guitar are analysed independently for the referenced and unreferenced clips. First the results of the clips without a reference are presented and discussed after which the reference clips results are covered.

25.2.3.1. Results of clips without a reference (part II of survey)

Analysis of the results of the first set of questions with the unreferenced clips shows an average percentage of correct answers of 27.1%. The results split per guitar are shown in Figure 25.3

From the results it can be observed that both the newly developed carbon fibre guitar and the medium range wooden guitar are most often not recognized. In contrast the high end wooden guitar and the carbon fibre guitar are significantly more often identified correctly. Additionally of the incorrect answers on the sound clips of the newly developed composite guitar 58% of the participants chose either the medium range wooden guitar or high end guitar as answer. Both these findings indicate that the newly developed composite guitar is very hard to detect as a non-wooden instrument.

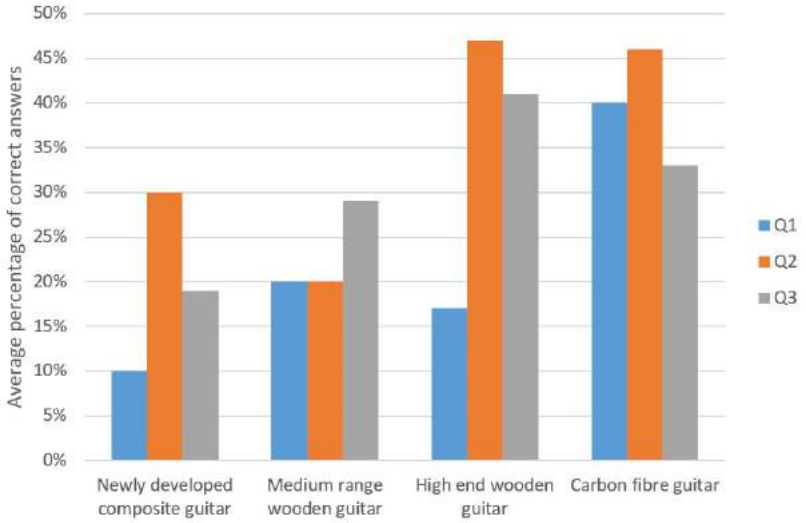


Figure 25.3: Average percentage of correct answers split by guitar for part II of the survey (clips without a reference)

25.2.3.2. Results of reference clips (part III of survey)

Analysis of the results of the second set of questions on the referenced clips shows an average percentage of correct answers of 31.4%. The results split by guitar are presented in Figure 25.4. Again out of the four guitars the newly developed composite guitar and the medium range wooden guitar received the lowest number of correct answers. In addition to the incorrect answers on the sound clips of the newly developed composite guitar 55% of the participants chose either the medium range wooden guitar or high end guitar as an answer. The carbon fibre guitar is recognized significantly more by participants.

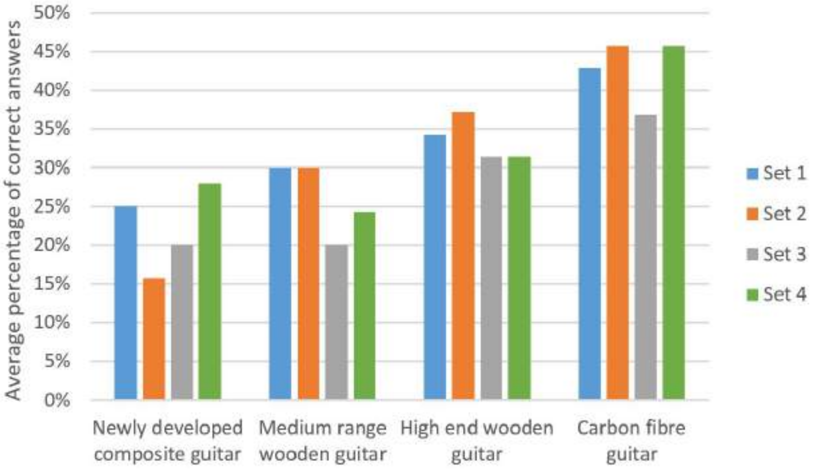


Figure 25.4: Average percentage of correct answers split by guitar for part III of the survey (clips with a reference)

25.2.4. Analysis of tonal qualities

An extensive analysis was performed on the ratings on the secondary questions of part II of the survey. This analysis provided however no statistically significant results. The average tonal qualities grades obtained for the guitars are listed below.

- Newly developed composite guitar: 7.2/10

- Medium range wooden guitar: 7.2/10
- High end wooden guitar: 7.3/10
- Carbon fibre guitar: 6.7/10

The grades are considered too close to each other to provide any strong conclusions. The reason for the close grading is that most participants actually did not provide any grades above 8 and below 6. Therefore the distinction between guitars is impossible to make.

The result on the tonal parameters such as warmth and definition also did not provide any reasonable conclusions. The results are extremely unpredictable between participants. As expected most participants are likely not familiar with the terminology and therefore could not make a real assessment of the sound clips.

25.3. Conclusion on psychoacoustic analysis

The psychoacoustic analysis convincingly shows that the newly developed composite guitar is significantly harder to distinguish from a set of both wooden and carbon fibre guitars than the carbon fibre guitar currently available on the market. For both the unreferenced as the referenced sound clips the results show that a large number of participants is able to correctly identify the carbon fibre guitar while the majority of the answers on the newly developed guitar misidentify the newly developed composite guitar as a wooden guitar.

The overall score on the test is considered to be fairly low. Additionally the guitar builders group, which was expected to score higher compared to the other groups, actually scored lower than expected. This can potentially be caused by the small sample group of only 5 guitar builders that completed the survey. Preferably the group sizes should be comparable as each of the groups has both very well performing participants and relatively bad performing participants. With the low number of guitar builders participating no real conclusions can be drawn on the average performance of this group.

The survey has a number of shortcomings. Even though the sound quality of the clips is very high and all clips are recorded under the same conditions in an anechoic room, the compression of the clips due to the use of YouTube was not anticipated. This resulted in a much lower sound quality making the survey significantly harder. Additionally the number of participants in the guitar builders group should ideally be higher. Finally adaptation to the guitar by the guitar player has a significant influence on the sound clips. According to experienced luthier Nick Benjamin, an experienced guitar player will be able to create a pleasant tone even on a carbon fibre guitar. Therefore the differences in sound of the four guitars might be smaller than they where expected to be.

26

Cost analysis of full composite guitar

An important issue raised with regards to the development of a specific product from a scientific point of view is: will the research yield a return in the long term or provide a considerable added benefit for society. Therefore in this chapter a competitive analysis of the full composite guitar in terms of material and production costs is presented.

First the cost of each of the components will be discussed after which the assembly costs and finally the overall costs are calculated. Although in all calculations the costs of equipment use is considered, it is important to create an estimate of the investment costs to provide insights into the pay back time of the machinery and other large investments. Finally the total cost price of the instrument is benchmarked against existing guitars made from either wood or composites.

The main cost numbers are discussed in the respective chapters. A more detailed breakdown of the costs can be found in Appendix C. In this breakdown the unit prices are mostly found in invoices from MC Technics which is the main supplier of composite materials and tooling for the Delft Aerospace Structures and Materials Laboratory (DASML). The mould costs are found using the total invoice by Jules Dock and are allocated by the number of labour and CNC milling hours per component. Finally the quantities needed are calculated from cutting patterns and actual uses during production. The calculated numbers are rounded up to account for material spillage and cutting efficiency of the fabric.

26.1. Component production costs

The prices of the components are listed in Table 26.1. Below the most important considerations with respect to the cost figures are discussed.

Table 26.1: Main component costs split by direct material, production tooling & materials and labour costs.

	Direct material	Tooling and production materials	Labour	Total
Soundboard and back	€ 49.06	€ 100.00	€ 700.00	**€ 849.06**
Fretboard	€ 39.75	€ 171.00	€ 245.00	**€ 455.75**
Sides	€ 42.75	€ 40.00	€ 175.00	**€ 257.75**
Neck	€ 36.25	€ 36.67	€ 245.00	**€ 317.92**
Neck block	€ 16.75	€ 6.50	€ 17.50	**€ 40.75**
Bridge	€ 6.00	€ 65.25	€ 17.50	**€ 88.75**
Nut and saddle	€ 5.50	€ 6.30	€ 26.25	**€ 38.05**
	€ 196.06	€ 425.72	€ 1,426.25	€ **2,048.03**

Soundboard - As discussed in chapter 16 the production costs of the soundboard and back are dominated by labour costs. The filament winding process is extremely intensive taking around 4-6 hours for one panel. During this process the winding process has to be monitored to make sure no fibre breakage, contamination due to loose fibres or the application of too little resin occurs. The post production is a slow process due to the voicing of the panels by removing material on the braces. Finally most of the finishing is required on the soundboard and back due to the porosity of the polyurethane foam. This requires several hours to perform to a sufficiently high quality.

Fretboard - The fretboard costs are dominated by the CNC milling and labour costs. Additionally the fret wire is one of the more expensive material components.

Sides - The cost of the sides is relatively low in comparison to its size. This is based on the assumption that the moulds produced can be used at least 300 times before replacement is required. If this number is reduced or more expensive aluminium moulds are required to reach this production capacity, the mould costs might increase by several factors increasing the total costs of the sides significantly. The sides costs are dominated by the labour costs.

Neck - Similarly to the sides, the neck costs are relatively low based on the assumption that the current moulds would be sufficient for the production of 300 pieces. The neck costs are dominated by the labour costs.

Neck block - The neck block is a relatively cheap component to produce. The limiting factor in production is the exothermic reaction. If this can be controlled, several neck blocks could potentially be produced from one larger mould which reduces the labour and mould costs significantly.

Bridge - Several bridges can be produced from one blank of material. This results in a relatively short time required for CNC milling of the bridge. Therefore the overall costs are relatively low and they are dominated by the CNC costs.

Nut and saddle - Similarly to the bridge, several nuts and saddles can be produced from a larger blank. Even though this high working efficiency can be achieved, the labour costs still make up the bulk of the costs.

26.2. Assembly and intonation set-up and finishing costs

The assembly material costs are dominated by the fast curing two component epoxy glues which are sold in small double tubes. These are considerably more expensive than the other glues used. Next to that, the tuning mechanisms are an expensive component for the guitar. As with the component costs the labour costs take up the biggest portion of the total assembly costs.

Table 26.2: Assembly, intonation set-up and finishing costs split by direct material, production tooling & materials and labour costs.

	Direct material	**Tooling and production materials**	**Labour**	**Total**
Assembly and intonation	€ 127.00	€ 8.75	€ 280.00	**€ 415.75**
Finishing	€ 113.50	€ 14.25	€ 350.00	**€ 477.75**
	€ 240.50	€ 23.00	€ 630.00	€ 893.50

26.3. Overall costs

The total costs of the guitar production is found to be just short of 3000 Euro. As can be seen from Table 26.3 the labour costs take up the majority of the costs. It should however be noted that for normal small shop luthiers producing up to 50 guitars a year, the labour costs are actually part of the compensation for the work by the luthier. The scenario considered in this section takes the labour costs as direct costs for the luthier to employ another person to construct the guitars. This is a scenario more comparable with the situation of larger guitar factories. Considering the case of a single luthier the total costs of the guitar would go down to around 900 Euro. This is, depending on the material choices, either lower or higher than for a wooden guitar.

Table 26.3: Total guitar costs split by direct material, production tooling & materials and labour costs.

Direct material	€ 436.56
Tooling and production material	€ 445.72
Labour	€ 2,056.25
Total	**€ 2,938.53**

The material costs are found to be the smallest part of the costs with only about 450 Euro in total. The additional costs which cover the use of small tools, tape and the use of larger tools such as a band saw and sanding belt are estimated to be around 450 Euro which is similar to the direct material costs for the guitar.

26.4. Investment costs considerations

The equipment used in the production of the guitar requires considerably investments. For the production of the soundboard and back materials a filament winder and large press are needed or a new machine should be produced and designed as discussed in chapter 16. Fast cutting of carbon fibre weaves can be done using a Gerber automatic cutter which comes with high machine costs and even higher license costs for the nesting software. Therefore setting-up a factory to produce these guitars is high risk as several hundreds of guitars should be sold in order to obtain an acceptable return on investment.

26.5. Competitive analysis and production optimization

Considering the guitar production costs of nearly 3000 Euro an acceptable retail price would come close to 4000 Euro when sold directly by the factory. In case the guitars are to be sold via distributors and shops the retail price is likely to be around 5000-6000 Euro. This makes the guitar considerably more expensive in comparison with other carbon fibre composite guitars and places them in the upper range of wooden guitars just below high quality hand built guitars. From the psychoacoustic analysis it can be concluded that the guitar could potentially be positioned in this price range. However considering the number of guitars to be sold to make the investment worthwhile investors might not be willing to provide the funds.

An option to improve on the cost position of the guitar is to redesign the production process. In this case the focus should be on the reduction of labour costs. This can be achieved in a number of ways which are listed below.

- The soundboard and back material production could be done using a dedicated machine instead of the currently used method of filament winding and polyurethane infusion in a large press. Even if the machine is considerably more expensive compared to the filament winding machine and press the labour hours can be reduced by at least a factor 2 which would result in savings of 10% of the total costs of the guitar.
- The main carbon epoxy components that are now constructed using vacuum infusion can be redesigned to be produced with pre-impregnated carbon fibre materials. Although the material costs might increase, the benefit of reduced labour costs is orders of magnitude higher. The material costs could potentially go up by a factor 2 while the labour hours can easily be reduced by 60% resulting in a overall cost reduction of 300 Euro which is again 10% of the total guitar costs.
- The finishing of the product is very labour intensive. Both the labour hours for the intonation set-up and the finishing are expected to go down over time with increasing experience. Between construction of the first and second guitar the number of labour hours was reduced by 70%. Therefore it is a reasonable estimation that the labour costs for intonation set-up and finishing can be reduced by another 250 Euro.

- The replacement of high cost materials such as the two component fast curing epoxy and Sicomin top clear by a cheaper alternative can reduced the costs by 50 Euro. Similarly the more efficient use of infusion epoxy saves another 30 Euro.

Summarizing the points above, the production optimization could easily reduce the production costs of the instrument with one third to below 2000 Euro. The resulting retail price between 3000 and 4000 Euro makes the instrument very competitive in the market. The main concern however remains the initial investment costs on which a further evaluation should be conducted when considering the pursue of a stable business in the future. Therefore it can also be concluded with respect to requirement C2 on cost efficiency, that the composite guitar can satisfy this requirement after additional development of the instrument.

27

Final conclusion and recommendations

The research goal of creating a composite guitar with similar acoustic properties to its wooden counterpart is successfully achieved. A new composite is developed that is able to replace wood for the most important two components for the production of the sound of a guitar, the soundboard and back. Additionally the combination of this newly developed composite in a complete composite guitar resulted in an instrument which is extremely hard to identify as a non-wooden guitar according to the psychoacoustic analysis conducted.

Critically reflecting on the research a number of comments can be made. Most important is the decision to cover as many aspects of the newly developed composite as possible such as the environmental sensitivity and all acoustic material parameters. This caused a limitation on the detail on each of the analyses. An example of this is the in-plane stiffness tests which were only conducted on the first two composite versions C1 and C2 and not on the final composites. Also a environmental sensitivity analysis conducted on the complete composite guitar and a comparable wooden guitar would have provided more data closer to a real-life scenario. Therefore although the successes of the research are considerable, from an academic perspective many of the tests conducted, apart from the acoustic analysis, can only be viewed as an initial indication and not as conclusive findings.

The new composite material developed has a large number of potential applications in other fields including aerospace engineering. There are many situations where foam is the weak link in a lightweight structure. Creating reinforcement in a foam has a limited impact on the overall density but has a very large potential to improve its strength and stiffness performance. Additionally a stiff foam can be a highly effective damper which has also a large number of potential applications. Therefore most promising applications should be further researched.

Within the field of musical instrument manufacturing the newly developed composite has potential to become a serious alternative to natural tonewoods. It is expected that with the current developments in the prices for high quality woods the composite becomes only more viable in the future. Main considerations for the successful entry of the composite in the market will be the ability to manufacture it efficiently. Before this is possible a large and risky investment is to be made into the development of a continuous production machine of the composite. Additionally the conservative field of acoustic guitar building has seen only a number of relatively small changes since the year 1850. Therefore the question ultimately remains if the customer wants to walk away from the romance of the wooden guitar.

A

Appendix: Photos of tested samples

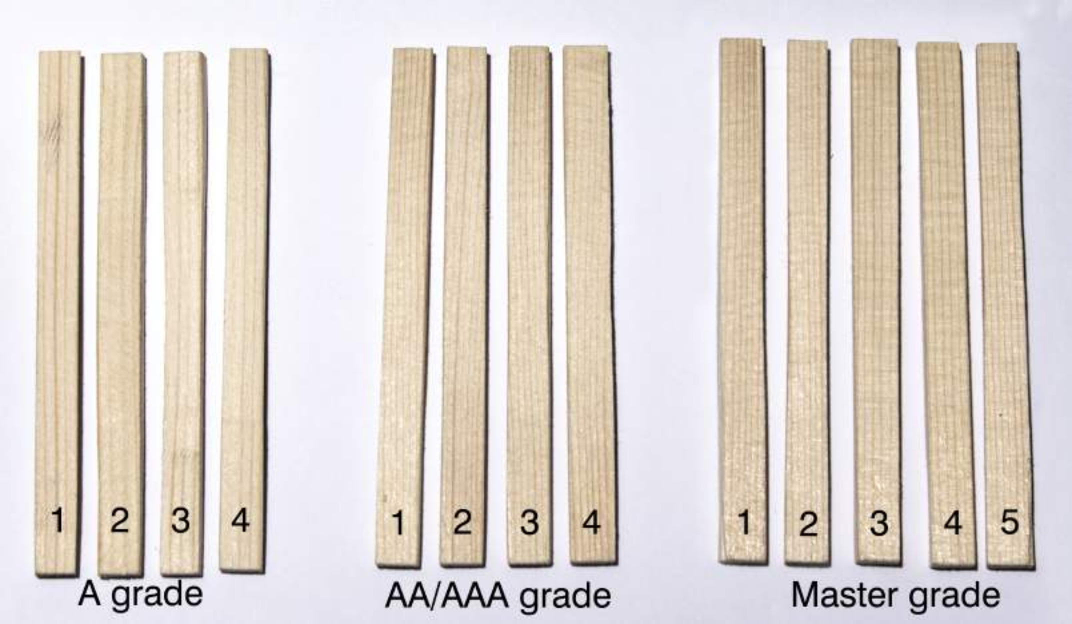


Figure A.1: Photos of the longitudinal samples used in the tests

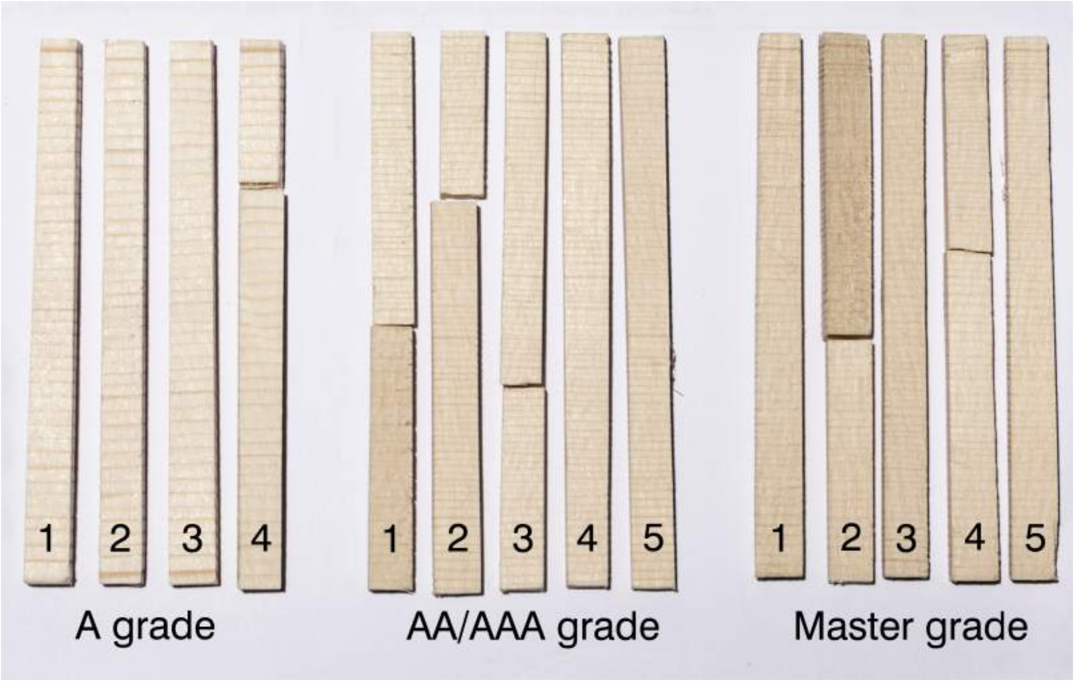


Figure A.2: Photos of the transverse samples used in the tests

B

Appendix: Stress-strain curves

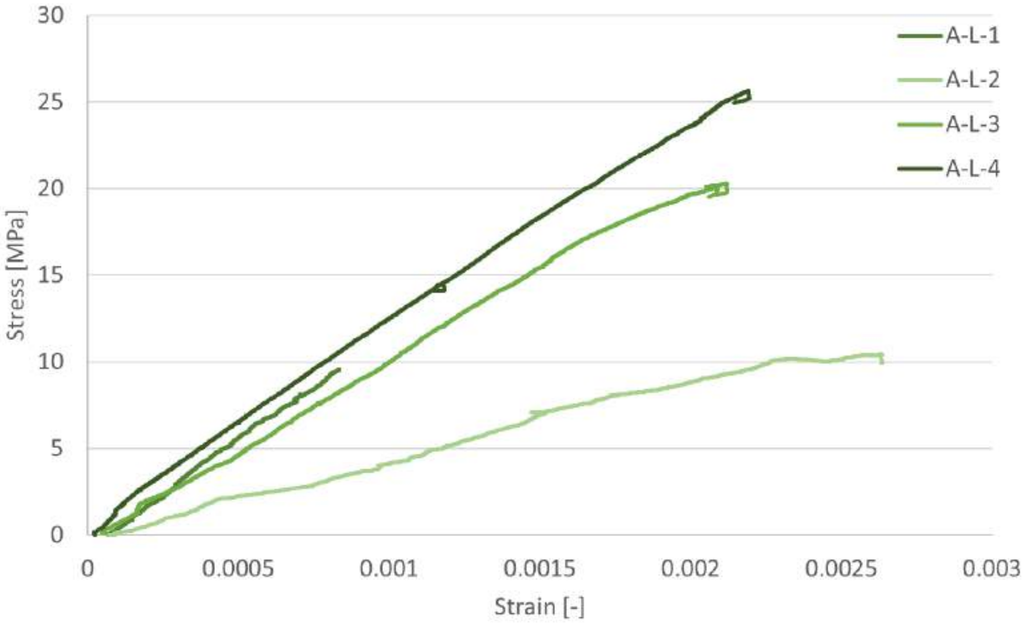


Figure B.1: Stress-strain curves of A-grade samples tested in longitudinal direction

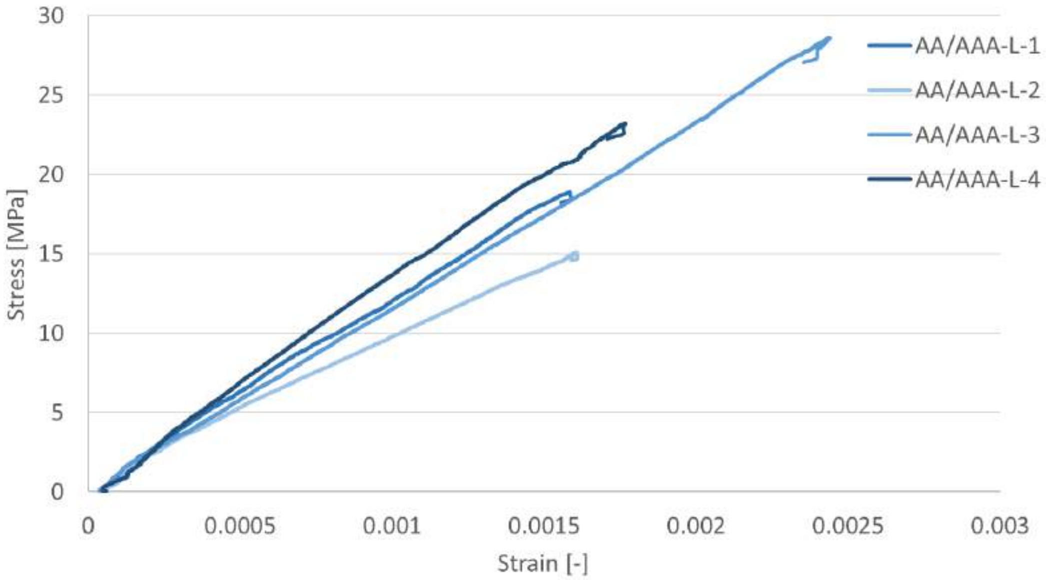


Figure B.2: Stress-strain curves of AA/AAA-grade samples tested in longitudinal direction

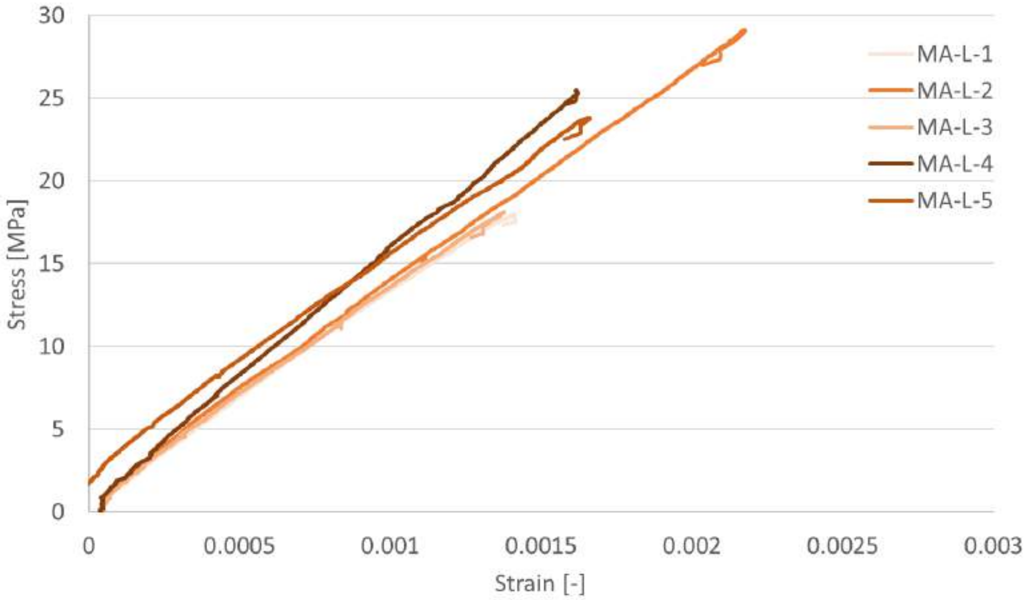


Figure B.3: Stress-strain curves of master grade samples tested in longitudinal direction

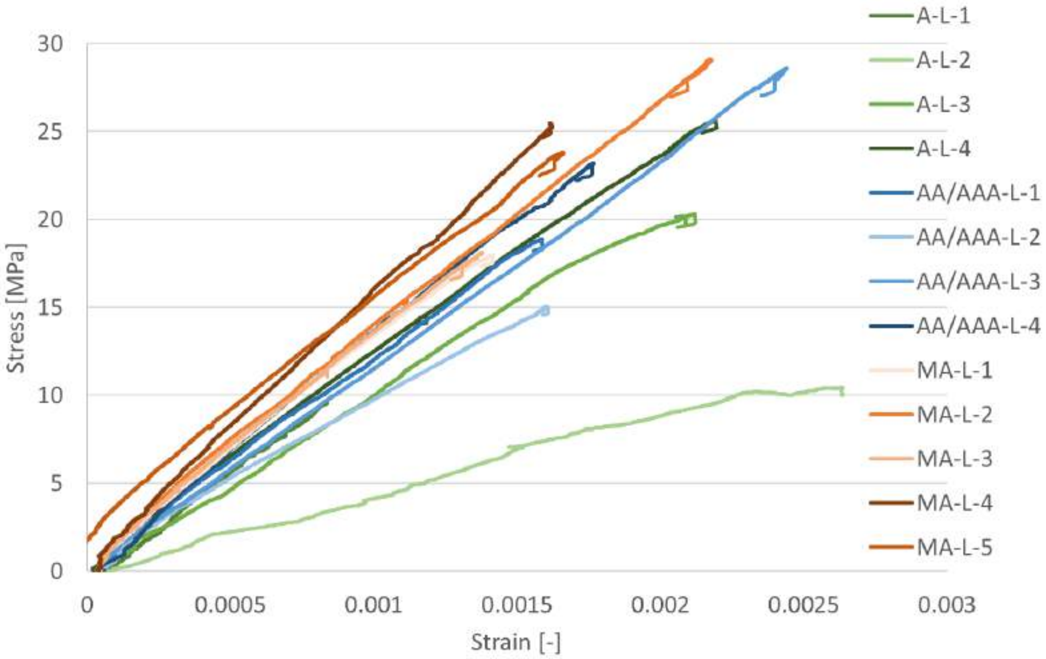


Figure B.4: Stress-strain curves of all samples tested in longitudinal direction

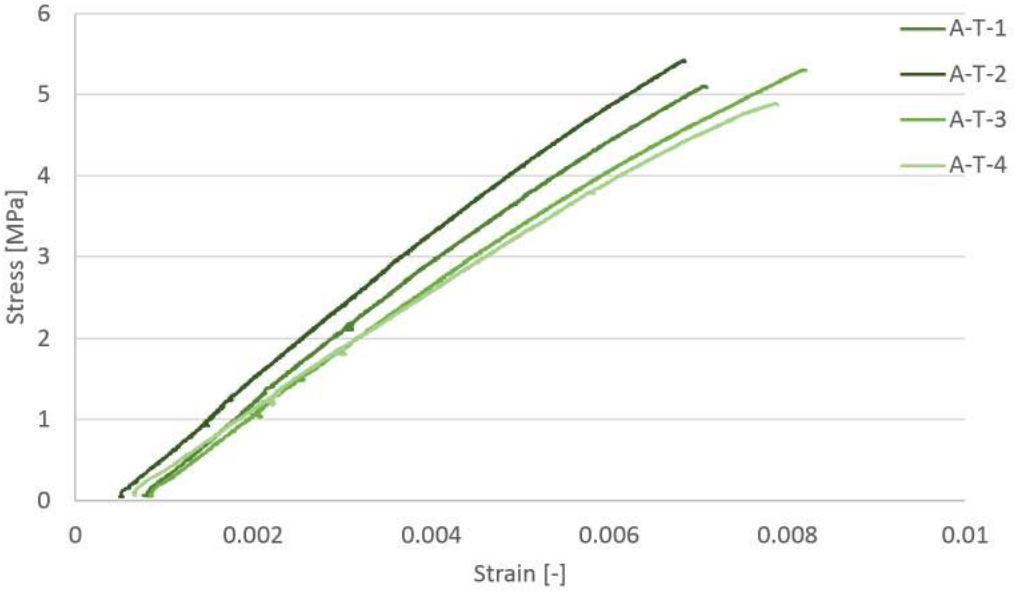


Figure B.5: Stress-strain curves of A-grade samples tested in transverse direction

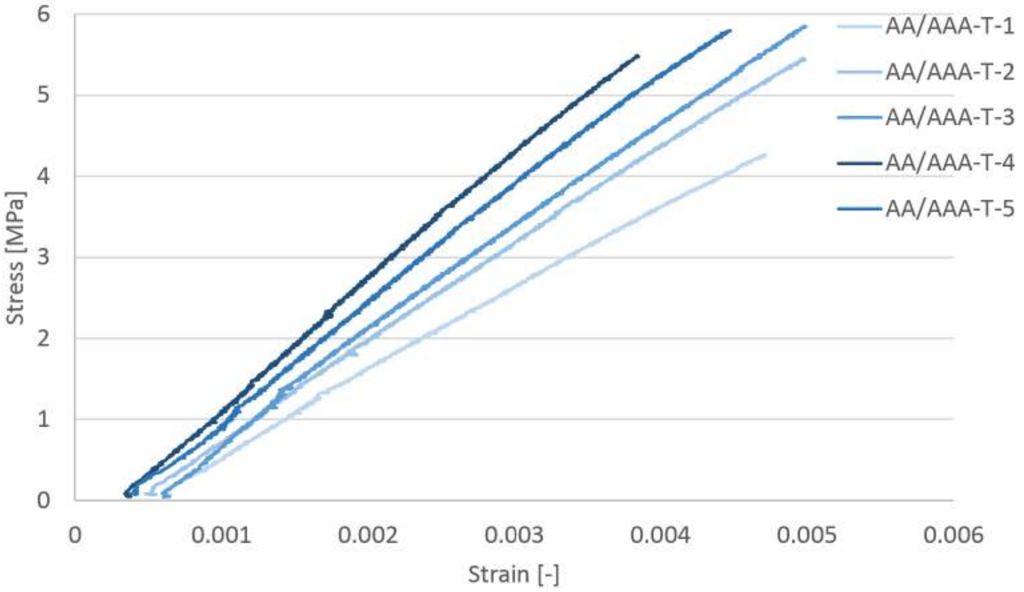


Figure B.6: Stress-strain curves of AA/AAA-grade samples tested in transverse direction

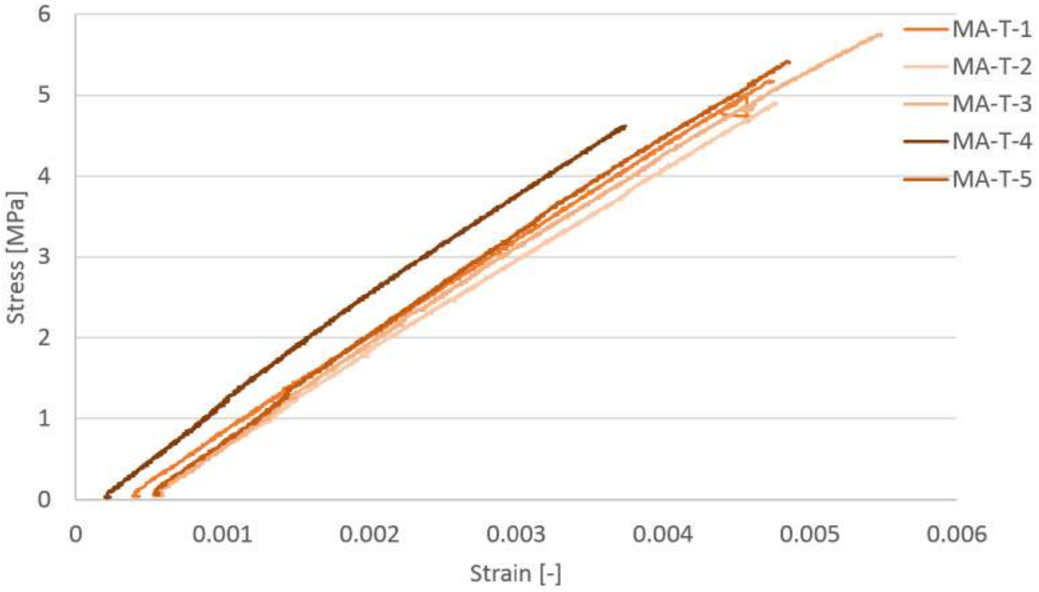


Figure B.7: Stress-strain curves of master grade samples tested in transverse direction

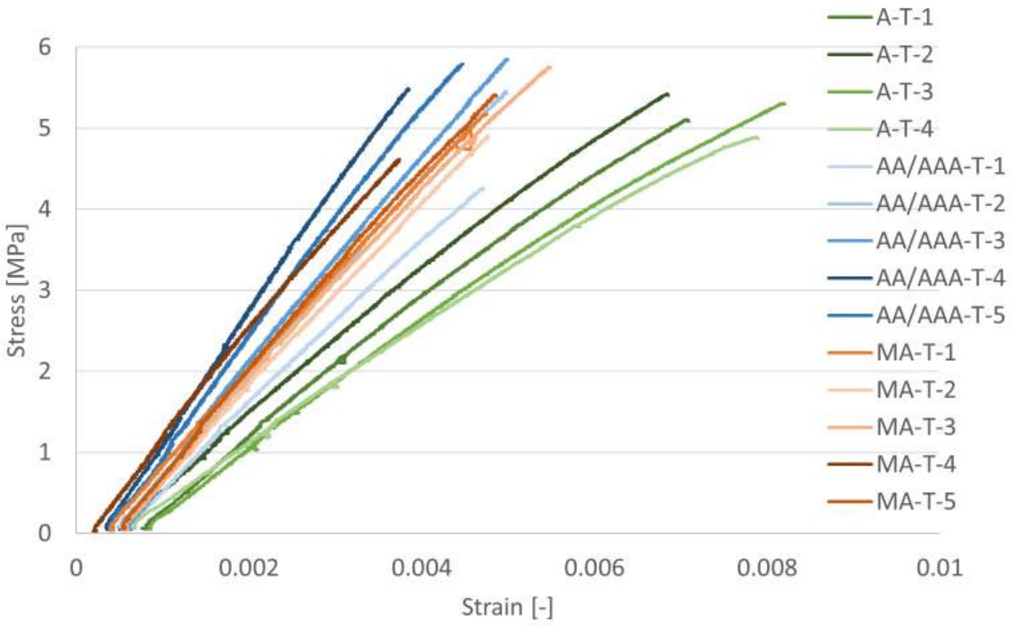


Figure B.8: Stress-strain curves of all samples tested in transverse direction

C

Appendix: Detailed cost break-down

Table C.1: Soundboard and back cost breakdown

	price/unit	*unit*	*quantity*	*unit*	*total price*
Material costs					
Carbon fibre 3k fillament	76.8	€/kg	0.2	kg	€ 15.36
Epoxy	25	€/kg	0.4	kg	€ 10.00
Flexibilizer	45	€/kg	0.3	kg	€ 13.50
Polyurethane foam	8.5	€/kg	1.2	kg	€ 10.20
Production costs					
Production materials	15	€/unit	2	units	€ 30.00
Tooling	35	€/unit	2	units	€ 70.00
Labour	35	€/h	20	h	€ 700.00
					€ 849.06

Table C.2: Fretboard cost breakdown

	price/unit	*unit*	*quantity*	*unit*	*total price*
Material costs					
Carbon fibre twill weave 200g	35	€/kg	0.2	kg	€ 7.00
Carbon fibre UD weave 280g	35	€/kg	0.05	kg	€ 1.75
Epoxy	25	€/kg	0.5	kg	€ 12.50
Fret wire	12	€/m	1.5	m	€ 18.00
3M K1 glass bubbles	25	€/kg	0.02	kg	€ 0.50
Production costs					
Production materials	12	€/unit	1	unit	€ 12.00
CNC milling	75	€/h	2	h	€ 150.00
Tooling excl moulds	5	€/unit	1	unit	€ 5.00
Mould	1200	€/unit	0.0033	unit	€ 4.00
Labour	35	€/h	7	h	€ 245.00
					€ 455.75

Table C.3: Sides cost breakdown

	price/unit	*unit*	*quantity*	*unit*	*total price*
Material costs					
Carbon fibre twill weave 200g	35	€/kg	0.65	kg	€ 22.75
Epoxy	25	€/kg	0.8	kg	€ 20.00
Production costs					
Production materials	20	€/unit	1	unit	€ 20.00
Tooling excl moulds	10	€/unit	1	unit	€ 10.00
Mould	3000	€/unit	0.0033	unit	€ 10.00
Labour	35	€/h	5	h	€ 175.00
					€ 257.75

Table C.4: Neck cost breakdown

	price/unit	*unit*	*quantity*	*unit*	*total price*
Material costs					
Carbon fibre twill weave 200g	35	€/kg	0.5	kg	€ 17.50
Epoxy	25	€/kg	0.7	kg	€ 17.50
3M K1 glass bubbles	25	€/kg	0.05	kg	€ 1.25
Production costs					
Production materials	20	€/unit	1	unit	€ 20.00
Tooling excl moulds	10	€/unit	1	unit	€ 10.00
Mould	2000	€/unit	0.0033	unit	€ 6.67
Labour	35	€/h	7	h	€ 245.00
					€ 317.92

Table C.5: Neck block cost breakdown

	price/unit	*unit*	*quantity*	*unit*	*total price*
Material costs					
Carbon fibre UD weave 280g	35	€/kg	0.15	kg	€ 5.25
Epoxy	25	€/kg	0.4	kg	€ 10.00
3M K1 glass bubbles	25	€/kg	0.06	kg	€ 1.50
Production costs					
Production materials	2.5	€/unit	1	unit	€ 2.50
Tooling excl moulds	2.5	€/unit	1	unit	€ 2.50
Mould	30	€/unit	0.05	unit	€ 1.50
Labour	35	€/h	0.50	h	€ 17.50
					€ 40.75

Table C.6: Bridge cost breakdown

	price/unit	*unit*	*quantity*	*unit*	*total price*
Material costs					
Carbon fibre UD weave 280g	35	€/kg	0.05	kg	€ 1.75
Epoxy	25	€/kg	0.15	kg	€ 3.75
3M K1 glass bubbles	25	€/kg	0.02	kg	€ 0.50
Production costs					
Production materials	5	€/unit	1	unit	€ 5.00
CNC milling	75	€/h	0.75	h	€ 56.25
Tooling excl moulds	2.5	€/unit	1	unit	€ 2.50
Mould	30	€/unit	0.05	unit	€ 1.50
Labour	35	€/h	0.50	h	€ 17.50
					€ 88.75

Table C.7: Nut and saddle cost breakdown

Nut and saddle	*price/unit*	*unit*	*quantity*	*unit*	*total price*
Material costs					
Carbon fibre UD weave 280g	35	€/kg	0.05	kg	€ 1.75
Epoxy	25	€/kg	0.15	kg	€ 3.75
Production costs					
Production materials	5	€/unit	1	unit	€ 5.00
Tooling excl moulds	1	€/unit	1	unit	€ 1.00
Mould	30	€/unit	0.01	unit	€ 0.30
Labour	35	€/h	0.75	h	€ 26.25
					€ 38.05

Table C.8: Assembly and intonation set-up cost breakdown

	price/unit	*unit*	*quantity*	*unit*	*total price*
Material costs					
Two component epoxy	15	€/unit	3	units	€ 45.00
3M 2623 Epoxy glue	60	€/kg	0.05	kg	€ 3.00
3M 9360 Epoxy glue	50	€/kg	0.1	kg	€ 5.00
Tuning mechanisms	60	€/unit	1	unit	€ 60.00
Strings	14	€/unit	1	unit	€ 14.00
Production costs					
Labour	35	€/h	8.00	h	€ 280.00
					€ 407.00

Table C.9: Finishing cost breakdown

	price/unit	*unit*	*quantity*	*unit*	*total price*
Material costs					
Sicomin top clear	55	€/kg	1.5	kg	€ 82.50
Black high gloss laquer	8	€/unit	2	units	€ 16.00
Black metallic high gloss laquer	15	€/unit	1	unit	€ 15.00
Production costs					
Tooling excl moulds	20	€/unit	1	unit	€ 20.00
Labour	35	€/h	10.00	h	€ 350.00
					€ 483.50

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