

Composite systems for musical instruments: the case of the acoustic guitar

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Master Dissertation

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Abstract

Acoustic guitars are now one of the most popular instruments. This, along with the rising issue of quality tree shortages, implies the development of an alternative material that may replace wood without diminishing its acoustic properties. Composite materials seem to be a viable option owing to their low weight, resistance to environmental conditions, and superior strength. Despite this, the sound of composite guitars is still inferior to that of their wooden counterparts, as it is not optimized.

The work presented in this thesis is one of the early steps toward the widespread use of composite guitars. To replace wood as the primary material in guitars, an appropriate alternative must be identified. The main goal of this thesis is to find a composite material that sounds as good as wood and solves the problems of this material without sacrificing sound quality.

Two sandwich composites were produced and evaluated. Standard-ply and thin-ply carbon prepreps were selected together with a PVC foam core for the sandwich materials. In terms of acoustic qualities, the results revealed that no material developed can replace the tested wood. CarbonS-1 was found to be promising, although additional material research is necessary for more detailed conclusions.

Keywords: Vibration, Sound, Composites, Wood, Guitar, Acoustics

Resumo

As guitarras acústicas são, na atualidade, um dos instrumentos mais populares. Isto, juntamente com a crescente escassez de árvores de qualidade, requer o desenvolvimento de um material alternativo que possa substituir a madeira sem diminuir as suas propriedades acústicas. Os materiais compósitos parecem ser uma opção viável devido à sua baixa densidade, resistência aos impactos ambientais e resistência superior. Não obstante, o som das guitarras feitas com materiais compósitos é ainda inferior ao das guitarras de madeira, porque não está otimizado.

O trabalho apresentado nesta tese é uma das primeiras etapas para a generalização de instrumentos musicais compósitos. Para substituir a madeira como material nas guitarras, deve ser identificada uma alternativa adequada. O estudo desta tese centra-se na descoberta de um material compósito que iguale acusticamente a madeira, resolvendo assim as dificuldades da madeira sem sacrificar a qualidade do som.

Foram escolhidos, produzidos e avaliados dois compósitos de sanduíche. Foram selecionados pré-impregnados de carbono de camada padrão e de camada fina juntamente com um núcleo de espuma de PVC como constituintes dos compósitos sanduíche. Em termos de qualidades acústicas, os resultados revelaram que nenhum material desenvolvido pode substituir a madeira testada. O CarbonS-1 foi considerado promissor, embora seja necessária investigação adicional para conclusões mais detalhadas.

Palavras Chave: Vibração, Som, Compósitos, Madeira, Guitarra, Acústica,

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1 Introduction

The guitar's tone, quality, and sound are all greatly reliant on the humidity and other environmental variables. Also, a small variety of woods can be used as tonewoods. This, paired with the environmental challenges and new laws for wood harvesting, results in a shortage of excellent timber [1]. Moreover, as a biomaterial, wood demands a considerable expenditure on quality control and on the drying process [2]. The use of composites to replace wood would give greater stability in terms of quality and dependability and give wider options in material selection. Moreover, it would provide the ability to build a bespoke instrument with the precise tone and quality the performer would desire.

Whilst in the case of mechanical constructions and applications such as aerospace or automotive, in the music business, the objective is not meant to be a maximum damping to decrease the noise and vibrations. The purpose is to adjust this parameter to produce an ideal solution for each preference.

The development of composites provides for greater performance in various applications [3]. There have been some studies attempting to use the expertise in composites garnered in other fields to benefit the musical instrument building industry. Since 1975, composite violins and guitars have been produced, and there are already various examples of models in the marketplace [3]. The choice of composites over wood as the core material for guitars is due to characteristics such as stronger resilience to environmental changes, reduced material variability, cheaper, manufacturing time, and the dwindling availability of particular wood species [3, 4]. Carbon fibre composites are specifically well suited for instrumentation owing to their high rigidity and low specific weight [5]. However, study is still required to understand the influence that several variables, such as fibre orientation, fibre type, and others, have on the sound generated.

At present, the primary difficulty is that composite-produced guitars have a worse tone than their wood counterparts [4]. The potential for wood has already been maximised through years of craftsmanship by luthiers (wood has been used since ancient Egyptian times). However, although the potential for composites is tremendous, it is still a novel method and thus requires a lot of study [6] and work to be done in order to allow the measurement and prediction of sound quality. This also involves the linkage of design modifications tied to particular sound quality enhancements [7].

To improve the sound of the guitar, knowledge of the energy route across the instrument is required. For example, it is vital to know that high and low frequencies may travel various courses through the guitar and that it affects the vibrations and sound production [7].

The objective of this thesis is based on the idea that if we restrict all the design variables from the guitar and try to approximate as closely as possible a carbon-based material to tone woods in terms of engineering properties, natural frequencies, and damping, the rest of the work is of the luthier, and a similar guitar can, in theory, be made with the same acoustic properties of wood guitars. This leads to the requirement to estimate the technical qualities of the carbon as well as the dynamics of the material, such as damping, natural frequencies, and modal shapes.

2 Background: Guitars

In this chapter the history, structure of the guitar as well as some context of how composite materials have been integrated into guitars will be detailed.

2.1 History

Only a fraction of the guitar's history will be discussed here. For further details, the author suggests reading the History of the Guitar chapter in *Engineering the Guitar: Theory and Practice* [8].

The history of the modern guitar began roughly 4000 years ago, with the classical guitar as we know it only taking place in the 19th century [4].

In the 19th century, guitars were not prevalent, being mostly found in Spain. However, thanks to a group of skilled and accomplished guitarists, the instrument began to transition into a professional instrument and to spread throughout Europe. As the popularity of the guitar began to expand, the number of guitar luthiers rose with it. But even though there were several of them by the mid-19th century, one stands out. Antonio Torres is considered the father of the contemporary classical guitar [9, 10].

Along with the development of the guitar design, numerous guitar players began to perform publicly and to introduce the music and the instrument to the public [9].

On the other side of the Atlantic, at the same period, the guitar began to develop in popularity at the other extreme of the socioeconomic spectrum. Slaves were being carried from Africa to the South of the United States and brought with them their culture and, notably, their instruments. As slaves steadily adapted to western civilization, they began to embrace the acoustic guitar [9].

Christian F. Martin was one of the two driving factors for introducing the guitar in the US. Having been an apprentice in Vienna, he utilised his experience and promptly built a career as a guitar manufacturer. This form of guitar was mostly used by the slaves after the Civil War, who invented what is known as blues and gospel, and the acoustic guitar was born with them.

At the same time, in Western America, the cowboys were also using the guitar as their preferred instrument.

By the turn of the 20th century, American guitar manufacturers began to establish themselves. Orville Gibson, founder of “Gibson Brands, Inc.” began to produce guitars and acquired his name for excellent big, archtop acoustic guitars.

Around the 1920s, the guitars were exclusively acoustic, as there was no way to amplify them. Solutions for this issue began to be developed progressively. Les Paul, a musician, composer, and inventor, was one of the most recognised and significant inventors. He built one of the earliest functional electric guitars.

The electric guitar with a solid body was introduced in 1948 by Leo Fender. After this breakthrough, new designs and alterations were discovered, but the models stayed essentially regular until the introduction of the composite materials in instruments and hybrid acoustic-electric guitars. It is here that the current study is concentrated. To enhance the acoustics and to alleviate the present scarcity of quality woods owing to environmental concerns and new policies [1].

2.2 Guitar structure

For a better understanding of the sound mechanisms that compose a guitar, the structure of steel-string acoustic guitars will be explained since they will be the focus of the thesis. It is also important to understand the type of material used for each component, its purpose, and why, in order to find the best substitute for it.

The main components of the guitar are the soundboard, bridge, saddle, sides, back, neck, fingerboard, soundhole, and strings. Nevertheless, the whole composition can be seen in Figure 1.

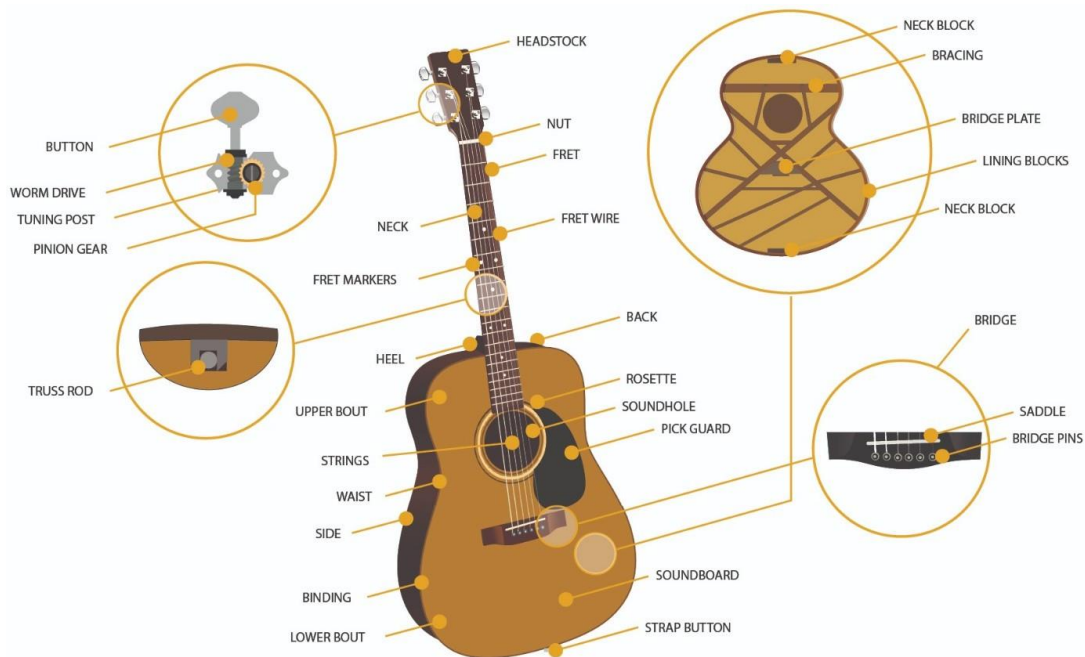


Figure 1 - Guitar components (Image adapted from [11])

In the following, we shall discuss the significance of some of these individual components.

The soundboard:

The soundboard is the major and most important component of the guitar. To it is ascribed the quality of the sound because it is via the vibration of this component that sound is formed [4].

Soundboard materials are selected largely for their density and sound efficiency. To obtain a high efficacy of sound radiation, high rigidity and low damping are essential.

The soundboard is commonly constructed of spruce or cedar wood and is built with a book-matched quarter-sawn so that the grain is perpendicular to the face of the finished top. These wood species are selected with a density of 400-500 kg/m³ and a grain direction stiffness of around 10-15 GPa. Wood is an anisotropic material, so the longitudinal stiffness would be roughly 9 to 15 times greater than the one in the perpendicular direction.

Geometrically speaking, even though its shape can change depending on the guitar model, the soundboard's thickness is usually around 2.5 mm. Also, a crucial aspect of the soundboard for simulation purposes is specifying its boundary conditions. Most guitars possess

the soundboard as a stiffening plate with its boundary conditions somewhere between clamped and simply supported.

Bridge

The bridge is a small component attached to the soundboard. It is one of the areas that the strings connect to. It serves as an effective technique to convey the vibrations from the strings to the soundboard [4]. It must be strong enough to withstand the stress of the strings, so strong and thick woods like rosewood and ebony are commonly used [12]. The common average string tension rounds between the 120 and 140 N which summed rounds the 840 N of total tension when stationary [13].

Saddle

The saddle is a piece of thick material with excellent vibration transmission, usually bone, that keeps the strings in the right place, keeps them from moving, and sends the vibrations to the soundboard through the bridge [4].

Sides

The sides are the stiff section of the guitar to enable the connection between the soundboard and the instrument's back. This portion of the instrument impacts the sound, although its importance is quite minimal, as they scarcely vibrate in the direction perpendicular to their surface [7]. So, normally it is not treated as an acoustic parameter when planning, frequently being used in poorer wood grades, acoustically speaking [10, 14]. The sides are crucial, though, as an ergonomic aspect [4].

With the influence these components have on the overall sound output of the guitar in mind, normally cheaper materials such as mahogany (when manufactured from wood) are employed for budgetary concerns. They also create fewer overtones but still offer appropriate toughness [12]. However, a greater assortment of woods is available for this use.

Back

The back of the guitar impacts, primarily, the low frequency patterns of vibration. These modes control the air produced and transported within the instrument, which has consequences for the music created [4]. The back, coupled with the top and their connection, are the key elements for the characterization of the instrument as an air pump. When the settings are adjusted for an efficient air pump, the energy needed to reach larger amplitudes is reduced.

Strings

The strings may be produced from many materials, such as Polyamide PA (Nylon®) or steel. The strings are a vital part of the music because it is via their vibration that the entire sound is created, and the vibrations spread to the rest of the guitar.

Neck

The neck is the section that comprises the fretboard, which in its turn is separated into the various frets. In the neck, mainly in acoustic guitars, there is, in its middle, the truss rod (it is a bar or rod made of steel that passes through the inside of the neck, below the fingerboard) used to regulate the neck relief and angle.

Braces

The braces are a series of reinforcements for the soundboards, and occasionally the back as well. Their major function is to support the wood but also disperse the stress across the soundboard. It can thus be recognised that various bracing patterns create different reinforcements, and it has an impact on the vibration of the soundboard and, subsequently, on the vibration modes. There are numerous classic bracing designs that are regularly employed. Other patterns exist as a tiny adjustment to the bracing alters the sound, hence each luthier may have his own particular choice of preference. This shift is vital to consider and it was determined that the bending stiffness that a specific bracing arrangement may provide to the soundboard is cubically dependent on the height and linearly dependent on the width of the braces [4].

In the case of steel-string guitars, which originated from the classical ones, it was determined that the tension of the strings demanded the body to have greater rigidity than the nylon ones. Christian Fredrich Martin (founder of “C.F. Martin & Company”, a renowned guitar manufacturer), devised the X-pattern bracing design that is still employed by lots of luthiers today [4, 10]. An example of x-bracing can be seen in Figure 2, while an alternative example is shown in Figure 3.



Figure 2 - X-Bracing on a Cutaway Taylor Acoustic Guitar [15]



Figure 3 - A Lattice-Braced Top by Chris Pantazelos [15]

The quantity of reinforcements offered by braces is also crucial, as over-built guitars have a poor impact on the melody playing and under-built guitars make distinct tones harder to identify [4]. Moreover, underbuilt guitars are vulnerable to mechanical failures and environmental factors, while over-built guitars typically sound quite brittle and might even result in a demand of amplification to hear the guitar.

In the long run, a composite guitar may not need bracing because the layup can be made so that it has the right amount of stiffness.

2.3 Composite materials in guitars

There are a variety of composite material-based solutions for many instruments. For example, in 2006, Pipe Makers Union LLC released the “Carbony Celtic Winds”. This consisted of a series of bagpipes, whistles, and flutes manufactured from carbon composites [16]. But from now on, more attention will be paid to guitars, since that's what this thesis is about.

In the 1960's Charles Kaman was one of the first to notice the possibilities composites offered in musical instruments. This engineer who founded Ovation Instruments (now Ovation Guitar), has another company in composites called Kaman Composites responsible for various breakthroughs [16]. He became one of the first to create and market a guitar manufactured with a glass-fibre reinforced composite body. The outcome was demonstrated in 1966 with the Ovation Roundback [16].

Carbon fibres composites have been used in guitars since approximately 1970 for prototypes and restricted editions. In 1975, a carbon fibre composite top plate was shown at a conference of the Acoustical Society of America [17]. Around the same time, in the 1970s, Ovation became the first business to create a guitar with a carbon fibre composite soundboard [16, 18]. A few years later, in 1995, RainSong's guitars started to build graphite guitars on a small scale and steadily expanded, becoming the first company to mass produce carbon fibre composite guitars (around 10 a month) [17].

The following decade, in the early-to-mid 2000's, guitars manufactured from carbon fibre started to become mainstream. They are starting to be created by more companies like RainSong, BlackBird (who developed the first totally hollow single-piece body carbon fibre guitar in 2007), Composite Acoustics, and Emerald [19].

Luis & Clark Stringed Instruments has been manufacturing and claiming to have sold more than 1100 carbon fibre composite instruments since the 1990s. This company also offers violins, violas, and bases [16, 18].

In 2022, Katashi Instruments launched the Karen Ultralight, a 3D printed electric violin with a futuristic frame made from recyclable polyamide and a birchwood fingerboard for a more familiar playing experience. This model has a relatively hollow body made through generative design, which still provides strength with minimal use of material [20].

Currently, the majority of composite materials used in instruments are fibrous polymers such as carbon fibre, aramid, Polyamide PA (Nylon®) fibre, and glass fibre [18]. There are a few composite acoustic guitar producers on the market, including RainSong, which employs a graphite composite for their instruments: Ovation, which uses a patented Lyrachord material of glass filament and bonding resin to manufacture its distinctively shaped guitars; Blackbird, which makes carbon fibre travel guitars; and Peavey Composite Acoustics, which also employs carbon fibre. Luis and Clark produce carbon fibre violins, violas, cellos, and basses [18].

In light of all these innovations and advancements, a major question arises: what are the differences and advantages of using composite materials instead of wood? Wood has been used for decades; therefore, arguments for shifting must be sufficient to overcome the inertia of history.

Some popular reasons to choose carbon fibre are [19]:

- Carbon fibre composites are more durable than wood and is not often harmed by bumps and bangs.
- Carbon fibre composite guitars are water resistant, immune to harsh temperatures and humidity, and have great tuning stability.

- A carbon fibre composite equivalent guitar will be much lighter than a wooden one.
- Wood has been demonstrated to attenuate frequencies at certain levels, leading to a guitar tone possibly turning muddy. This isn't the case with carbon fibre composite; meaning the tone will be crystal clear from the highest notes to the lowest.
- Long-lasting setup: carbon fibre composite keeps its form extremely well due to its durability, so once cast, you can be guaranteed of precise intonation without the neck bending, bowing, or twisting under the strain from the strings—meaning no adjustments, or expensive trips to the luthier.

However, not everything is better in carbon fibre composite guitars. There are also some downsides, such as [19]:

- Carbon fibre composite carries heat far better than wood does—meaning whenever users are playing outdoors in full sunlight or in frigid weather, they could notice their guitar growing hotter or colder, making it difficult to play.
- Carbon fibre composite is reported not to generate an attractive tone and to sound empty, lacking the richness provided by wooden instruments.
- Wooden guitars tend to be louder and generate more sound in contrast to their carbon fibre composite cousins. This isn't a problem if you're playing with it plugged in, but might be noticeable if you're playing purely acoustic.
- Differences across guitars and playing styles aren't as evident as the complexity of wooden instruments, which means nuances between different guitars due to the wood ageing or growing or altering, or the nuanced sounds you can get out of wooden guitars with sensitive playing depending on the instrument are not present
- The aesthetic of the carbon fibre composite weave might be a turn-off to certain players.

3 Literature review: Guitars

The dynamic behaviour of the guitar will be described in this chapter. This behaviour is of the utmost significance due to its tight relationship to the sound generated. While referring to the behaviour in general, component dynamics such as strings and the "sound box" formed by the empty space within the guitar will be discussed in more depth.

The majority of research conducted to describe stringed musical instruments has been focused on violins owing to the instrument's historical popularity, longevity of existence, and uniformity of production. In order to make certain progress, the violin and guitar were matched in several instances as having equal responses.

Here, the guitar acoustics as a whole will be explained as well as how and what influence some specific components have on the sound produced.

3.1 Physics and Acoustics

It is common knowledge from observing a guitarist or playing a guitar that the sound begins with the plucking of one or multiple strings. However, the sound mechanics that transform the strumming of the string(s) into the sound we hear are much more complicated. Understanding the fundamental dynamic response of the structure is the first step to understanding the instrument and how it generates sound [9].

Any moving surface, including the surface of a guitar body, may create sound. To be more explicit, the pressure created in the surrounding air is proportional to the moving surface's velocity, as explained by the Bernoulli's equation (Equation 3.1).

$$\Delta p = \frac{1}{2} \rho (V_2^2 - V_1^2) \quad 3.1$$

p as pressure (N/m²)

ρ as density (kg/m³)

V as velocity (m/s)

Another technique of making sound is to push a volume of air at a resonant frequency, causing the air to vibrate by compressing and expanding. We shall explore further in this chapter how this might alter the sound.

In the case of acoustic guitars, sound is transmitted by radiating it from both the soundboard and the soundhole [15], and so the responsiveness of the body and the body's interaction with the air are both vital. In other words, adding to the regular process of body vibration in acoustic guitars, the contact between the air within the body and the body is an essential issue to consider.

When contemplating dynamic behaviour and vibrations, two ideas must be properly differentiated. The natural frequencies emerge first, followed by the mode shapes. Both are equally significant, but in a manner that complements each other. The natural frequencies pertain to the body's fundamental vibrations and the rate at which it vibrates when disturbed, and the mode shapes characterise the deformation the component would exhibit when vibrating at the natural frequency.

Natural frequencies are the frequencies that may translate a low-level force input into a response with a bigger amplitude. Simply explained, they are the frequencies at which the material or structure has a preference for vibrating. These may also be termed eigenvalues, as the resonant frequencies are answers to the eigenvalue equation that originates from structural models of instruments. Every material and elastic structure has its own inherent frequencies [7, 9]. The resonant frequencies are not considered the property of the system as they are highly affected by surrounding media or damping media. This is basically the real natural frequency that can only be measured experimentally.

Full-sized acoustic guitars often feature a first body resonance in the 95–105 Hz range and a second body resonance in the 190–210 Hz region. Many luthiers have target frequencies, but no one can agree on what they should be.

The mode shape is the form that comes from the vibration of the structure when excited at the natural frequencies [9]. It is the vibrational form that a structure develops when energised by a given frequency. In this pattern, there will be lines (node lines) that don't move, which are the kind of bending points for separating the sections that vibrate in various directions either up or down. Acoustic guitar physics explanations commonly reference monopole and dipole modes; thus, a brief explanation is needed. Monopole modes feature just one antinode (the region of greatest displacement in a standing wave system) and no internal node lines. Dipole modes are characterised by two nearby areas that move out of phase with one another and are separated by a node line [7].

These forms produce diverse patterns which might be labelled Chladni patterns. These forms are significant as they offer feedback on the sound produced. However, the relationship between, for example, the Chladni patterns of a soundboard and those of a full guitar is hard to generate. A lot of study has been done on these empirical links between free plates and the finished instrument, especially for violins [10, 21]. Nevertheless, there are final changes that may be made to a fully assembled guitar to modify these patterns.

The first mode shape, sometimes known as the breathing mode, is one in which the top and back move in separate directions, causing the interior volume to fluctuate as the body vibrates. This causes the soundhole to generate low-frequency sound. The second mode is identical to the first, except that the top and back move in tandem. This causes the top to emit more sound, while the soundhole generates significantly less. Typically, the third mode is the first with a centre node line [7]. These first three mode forms may be better understood by referring to Figure 4, in which they are shown.

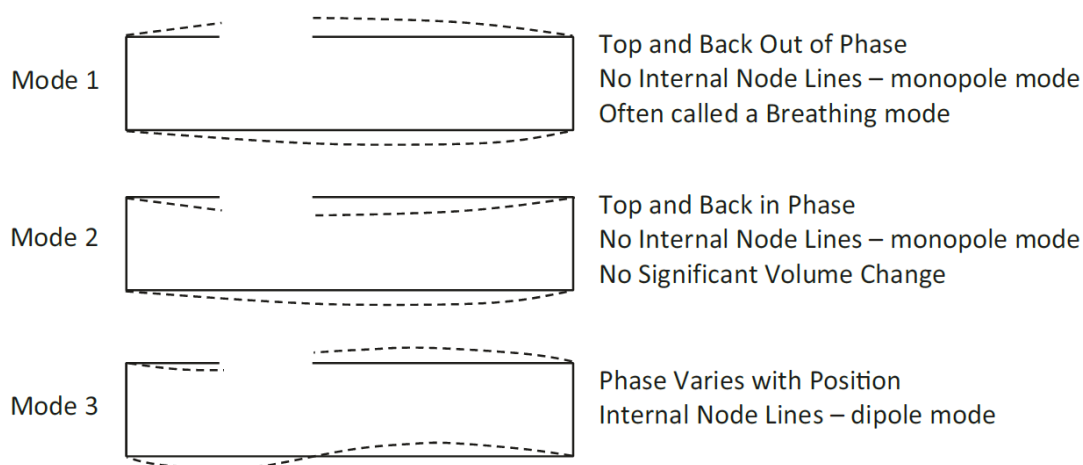


Figure 4 - First three modes of most acoustic guitars [7]

In terms of the guitar modes, Christensen says that T(1,1), T(1,2) and T(3,1) are the main radiators of sound. But it is agreed that the first mode is the biggest contributor to the sound radiated [22].

Vibrations

Before delving into the mechanics of how acoustic guitar structures vibrate, it's crucial to grasp the fundamental role structural vibrations play in acoustic guitar sound production processes.

Vibration is the fundamental foundation of the guitar's functioning since all the energy is supplied by the vibrating strings to the guitar's flexible structure. We then need a way to present this dynamic behaviour. The most common way is by using the frequency response function (FRF). In order to collect and analyse this data, it is common to excite the structure and measure the motion using an accelerometer. The data is then mathematically transformed into the frequency domain and is presented in its final form as the FRF [7, 15]. This data transformation of the recorded data by the accelerometer into the frequency domain is done using the Fast Fourier Transform (FFT). This way, the resonant frequencies can be seen and analysed based on the data recorded by simply exciting the structure [7, 15].

There are several ways this excitation can occur. The most common is using a small hammer that hits the structure at a single point. However, that leads to results that only show the dynamics of the instrument in the middle of the driving point and the response point. This can be minimised by taking data from a collection of points, but it takes a long time and requires expensive software.

With all the knowledge gathered so far, it is tempting to believe that a FRF may predict sound quality since it would correlate the vibrations (the basis of the sound) with the sound produced. They are undoubtedly connected, and several luthiers have investigated such connections. However, there is still no solid definition of measured guitar sound quality and no piece of literature that consistently links sound quality to specific elements in FRFs [7].

Still, inside the vibration topic, the vibration of a string is the most important element when one wants to understand the behaviour of the instrument. It has been seen that the starting point of a guitar sound is the plucking or strumming of one or more strings, and so the starting point in terms of components and their influence on the sound will be a single string.

A string is a simple structure with a special feature: the resonant frequencies are integer multiples of the fundamental [9]. The expression for the ideal string's frequencies is shown in Equation 3.2.

$$f_n = \frac{n}{2L} \sqrt{\frac{T}{\rho}} \quad 3.2$$

f_n as frequency (Hz)

T as tension (N)

L as length (m)

ρ as density (kg/m³)

n as number of the frequency

The modes of a vibrating string are well studied, and are easier to understand than the normal modes of the whole instrument. The single string mode shapes can be seen in Figure 5, and as can be seen, $n = 1$ is the fundamental frequency and $n > 1$ the harmonics.

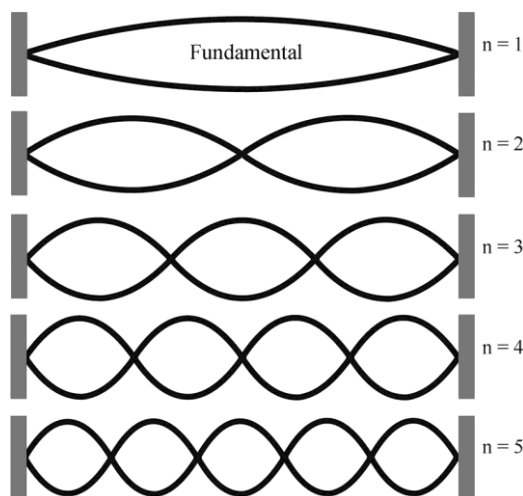


Figure 5 - String mode shapes [23]

While the ideal strings are important to understand, they do not describe precisely the actual strings. Strings have qualities that alter their response from the ideal, and these variances must be considered. Variable tension, high displacements, and non-zero bending stiffness are three key aspects that might be considered while refining the formula for real strings. When it comes to guitar strings, displacement is quite minor in comparison to length [15]. As a consequence, the tension remains rather consistent. Instead, the assumption of zero bending stiffness seems to be the biggest reason why ideal predictions don't match up with how strings act in the real world [15].

Because the equation that explains the behaviour of a vibrating string and incorporates the bending stiffness is very difficult to solve, the published answers are just approximations. Fortunately, the approximations are reasonably correct. There are two simple formulas in the literature for figuring out the frequencies of strings with bending stiffness. The easiest one, shown in Equation 3.3, is in the book "Technology of the Guitar" [15].

$$f_n = \frac{n}{2L} \sqrt{\frac{T}{\rho}} \sqrt{1 + \frac{n^2 \pi^3 E r^4}{4L^2 T}} \quad 3.3$$

When a string is plucked, the string starts to vibrate. As time passes, with the vibration, the high-frequency components of the motion disappears, and after one second or so, the sound becomes more mellow [21]. At the same time, the kinks of the string start to disappear, and the shape gradually approximates that of the fundamental mode of vibration.

Once we understand this, we can start to look into how the sound of an acoustic guitar is actually made.

Whole guitar acoustics

Now that the fundamentals of vibration and notions such as natural frequencies and mode shapes are grasped, further steps may be taken to comprehend the whole guitar system.

It is now possible to describe the interactions and effects between the string, soundhole, and body.

One widespread fallacy is that only strings vibrate and that the sound emanates from the soundhole when, in fact, the whole body vibrates while it is played and only some portion of the sound comes through the soundhole. Generally, it derives from the soundboard vibration, more specifically, from the lower bout (see Figure 1) [10].

A vibrating object can only make sounds if the motion of the body causes pressure waves in the surrounding air. As the strings don't displace much air, their movement generates minimal sound (this can be noticed especially in electric guitars as the sound with no amplification is exclusively obtained from the strings) [15].

The original power, however, originates from the strings, and it may be claimed that all the energy that manifests as sound comes from the strings [7]. The energy flow of a guitar is illustrated in Figure 6. We can notice that the sound originates in the strings and that the top plate has the biggest effect.

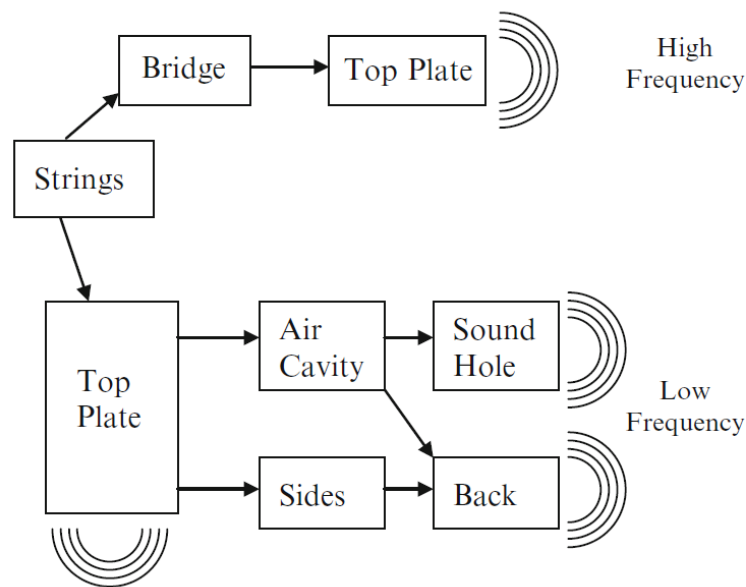


Figure 6 - Schematic of Energy Flow in a Guitar [24]

String frequencies determine the overall vibrating motion of the instrument. Furthermore, the purpose of instrument structural dynamics is to vary the instrument's response to the same initial force [7, 15, 21]. To put it another way, the structure serves as a filtration system. The energy that enters the system is released as the guitar's resonant frequencies. When the strings are damped and the instrument is free to react, the response is dominated by the structure's natural frequencies. On the other hand, when strings are allowed to vibrate, the effect is predominantly the strings' resonant frequencies, with alterations of the body and neck [7].

Throughout this chapter and the following chapters, the term coupling will appear several times, and so it is necessary to say that, from here on, it will be used to allude to the vibration interaction between two or more components [21].

A sequential explanation will be provided, beginning with the plucking and concluding with the produced guitar sound. However, since there is no sequential route in real life since, as everything occurs simultaneously, an imagined sound path will be developed to aid comprehension of this process.

A single string causes the saddle to vibrate, so it is reasonable to assume that it also influences and creates a little vibration in the other strings, generating harmonics and producing

a more complex and rich sound. Considering that all six strings are often played simultaneously, we may begin to appreciate the complexity of sound produced by strings alone.

After the string is plucked or strummed, the vibration is carried to the saddle, which conveys it to the bridge and finally to the soundboard, which amplifies the sound together with the rest of the body. The soundboard also carries the sound to the sides and rear.

Acoustic guitars' dynamic nature is heavily dependent on the air trapped by the body. It may even be argued that the low-frequency sound of an acoustic guitar is greatly impacted by the lowest resonance frequency of the air within the instrument body. The sound is created by the air displaced inside the body as a consequence of the simultaneous vibration of the back and top plates. Due to the air inside having mass and stiffness (because of its compressibility) and the capacity to transmit waves, it interacts with the vibrating structure around it. This creates a circular cycle, making sound prediction and modelling more difficult. Luthiers instinctively comprehend by experience how the volume held by the body and the size of the soundhole affect the sound and adjust those values to accomplish tonal objectives [7].

It can be concluded then that the sound system is quite complex. Any minor change in any of the components changes its interaction with all the other components, which modifies their reaction with other components they interact with or have influence over and so on [21]. This circular cycle is illustrated in a simpler way in Figure 7.

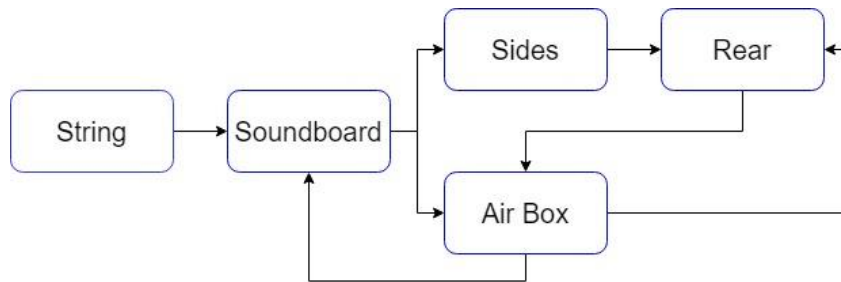


Figure 7 - Guitar sequential sound mechanism

The air within impacts the sound with greater effect in the lower range of the instrument than in the upper range. It operates, in a similar manner as when someone blows over the top of a bottle, there is a slight vibration of the air (Helmholtz oscillator). The air inside the body is related to the lowest of the resonances of the top plate (80-150 Hz) and, to some degree, it connects the motion of the top and rear plates [6, 21]. The Helmholtz resonance of the guitar is created by the springiness of the air within the body and is the lowest resonant frequency [6]. This resonance frequency is provided by Equation 3.4.

$$f_H = \frac{c}{2\pi} \sqrt{\frac{A}{VL}} \quad 3.4$$

f_H as frequency (Hz)

A as area (m²)

L as length (m)

c as speed of sound (m/s)

V as volume (m³)

The “air box” (space inside the guitar) works as a Helmholtz oscillator because when the soundboard vibrates, air tends to enter the space within the body. When this occurs, the air compresses and pushes a small amount of air out of the body. Consequently, the momentum forces air back in, generating a cycle and vibrating like a spring. The movement of the body also assists with this process, creating an even larger pressure. For frequencies below the Helmholtz resonance, the soundboard and air are in phase with it, while for higher frequencies they are in opposing phases [25].

Currently, there is no straightforward way to estimate the resonance frequencies of the body or air. Calculating them for the body combined with enclosed air is, as one would think, more complex. They are almost always measured in practice, but this may change as analytic and numerical tools evolve.

The sound quality of the guitars is thus largely impacted by the body and soundboard, as it is their vibration that enhances and alters the sound. The bigger the body is, the more air particles may be retained within the chamber, and the louder the volume is created. However, the size of the soundboard and body is not all there is. For example, if a soundboard is overly hefty or rigid, the lower tones will not travel efficiently, resulting in a thin-sounding guitar. The more flexible the soundboard is the quicker the energy that arises from the vibration decays, yielding a louder sound. The soundboard boosts the sound, but not in the same way an amplifier would; it only converts the energy from the strings and makes the transfer of that energy into sound more efficient [12, 14, 21].

It can be shown that the frequency is mostly influenced by the instrument's volume and soundhole diameter [6]. Two diagrams are shown in Figure 8 and Figure 9 to highlight the dynamic contrast between low and high frequencies. Here, the significance of dynamics may be better understood since we can see that, for various frequencies, different components and energy systems are employed.

Some elements of the sound, such as brittle, bright or warm, arise from the weight each frequency has on the final sound, meaning they are reliant on the mode shapes.

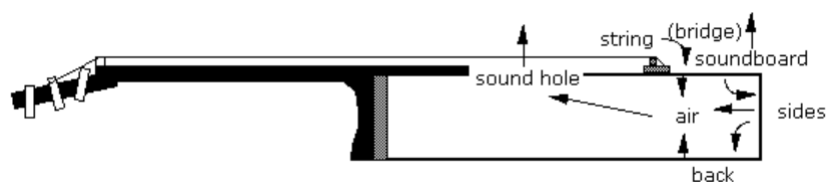


Figure 8 - Guitar dynamics for low frequencies [21]



Figure 9 - Guitar dynamics for high frequencies [21]

Adding to these dynamics, if we add the static loads as well, for low frequencies, we can see in Figure 10 that the diagram starts to get more and more complex.

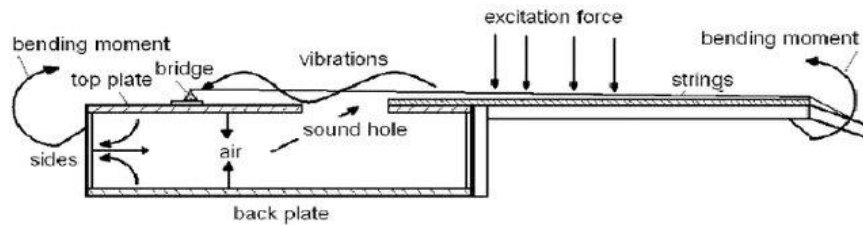


Figure 10 - Static and dynamic load of a guitar [26]

It is essential to note that, while we are mostly discussing the soundboard, the bracing is a crucial component of the top and has a profound impact on the guitar's dynamics. Since the bracing provides support and is in close contact with the soundboard, its dynamic behaviour is altered by the slight alteration of the bracing. As the guitar-building process nears its conclusion, luthiers do not adjust the bracing arbitrarily or without fundament to improve the instrument's tone.

The physics guiding the structure's and confined air's related behaviour have long been recognised, but they cannot be properly described by a few simple equations. Complex finite element models with hundreds of connected equations are needed instead. Researchers have shown that these models can accurately mimic how guitars behave at low frequencies, but they are still expensive to make and their value has not yet been proven [7].

Mathematical models

Many pieces of software exist that are able to predict performance. In particular, in the aerospace, aeronautical, and automotive industries, these pieces of software are used in order to have a clearer idea of how the product will function [7].

However, in the guitar design industry, the software doesn't work the same way, even though it exist nowadays. The physics of an acoustic guitar are well understood, and expensive commercially available software can properly replicate those principles [7]. One example of such software is COMSOL Multiphysics, a cross-platform finite element analysis, solver, and multi-physics simulation software. Using this program, mode shapes and sound fields can be calculated, for example, as shown in Figure 11.

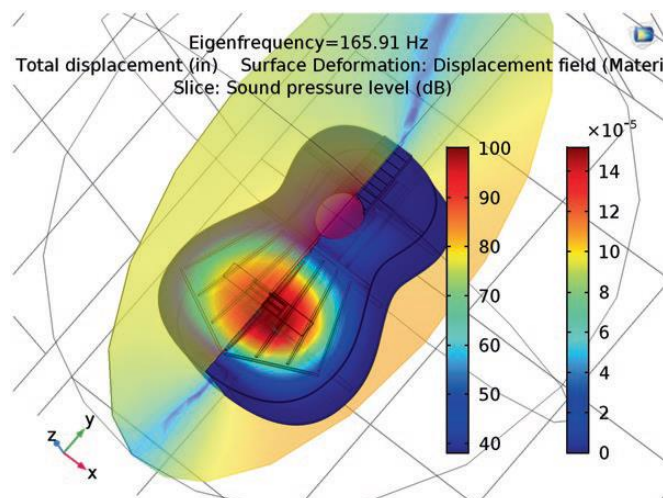


Figure 11 - Calculated mode shape and sound field around a classical guitar using COMSOL Multiphysics [7]

Knowing the complexity of the guitar system, we can understand the need for complex numerical models. However, there are simple models to approximate and describe guitar systems at their basic level. The most well-known is a basic discrete model introduced in 1980 by Christisen and Vistisen [22]. For low-frequency guitar function, the frequency response of sound pressure and top plate mobility predicted by the model are in excellent quantitative agreement with experimental data. They also discovered the Helmholtz resonance as the antiresonance in the top plate mobility spectrum. Numerous papers and books demonstrate how this model, as well as more complex variations of it, can properly duplicate the first few peaks in a measured frequency response function [7].

For several reasons, no luthiers currently make use of these pieces of software. The first is the price. The software licences are expensive because of their complexity, and it takes a long time for highly skilled personnel to create and develop these models. Because it incorporates assumptions about material qualities and other factors, the first version of the model is frequently not precise enough to be useful. Rather, it is frequently necessary to tweak it to match test results. Since manufacturers can create prototypes rapidly, creating test devices to refine a design is both faster and less expensive [7, 22].

Secondly, there is no reliable method for forecasting sound quality from computed findings. The distinctions between a mediocre and a great guitar are subtle and subjective. After the cost of creating a precise math model of the instrument, the question of what to do with it remains. It would be needed to devise a method of linking computed forecasts to sound quality [7].

Still, as computing power grows, innovations are made, and they become cheaper and easier to use, computational software will eventually play a big role in this field.

3.2 Global properties of guitars

In the previous chapters, the main components have been explained. Here we will discuss how different properties, both geometrical and engineering, influence sound.

The most influential qualities were discovered to be macro properties [4]. Knowing that, the main thing is to duplicate composite guitars' macro-properties as closely as possible to their wood counterparts, and then reproduce the structural and design characteristics.

Design properties

There is limited understanding of how design modifications affect sound and how to quantify or forecast such changes. However, there are certain broad notions that have emerged from research and years of luthier practice.

In terms of global design, it can be said that guitars are often shaped in the shape of an 8, with the top, back, and sides forming the "box" as well as the lower bout, upper bout, and waist. This general guitar look is so familiar that it can be forgotten that each design choice has a purpose for sound generation.

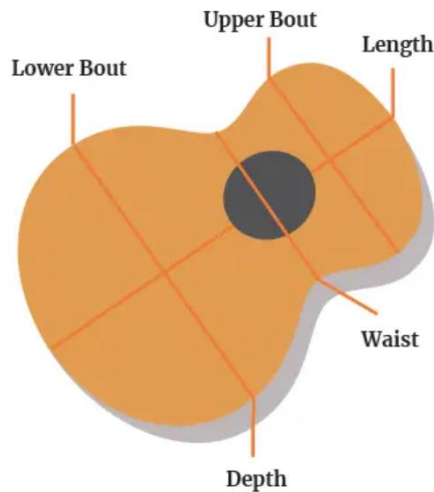


Figure 12 - Acoustic guitar bodies shape [14]

It has been found that the frequency response and loudness of the guitar are modified by the guitar's volume. Larger guitars produce louder sounds and improve low-frequency tones. The contrary is also true, owing to the air inside the body having more or less air to be mobilised [7, 14].

Also, increasing the width of the soundhole tends to raise the initial resonant frequency, roughly corresponding to the behaviour of an ideal Helmholtz resonator. However, there is no straightforward link between body volume, soundhole diameter, and initial resonant frequency [7].

The shape and size of the soundhole both have an effect on its tone [14] as they alter the way sound travels through the body.

Changes in the breadth of the waist, for example, can have an effect on sound perception. When the waist is widened, the size of the lower bout expands, resulting in an emphasis on the bass frequencies. When the waist is tightened, the sound becomes more balanced because it emphasises mid and upper-range frequencies. Furthermore, elongation with a broad waist relative to the lower bout emphasises the mid-frequencies [14]. All these variations may be traced back to alterations in the lower bout, which can be lengthened to emphasise bass frequencies or shortened to emphasise higher frequencies. In the diagram presented in Figure 13, it is easier to understand these influences.

More than just varying the shape, the thickness in different parts of the body and other properties can also be improved to enhance the modes of the soundboard [5].

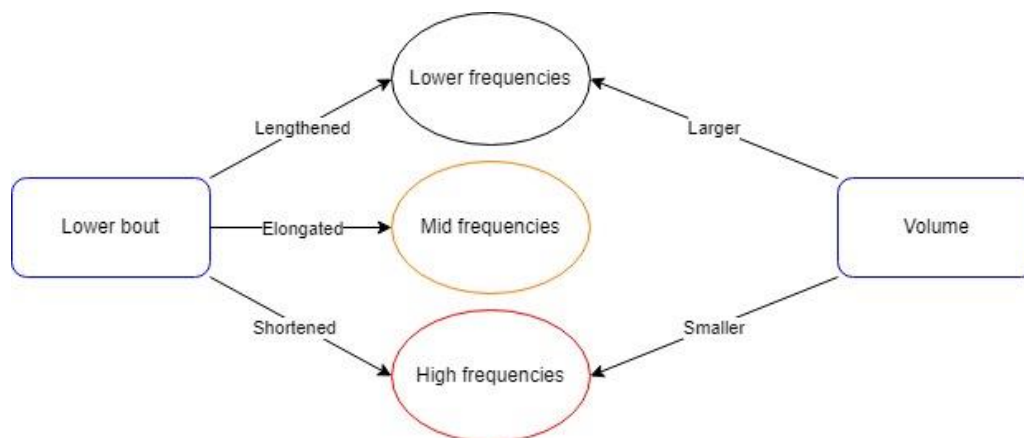


Figure 13 - Design properties influence on the frequencies

In the case of composite instruments, changing the fibre direction in the layups has a significant effect on the amplitude of the sound produced as well as on the tonal colour of that sound [5].

Important engineering properties

Not until recently, have the mechanical properties of good quality woods been under investigation. Although there is still a lot of discussion, there is some agreement that materials with a high specific modulus and low internal friction in the grain direction produce the best top plates. Nevertheless, there are a lot of engineering properties that influence the sound quality of a plate which shall be further explained in this section [3].

There is general consensus in the literature that the most important material properties for wood are its low density, large specific Young's modulus, low internal friction in the longitudinal direction (parallel to the grain), and large elastic anisotropy [27].

Also, mainly three parameters influence and determine the acoustic performance of a material: density, Young's modulus and damping [4, 28]. Together they determine the speed of sound, the eigen frequencies and intensity of the radiated sound.

In terms of acoustic properties to measure the acoustic performance, the most important are the speed of sound within the material, the acoustic impedance, the sound radiation coefficient, and the loss coefficient [4, 28].

Most of these properties, as we can see in the Equations 3.5, 3.6 and 3.7 are related to the modulus of elasticity and density [28]. This gives an indication that these two engineering constants might be the most important to consider. Moreover, many physical and mechanical properties of wood are related with its density making it a critical element [28].

Density influences the velocity of soundwaves. The denser a wood is, the more volume it generates, but there is also an increase in frequency contrast and a decrease in the noise reduction coefficient. Conversely, the softer it is, the greater the wave absorption, resulting in a warmer sound with better sustain and a higher noise reduction coefficient [28].

PROPERTY	EQUATIONS [4, 28]	
Speed of sound	$c = \sqrt{\frac{E}{\rho}}$	3.5
Specific acoustic impedance	$z = \sqrt{E\rho}$	3.6
Sound radiation coefficient	$R = \sqrt{\frac{E}{\rho^3}}$	3.7
E	as Young's Modulus [Pa]	
ρ	as density [kg/m ³]	
c	as speed of sound [m/s]	
z	as specific acoustic impedance [Pa.s/m]	
R	as sound radiation coefficient [m ⁴ .kg.s]	

The acoustic impedance is used to measure the transmission of vibrational energy from one medium to another. Soundboard quality woods have a low acoustic impedance, which is beneficial to the transmission of sound to the air [28].

The sound radiation coefficient enables the quantification of the damping of a body's vibration due to sound radiation. In the example of soundboards, a large coefficient is desired if a loud sound is wished. To maximise loudness, it is required to maximise the amplitude of the vibrational response to a given force (frequency response function). After some mathematical simplifications, it can be concluded that it is simply needed to maximise the sound radiation coefficient to maximise the average amplitude or loudness [28]. Nevertheless, sound radiation and loudness are not the main characteristics of an instrument, and a too-loud instrument may even be undesirable.

The speed of sound is also important as this characterises the vibrational frequencies of the materials, and the whole basis of the study is based on vibrations.

An additional parameter is the loss coefficient, which is the energy dissipated as heat by internal friction when a solid material vibrates. Unlike the previous parameters, the loss coefficient is independent of density and Young's modulus. This parameter ranges from around 0.1 for hot, moist wood to about 0.002 for air-dried wood at room temperature [28, 29].

The Q-value, also known as the quality factor, describes how sound decay relates to frequency and energy dissipation. For every single resonance frequency (the frequency of the peak in graphical charts shown in the frequency domain) for any given material, there are a number of frequencies close to resonance that induce vibrations of almost the same magnitude. Quality or Q-factor refers to the width of the resonance curve. The less energy is lost, or "dissipated," by a system, the higher its Q-factor. This means that the system is more selective about the frequencies that will get it to resonate [10, 30].

Moving on to other properties, strength and flexibility, along with bending stiffness, are important since the wood needs to vibrate and withstand the forces applied when the guitar is played [31]. On top of that, there is a correlation between the shear modulus and the high-frequency behaviour of a top plate [3]. Also, the instrument needs to have a high anisotropy so that it can respond better to a wider range of frequencies [3].

Since there are a lot of properties to work with, there is a need to create ratios such as flexibility/strength, stiffness/density. The ratio of stiffness/density, together with a higher damping, leads, for example, to an instrument with less sound radiation, meaning less power [31].

Many of these properties are influenced by different parameters. For example, many of these important properties, such as density, Young's modulus, damping, and shrinkage, are highly dependent on the moisture content [28]. Humidity affects damping, and a relative humidity of 45-55 percent is usually considered ideal. The higher the humidity, the duller the instrument will sound. Humidity also causes structural damage since it causes physical changes on the wooden body, which can lead to tuning, intonation, and even permanent damage. One of the perks that composite guitars may have is that they are less susceptible to humidity issues.

Furthermore, the resonance of the soundboard is affected by the density, moisture, strength, and flexibility since they affect the speed of sound waves and their amplitudes [12].

3.3 Materials

It can be expected that different materials, or even the same materials but with different properties, can lead to a whole new range of sound and timbre. The use of composites enables the possibility of changing each chosen variable to arrive at a similar or even an improved material compared to the woods currently used.

Table 1 - Mechanical properties of common materials for guitars [7]

Species	Density (g/cm ³)	Modulus (GPa)
Sitka spruce	0.36	9.9
Western red cedar	0.32	7.7
Honduran mahogany	0.6	10.3
Unidirectional carbon fibre	1.7	127

In this chapter, wood, composites, and foams will be under investigation to understand their properties and composition, some history, and to get a better understanding of how the materials are made.

Furthermore, an introduction to metamaterials is made since they seem promising for the creation of an optimal solution and personalised instruments.

Carbon fibre composites will be the main material under investigation due to previous research by Max [4] and T. Ono [2, 27] having achieved good results. However, the proposed materials in this work are sandwich materials with foam as the core as an alternative to the fibre reinforced blown foam composite of Max and T.Ono's work. Different types of foams will give different results and so, in this sense, foams will also be further explored.

Wood

Wood is a natural orthotropic composite material composed of cellulose fibres surrounded by a lignin and hemicellulose matrix, which implies that it has distinct mechanical properties in each of the three mutually perpendicular axes [3]. It possesses physical and mechanical qualities that can only be matched by man-made materials, making it distinctive and a popular option for many applications [32].

Inside the wood material family, there are many subdivisions, each one with its own specific properties. Tonewood is the term used to describe the acoustically chosen woods for instruments [12].

The process of choosing wood is an important task because the wood influences the frequencies of the guitar. Usually, different types of wood are used for different components of the guitar, which then requires good compatibility between the different wood types [12].

The best woods suitable for each part of an instrument have been decided over experience and tradition between instrument makers [27]. Since wood has been used for millennia, there has been a great deal of iteration, and we can assume that the optimization of the material choice has been reached or almost reached. However, to understand the choice of wood for instruments, one needs to understand a bit about wood growth, harvesting, and some of its characteristics.

There are, essentially, two types of wood: evergreen and deciduous. The first being the trees that maintain their leaves all year-round, such as cedar or spruce. The last, on the contrary, shed their leaves every fall, and they are more susceptible to environmental conditions. When deciduous trees shed their leaves, their growth spree is decreased and the result is a more dense and harder wood, giving them their common name of “hardwoods” [12].

Hardwoods are essentially unsuitable for soundboards since they are denser, which means more energy is required to extract the same level of vibration as other woods. Mahogany is an exception to this rule, and it is regularly used for soundboards. Nevertheless, it is a softer hardwood than most hardwoods [12]. On the other hand, soft woods cannot usually be used since they don’t have enough strength to handle the forces in action on the guitar.

Historically, the best solutions found were some softwoods that have a good flexibility and tensile strength ratio. Spruce is an example of such a wood. The use of soft woods is the reason why acoustic guitars usually require pickguards (components inserted on the outside of acoustic guitars, often on the surface of the soundboard under the soundhole) [12].

Woods for soundboards are especially hard to choose since they require a high speed of sound and a high sound radiation coefficient, but also because soundboards are the main vibrator and influencer on the guitar sound [28].

In Table 2, some examples of common wood types for several guitar components are shown. Spruce is the common choice for soundboards since it has great availability, it ages well, and it sounds better with the passing of time. It is also light and has a good flexibility/strength ratio, resulting in a more wide and dynamic range [3].

Table 2 - Common wood types for different guitar components [7]

COMPONENT	WOOD
Soundboard	Spruce, Cedar, Mahogany, Walnut, Koa, Cocobolo
Back	Mahogany, Rosewood, Maple, Walnut, Koa, Cocobolo
Sides	Mahogany, Rosewood, Maple, Walnut, Koa, Cocobolo
Fingerboard	Rosewood, Maple
Neck	Maple

Sustainability poses the biggest threat to these materials being used for guitars. Scarcity of wood is beginning to occur as rules and regulations for wood cutting become more stringent. Slowly, guitar materials will have to change since scarcity makes the wood more expensive. Composite materials may solve this problem.

Foams

Foam is ubiquitous in our daily lives. The processes that produce most food, detergents, and plastics depend on them. Foams are also often used for cushioning and packaging and to protect against impact. Some examples of everyday foam are dough, coffee cups, coolers, to-go boxes, plates, and bowls.

Foams are mostly bending structures with simple combinations of solids and gases. They are created by inflating polymers, metals, ceramics, or glasses with a foaming agent. This means that gas is injected into one material, much like yeast does in breadmaking [33].

In comparison to other engineering materials, foam typically possesses a relative high strength-to-weight ratio as well as superior acoustic and thermal insulation qualities.

As indicated in Figure 14, foams may be divided into three major categories: two-dimensional (2D) honeycombs; three-dimensional (3D) open-cell configuration; and three-dimensional (3D) closed-cell configuration [34]. In open-cell foams, the cells are linked by struts and the cell walls are shattered, allowing fluid to travel between the cells. In contrast, the cells in closed-cell foams are completely surrounded by cell walls, preventing fluid movement. The closed-cell arrangement is often more durable than the open-cell configuration [34].

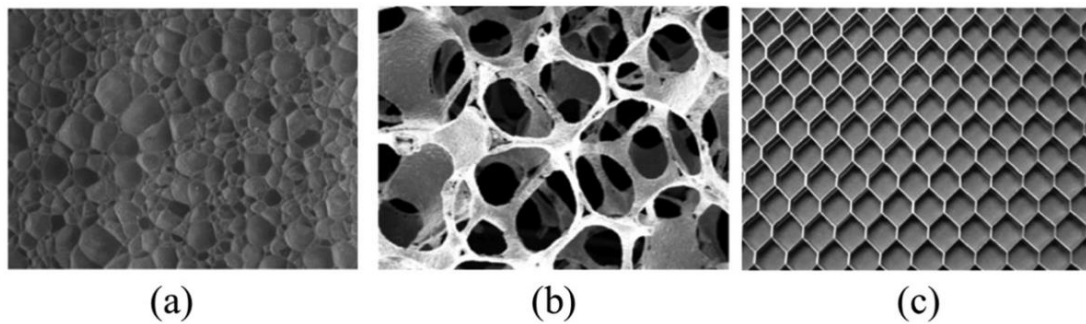


Figure 14 - Cell structure of foam material (a) closed cell - (b) open cell - (c) honeycomb [34].

Figure 15 depicts an idealised low-density foam cell where it can be seen that the cell is made up of solid cell walls or borders around a void holding a gas or fluid [33]. Foams possess the feature that, when loaded, their cell walls deform, resulting in the effects seen in Figure 15 [33].

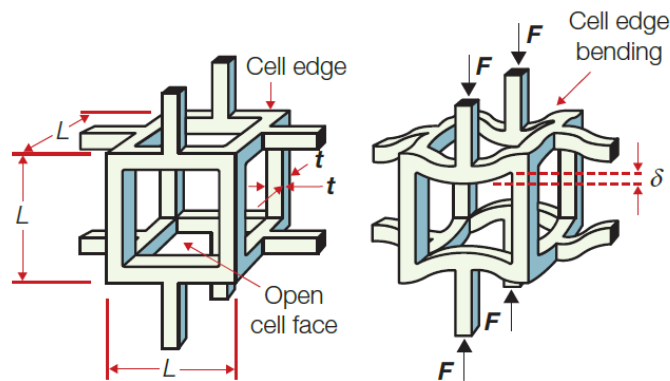


Figure 15 - A cell in a low-density foam. When the foam is loaded, the cell edges bend, giving a low-modulus structure [33].

The mechanical response of foam material is determined by the cell microstructure, including cell size and cell topology, bulk material parameters, and foam density. The effect of cell microstructure on the behaviour of foam materials is a result of the fact that the deformation process of foam material at the cell level is regulated by bending and stretching of the cell wall, followed by buckling and tearing in the post-yield stage [34].

In general, foam materials are not used in situations where tension and shear loads predominate. Nonetheless, they are often used when compression loads are anticipated. The ability of foams to withstand significant strain deformation while maintaining a low constant

stress level is the most desirable characteristic of foams prior to the densification zone. Furthermore, open-cell structures are good at sound absorption.

Now, a few examples of foams with engineering applications will be explored.

Polyvinyl chloride (PVC) foam

PVC foam, commonly known as polyvinyl chloride foam, is a robust, free foam PVC sheet material with closed cells. Due to its great adaptability, PVC foam is perhaps one of the most commonly used materials in the world [35].

This material is simple to manipulate and may be sawed, die-cut, drilled, or bonded to satisfy the requirements of a variety of applications. PVC foam has several benefits, including outstanding impact resistance, high strength, excellent durability, minimal water absorption, good corrosion resistance, and fire resistance, to mention a few. These advantages make this material ideal for withstanding all sorts of indoor and outdoor situations, including severe weather. PVC foam is an excellent alternative to other materials, such as wood or metal, and it can often last for forty years without degrading [35].

PVC foam may have a wide variety of properties, including stiff or flexible foam types. It is possible to generate both open and closed kinds of cells. On the one hand, extrusion operations are used to create sheets and rolls, while on the other hand, PVC may be foamed at atmospheric pressure to create, for instance, wallpaper or synthetic leather. PVC foams have excellent chemical stability, fire retardancy, and weather resilience, making them valuable for maritime applications, for example [36].

Some of its applications are architectural columns, decorative shutters, store fixtures, shower pans, furniture, outdoor kitchens, and other anti-microbial solutions, marine upholstery substrate, swim platforms, coring material for backing plates, and cup holders, to name a few [35].

Rubber foams

Rubber foam is not created from plastic but rather from rubber, despite being classified as a foam. There are several varieties of rubber foam available:

- NBR (nitrile butadiene rubber)
- EPDM (ethylene propylene diene monomer)
- Standard caoutchouc

EPDM rubber, a form of closed-cell rubber is a highly insulating rubber foam. It is highly soft and has a smooth surface, making it flexible and simple to construct as pipe insulation, for example. EPDM rubber foam is susceptible to disintegration when exposed to light, oxygen, and heat. Due to this deterioration, indoor applications are preferred, and the product's state and function should be evaluated periodically [36].

Polyurethane

Polyurethane or PU foams are widely used, primarily for furniture padding, mattresses, seats, and textile backing [36]. It is also used in the walls of most refrigerators and freezers (low density flexible foam), automotive and truck seating (low density rigid foam) as well as electronic parts (hard solid plastic) [37]. In the polymerization of polyfunctional alcohols with isocyanates, an expanding gas is entrapped to produce PU foam. The kind of polyol employed

largely determines the product's qualities; depending on the manufacturing procedure, closed or open cell structures may be produced [36].

The physical properties of PU foam are often categorised by their associated densities [36]. Moreover, due to its crosslinked nature, it is difficult to recycle PU foam. At the conclusion of its useful life, PU foam is often chopped into foam flakes that are utilised to create fresh PU-sheets [36].

Polyethylene (PE foam)

Polyethylene is a member of the polyolefin family. It is one of the most extensively used plastics in the world and it is the foundation of polyethylene foam. It has a variety of applications, including insulation, sports equipment, the automobile sector, packaging, and the footwear industry [36].

PE foam generally has a closed-cell structure. While open-cell PE foam is possible to make, it is quite uncommon. Furthermore, crosslinking polyethylene may enhance material strength [36].

The benefits of PE closed-cell foam are its low weight, durability, and flexibility. In addition to being resistant to water, dampness, and chemicals, its vibration dampening and absorption properties make it very durable. PE's thermal and acoustic insulation properties are also exceptional [36].

It may also be moulded or thermoformed into a three-dimensional structure and be laminated to thicknesses of great magnitude.

Polystyrene (EPS and XPS)

Polystyrene foam is made of polystyrene, as the name indicates. The production can be started by filling gas filled beads into a heated mould or by extrusion of polystyrene by injecting expansion gas into the extruder. Extruded polystyrene insulation (XPS) and expanded polystyrene insulation (EPS) are widely used in a variety of applications, including construction, automotive, and packaging. As it is a quite stiff foam type, it is preferred for applications which do not require high flexibility and resistance against creeping under load. It has many benefits, including being cheap, clear, stable in size, and adaptable to radiation sterilization [36].

Thermoplastic elastomer foam (TPE foam)

TPE foam encompasses a wide variety of foam kinds. By mixing different elastomeric and thermoplastic raw materials, the qualities of the end product may be significantly altered. TPE materials have been developed to replace natural rubber since natural rubber resources are limited. Compounding the TPE material requires specialised knowledge. Sealings and gaskets with high mechanical requirements are common [36].

This material is naturally transparent but can be coloured, as can be seen in Figure 16. Its applications are cups and plates, and in its expanded form it is used for packaging [37].

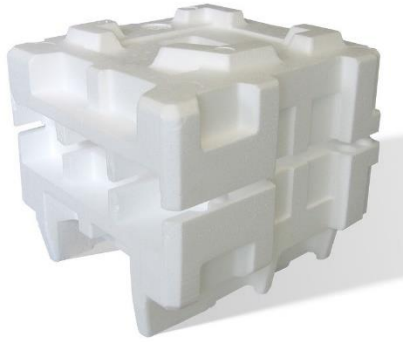


Figure 16 - Polystyrene foam [37]

Composites

The expansion of the number of applications worldwide has forced the creation of materials with special features that do not coexist in nature. The solution was the creation of composite materials. A large part of composites emerged in order to increase combinations of mechanical qualities such as stiffness, toughness, and ambient and high-temperature strength [38].

Composite materials are, essentially, any multiphase material that displays a significant proportion of each component phase's properties, resulting in a superior combination of features [38]. In “Materials Science and Engineering: An Introduction” [38], the authors dubbed this the principle of combined action. Accordingly, the combination of two or more materials leads to improved property combinations. Composites may be multiphase metal alloys, ceramics or polymers.

In terms of composition, composites are formed by two phases: the matrix, which is continuous and covers the other phase (the dispersed phase). The characteristics of the composite are a function of the properties of the component phases, their relative quantities, and the geometry of the dispersed phase. By geometry, it means the form of the particles and the particle size, distribution, and orientation [38].

As can be seen in Figure 17, composites can be classified into four sections: particle-reinforced, fibre-reinforced, structural, and nanocomposites. The first has the dispersed phase's particles in the same dimensions in every orientation; the next has the dispersed phase in the form of fibres; the third is multi-layered and created to have low densities and excellent structural integrity. The last has the scattered phase particles on the order of nanometres. For musical instrument applications, the most commonly used are particle-reinforced and fibre-reinforced.

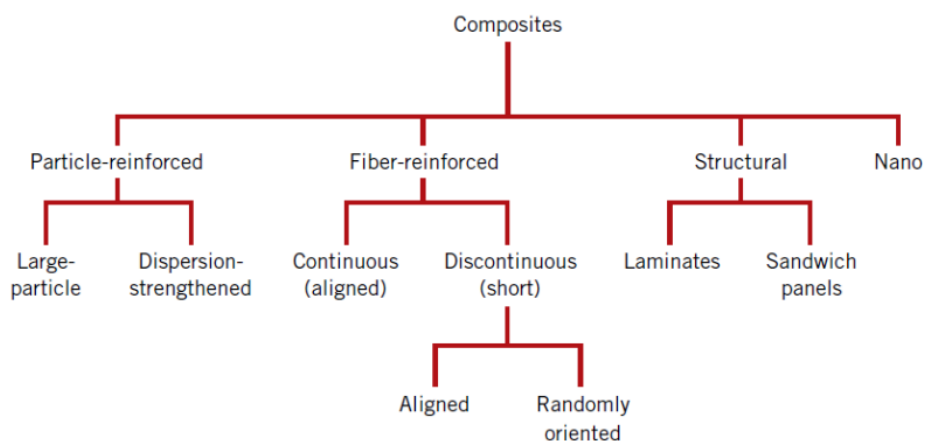


Figure 17 - A classification scheme for the various composite types [38]

A lot of research has been put into creating the perfect material for each application. In the case of composites, the main driver for innovation has been the aerospace industry. The reason for composites' being so successful is mainly due to their high specific strength, high modulus, light weight, and affordable cost [39]. Nowadays, carbon fibre composites are the most common and widely used in the engineering industry. These materials possess excellent properties such as high specific strength, high specific stiffness, corrosion resistance, and high damage tolerance [40].

For the past several decades, numerous composite materials have been studied to supplant wood as the primary material for musical instruments. Several materials such as fibreglass composites, carbon fibre composites, bamboo, and wood fibres have been explored for this application [3]. Some of them will be addressed in this chapter, with the major emphasis on carbon fibre composites because much of the research has been on those materials and because the partnered company "Everythink" already uses a carbon fibre composite in their composite electric guitars.

Further in the thesis, composite analysis will be done. One of the most important theoretical tools for composite analysis is the Classical Laminate Theory (CLT). CLT enables stress-strain analysis of arbitrary laminated systems (with plane laminae) subjected to mechanical or thermal load. With it, it is possible to account for an arbitrary number of layers, layer thicknesses, and material types (isotropic, anisotropic). Classical laminate theory allows for the calculation of stresses and strains within layers, apparent laminate properties, and overall deformation of the laminate (bending, twisting) [41].

In Chapters 7 and 8, CLT will be used to simulate materials and their properties, and Chapter 5.6 will explain more about how it is used.

Carbon fibre reinforced polymer (CFRP)

Carbon fibre reinforced polymer (CFRP) is the most commonly used reinforcement in advanced polymer-matrix composites. There are several reasons for this to happen [38]:

- They have high specific modulus and specific strength;
- They retain their high tensile modulus and high strength at elevated temperatures;
- At room temperature, carbon fibre composites are not affected by moisture or a wide variety of solvents, acids, and bases;
- They display a range of physical and mechanical qualities, enabling composites incorporating these fibres to have particular designed features.

In the most fundamental carbon fibre composites, the fibres are aligned in a single direction, which is referred to as a unidirectional laminate, comprised of a unidirectional carbon fibre arrangement and a matrix. Engineering parts that use this carbon fibre fabric possess a maximum strength in the fibre direction and are extremely stiff. However, during a layup, the fabrics can also be overlapped in multiple orientations so as to achieve strength in more than one direction without losing their stiffness. Furthermore, other fabrics can also be used for the layup to obtain different properties [42].

When compared with woven carbon fibre laminates, unidirectional fabrics are more economical since they have lower overall fibre content and a less intensive weaving process, which, except for high-performance parts, is enough to meet the requirements.

For unidirectional carbon fibres, it was found that the natural frequencies of the first four modes decrease as the fibre orientation increases. However, the influence of the fibre orientation is different for each orientation [40].

Regarding CFRP, studies found that the appearance of a twisting mode led to an increase in damping due to the increase in in-plane shear deformation. Plus, shear deformation is the main factor of damping for each mode [40].

It's important to note that these materials are a good alternative to wood because they are resistant to moisture and last a long time.

Thin-ply composites

Conventional composites are usually made of plies of material, giving a total thickness of, usually, at least 1.5 mm when cured [43].

Ply area weights of less than 100 g/m² and thicknesses of less than 100 µm are commonly considered thin plies. Thin plies of carbon fibre are usually 20–60 µm thick and weigh 20–60 g/m², while standard plies of carbon fibre are usually, at least, 125 µm thick and weigh 125 g/m² or more [40].

Standard plies are called thick plies when the thickness and areal weight exceed 200 µm and 200 g/m². Currently, the thinnest unidirectional thin-ply CFRP prepreg commercially available has a fibre areal weight of 15 g/m² [44].

Recent research indicates that thin plies have the potential to reduce structural weight and improve performance owing to their unique structural features, such as [43]:

- Enhanced damage tolerance;
- Resistance to microcracking;
- Enhanced ageing and fatigue resistance;
- Reduced minimum-gage thickness;
- Thinner sections capable of withstanding severe deformations without incurring damage;
- Enhanced scalability.

While thin-ply laminates were first created to address the damage tolerance limitations of CFRP laminates, they have since expanded the design space for laminated composites and the possibilities of pseudo-ductile composite materials. In the past 15 years, there has been a significant increase in research on these materials [43]. Nonetheless, until now, the majority of thin-ply composites have been used in relatively thin aircraft structures and high-performance sports (including racing), with niche applications in micro speakers and watches [43].

Even with some areas showing progress, these materials have not been fully explored and are still in development, particularly in the aerospace industry. For example, NASA Langley Research Centre (LaRC) and Glenn Research Centre (GRC) conducted cooperative research in support of the NASA Convergent Aeronautics Solutions (CAS) project to examine the possible advantages of using thin-ply composites in aircraft structures [43].

The primary difference between standard-ply and thin-ply laminates is their microstructure. Understanding the property changes brought about by the use of thin plies requires an in-depth knowledge of the various microstructures [44]. A reduction in the number of fibres per ply is one alteration to the microstructure that enables more flexibility in ply orientation compared to a laminate with conventional plies of the same thickness. This provides for a more homogeneous microstructure and may even aid in the minimization of voids and inter-laminar resin-rich zones during component processing [44].

Due to the spreading process and the increased number of resin-rich interlaminar layers, thin-ply laminates often have a lower fibre volume percentage than standard-ply laminates. Notably, it has been shown that the fibre volume percentages of thin, standard, and thick-ply

laminates with comparable stacking sequences are almost identical. Therefore, it is not always possible to ascribe the property changes generated by applying thin plies to the fibre volume fraction [44].

Thin plies provide new opportunities for composite structural design by allowing more flexibility in ply orientations, thus expanding the design space for composite parts. This is especially helpful for the development of thin structures, whose number of plies and associated orientations were previously constrained. The benefit of using thin-ply materials may be lessened in thicker structures [44].

Figure 18 illustrates how the use of thin plies provides more design flexibility. This could be beneficial for musical instruments. With this freedom, smarter layups are possible, and for each part, different layups with different orientations may be enough to give it the mechanical and dynamic qualities it needs.

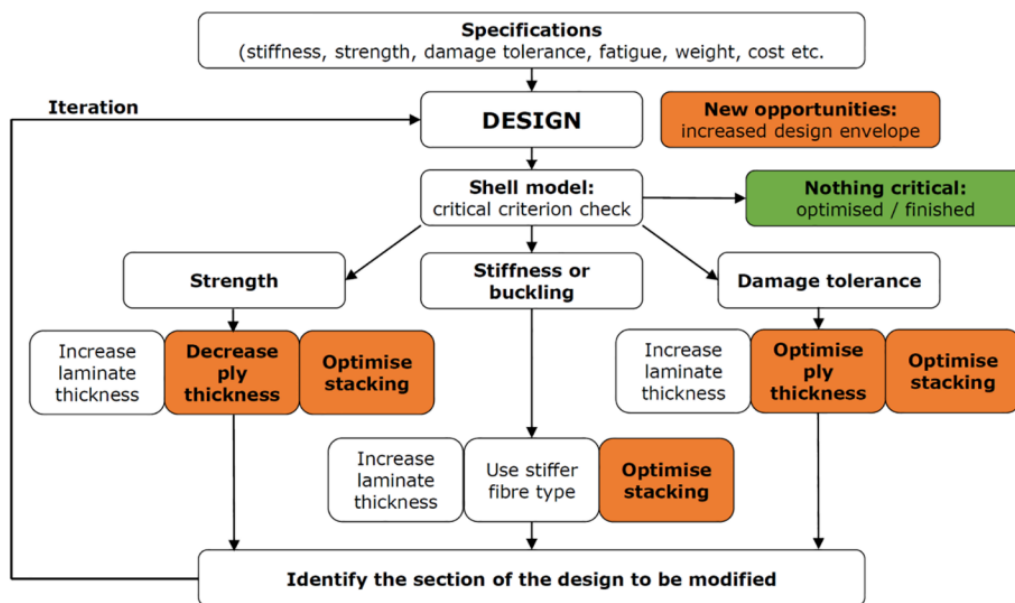


Figure 18 - Typical composite laminate design flowchart with additional opportunities enabled by thin-ply highlighted in orange [44].

When compared to laminates made with standard or thick plies, high fibre dispersion (reduced resin rich regions) in thin plies, combined with uniform microstructures and low void volume fractions, often results in benefits in a variety of mechanical properties [44].

Thin plies offer improved in-plane static and fatigue performance compared to standard-ply and thick-ply laminates. Thin-ply laminates are less vulnerable to free-edge delamination, which contributes to their increased fatigue life. Furthermore, improvements in strength typically range between 10 and 20%, and improvements in bolt bearing strengths and buckling performance have been observed in thin-ply laminates [44].

Also, in "Application of natural fibre composites to musical instrument top plates" [3], it was found that sandwich structures have "enough high bending stiffness and a low enough areal density as well as comparable internal friction to Sitka spruce."

A sandwich structure or composite combines two materials, with one material defining the faces and the other the core, to create a structure with high bending stiffness and strength at a low weight. The separation of the faces from the core increases the section's second moment of area and section modulus, resulting in a structure that is resistant to bending and buckling [33].

Sandwiches are used in situations where weight reduction is essential, such as in aeroplanes, trains, vehicles, transportable buildings, and sporting equipment. Nature also employs sandwich patterns: cross-sections indicate that the solid sides of the human skull, the wing of a bird, and the stem and leaves of many plants are separated by a foam-like core [33].

The faces bear the majority of the weight, so they must be rigid and sturdy. As they are the outside surfaces of the panel, they must also be resistant to the operating environment. The core comprises the majority of the panel's volume; it must be light, stiff, and strong enough to withstand the shear stresses required for the whole panel to operate as a load-bearing unit (if the core is much thicker than the faces, these stresses are small) [33].

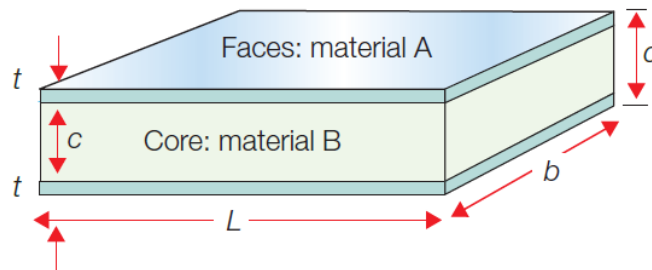


Figure 19 - Sandwich material. The face thickness is t , the core thickness is c , and the panel thickness is d .

Metamaterials

Metamaterials, which are intelligently built artificial structures, are marked by supernormal physical properties that natural materials do not provide [45].

In the sector of electromagnetism, the definition of metamaterials was first theoretically proposed by Veselago in 1968 as “macroscopic composites with a synthetic, three-dimensional, periodic cellular architecture meant to provide an optimal combination, not present in nature, of two or more reactions to specified excitation” [46]. They may be considered as a material in which its attributes are a product of its structure and not only of its chemical makeup [46].

Since then, metamaterial research has led to the creation of many different branches of metamaterials, such as electromagnetic metamaterials, optic metamaterials, mechanical metamaterials, acoustic metamaterials, thermal metamaterials, and microwave metamaterials [45].

The use of metamaterials is, by definition, trying to manufacture the optimal material for the optimal design in micro and macro design. By, for example, arranging a mass-spring-damper system along with the design of the guitar and mechanical necessities, we can, theoretically, arrive at an optimal solution [47].

Acoustic metamaterials (AMs), one of the most significant embranchments of metamaterials, consisting of a unique sort of artificial periodic super atom with subwavelength thickness, were originally found and described by Liu et al. [45, 48].

Acoustic metamaterials are artificial materials that include periodic arrangements of sub-length microstructures termed unit cells that are meant to control sound waves in a way not present in traditional acoustic materials [49]. These metamaterials have received a lot of attention over the last few decades since they enable a vast choice of new material parameters that can be used for different applications. For instance, with them, it has been possible to create small structures that can control the wavelength of sonic waves, specifically in the low frequency space [47]. The use of carbon fibres in this type of material allows for a better strength to weight ratio, allowing for better dampening since a lot of vibration absorbers raise the weight and the desired material must have the possibility of being low weight [47].

The way these acoustic metamaterials can manipulate sound is by controlling the critical acoustic properties of the material, namely the adiabatic bulk modulus and the effective mass density. The adiabatic bulk modulus is defined as the resistance to compression of the fluid medium, while the effective mass density (also called dynamic mass density) is the ratio of the force acting on a body and the net acceleration per unit volume produced in the body in the direction of the force. These two properties (also called bulk acoustic properties) are what define the speed of sound propagation in a fluid, as can be seen in Equations 3.8 and 3.9 [50].

$$\nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0 \quad 3.8$$

$$c = \sqrt{\frac{B}{\rho_0}} \quad 3.9$$

p = acoustic pressure function [N]

c = speed of sound wave in the medium [m/s]

B = bulk mass modulus of the medium [Pa]

ρ_0 = mass density of the medium at equilibrium [kg/m³]

Scope of acoustic metamaterials

If a material can be made to have one of the following characteristics, it is capable of breaching mass-frequency law:

- If a material becomes anti-resonant at desirable broadband low frequency ranges, it may function as a perfect sound blocker.
- If a material becomes resonant at specified broadband frequencies and is combined with some dissipation mechanism, it may function as a perfect sound absorber.
- If a material possesses a negative speed of sound, it may bend sound waves sharply and may accomplish reverse wave propagation.
- If a material possesses imaginary speed of sound, it will not transmit sound.

The objective of exploring metamaterials for musical instruments is to identify a material that may be uniquely created with the potential of absorbing specified and controllable ranges of frequencies [51]. When an absorbent material is coupled to the musical instrument, the sound alters through the muting or attenuation of various harmonics. Furthermore, if the

spectral content of a sound is modified perceptibly but the loudness and fundamental frequency remain fixed, we say that the timbre changes. Metamaterials might thus generate acoustically synthetic materials, termed tunable mechanical metamaterials, and with them it could be feasible to evaluate the potential of sound manipulation that they allow for the changing of the tonal characteristics of musical instruments.

Until now, metamaterials have not been particularly used in musical instruments. However, there has been research conducted in this industry for some time. Some of the research done, with particular emphasis on the authors that have been researching with musical instruments in mind, will be presented. In the review made by Liao et al. [45], the reader can further investigate the latest progress in research of AM structures.

Oñate et al. [51] investigated the use of metamaterials with squared arrays of circular holes in a silicone elastomer matrix. These materials are artificially constructed composite materials that permit modification of the dispersive characteristics of vibrational waves. These metamaterials have a negative Poisson's ratio, which means that when the structure is stretched in the axial direction, it expands in the transverse direction [52, 53]. This is different from most materials, which stretch in the axial direction when they are stretched. While studying what would happen if metamaterials were used in a dynamic system, Oñate found that soft, 2D periodic structures called mechanical metamaterials could have band gaps between 300 Hz and 1000 Hz (hearing regime), depending on how much they were deformed.

X. Xiao et al. [47] investigated the use of acoustic metamaterials with carbon fibre-reinforced polymer (CFRP) and a mass-springer-damper system to act as vibration dampers.

Also, Acoustic metamaterials could be a technique to enhance the timbre of mechanical instruments much beyond their existing sound capabilities. It was demonstrated that it was able to stretch the timbre diversity of a drum by adopting metamaterials. In standard drums, the drummer can only modify the sound by hitting different places. With this new drum, the drummer is able to make totally unique sounds by hitting the membrane at various points within the ring [54].

Tunable mechanical metamaterials may be used as a technique to produce mechanical filters that enable us to increase the acoustical characteristics of musical instruments, adjusting their tonal qualities in a dynamic and reversible manner.

However, the complexity of the envisaged AMs creates considerable impediments to manufacturing processes, which otherwise would serve as a bridge between practical usage and theoretical research and structural design. Fortunately, developments in advanced manufacturing technologies have offered new prospects for the quick expansion of AM technology [45]. Of these advances, additive manufacturing stands out, with Fused deposition modelling (FDM), a low-cost, high-speed, and simple operation technique, having become the most widely used additive manufacturing technology for making AMs.

To summarise, AMs have drawn broad attention because of their extraordinary ability to control acoustic waves. They have various unique qualities that enhance their practical applications in many domains, such as acoustic cloaking, acoustic lenses, acoustic absorption, noise reduction, and supersonic sound transmission.

But acoustic metamaterials are still a long way from being a common technology, and a lot of research needs to be done to figure out the right mechanical, vibrational, and acoustic properties.

4 Introduction to main thesis research

The core of the research conducted in this thesis arises from the conclusion that sandwich composites are promising materials for string instruments, given their suitability to tailor the specific elastic properties by properly designing the laminates of the facesheets and properly selecting the core materials and thickness. Hereafter, the focus will be on the soundboard of acoustic guitars, since it is the most important acoustic component of this instrument.

The research hypothesis resides on the principle that, if a material has the same engineering and acoustic properties as wood, it could be used to replace it in an acoustic guitar with the same design.

Firstly, the approach proposed to analyse the most important acoustic and engineering properties of the materials considered in this study is described. Having presented the analytical methodologies, a baseline of wood is established. This baseline serves as the primary reference for the proposal of a composite alternative.

In the chapters that follow, the process of composite material and layup choice is described. Once feasible choices are found, the material is produced and tested and their suitability as a substitute for wood in guitars are addressed in depth. The two materials tested were named “CarbonS-1” and “CarbonT-1” with S referring to a standard-ply composite and T to a thin-ply composite.

Finally, a discussion about the results obtained in this thesis is presented, followed by the conclusions and suggestion for future development and future research.

5 Methodology

This chapter describes the testing procedures used in this thesis for the examination of wood and composite samples. Following the explanation of this experimental methods is a description of the composite analysis approach.

The manufacturing processes for the wooden and composite plates, as well as the wooden and composite samples tested, will be described in detail.

5.1 Density calculation

The density of each sample was determined for each specimen by measuring and weighing the specimens at several places. Equation 5.1 is used to determine the sample's density using these measured data.

$$\rho[\text{kg/m}^3] = \frac{m[\text{kg}]}{V[\text{m}^3]} \quad 5.1$$

5.2 Digital Image Correlation

Digital Image Correlation (DIC) was used to monitor strain. Using a camera, this technology detects the relative movement of a speckle pattern during mechanical testing. Photographs are taken continuously during the testing of each sample, and then image correlation software is used to determine displacements and strain. Therefore, in order for the coupons to have the speckle pattern, they must be painted.

First, white spray paint was applied to the samples, and then black spray paint was used over the white regions to create the speckled pattern. During the tensile testing, the painted portions of the coupons were positioned such that they could be photographed.



Figure 20 - DIC set-up with tensile test machine. DIC camera is inside the green circle and the orange box is the light source.

Since the conducted tests were deemed uniaxial tensile tests, plane stress was assumed. As a result, 2D DIC was used, which meant that a camera parallel to the tensile testing equipment photographed the painted face of the specimen at a pace of 100 milliseconds between images. Figure 20 depicts the setup and the tensile testing machine used.

At the beginning of the tensile test, manual image sampling was started in tandem with the test. After the mechanical test was completed, strain data was gathered using the image correlation tool VIC-2D. Microsoft Excel was then used to analyse the data along with the tensile testing machine's strength and displacement.

5.3 Stiffness analysis method

As described in section 3, the Young's Modulus is one of the most prominent sound properties. A stiffness analysis is conducted in order to determine the value of stiffness and Poisson's ratio for each material.

The testing of stiffness is performed using two distinct methods. In terms of the actual testing, both procedures are identical. However, their data gathering systems vary. The first choice was the Stiffness method 1, but, for cost considerations, it was deemed unsuitable for the whole thesis, and the second was pursued.

Stiffness method 1

Since a baseline for wood is required for comparison purposes and to allow the development of new materials, it would make sense to test wood first. However, the acquired wood had not yet arrived, so a study of the carbon prepreg was conducted first.

This initial procedure was performed on carbon fibre laminated prepreg in accordance to the ASTM D3039/D3039M standard. The Material Testing System MTS 810, a uniaxial servo hydraulic universal testing machine equipped with a 100 kN load cell and strain gauges connected to the samples, was used for this procedure.

Two strain gauges were installed in every sample made with a 0-degree orientation (longitudinal layup) in order to calculate the Poisson's ratio (the two strain gauges were installed perpendicularly to each other). One strain gauge was installed on the other samples with a 90-degree orientation (transverse layup). Figures 21 and 22 show the strain gauges installed on the samples. In the first, the strain gauge in the perpendicular direction to the fibre is shown with a green arrow, and the longitudinal one is shown in orange. In the last, since only one strain gauge is applied, it can be seen that it is glued perpendicularly to the fibre direction.



Figure 21 - Strain gauges installed on the 0-degree samples (orange arrow: longitudinal strain gauge; green arrow: transverse strain gauge)

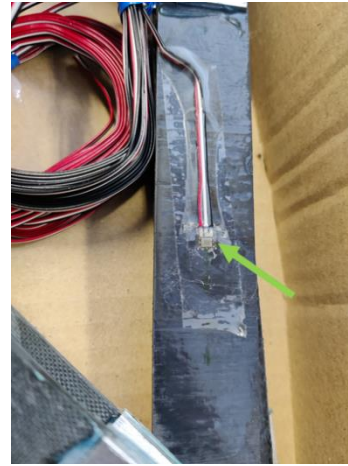


Figure 22 - Strain gauge installed on the 90-degree samples

Strain gauges of the C4A-06-060SL-350-39P model with a gauge factor of 2.09 were used. Table 3 provides further information. Using the M-Bond 200 strain gauge adhesive, the strain gauges were connected to the composite samples. In addition, Figure 23 depicts the test setup.

Table 3 - Strain gauge information

Model	C4A-06-060SL-350-39P
Grid resistance	350.0 $\pm$ 0.3%
Gage factor @ 24°C	2.09
Transverse sensitivity	1.8 $\pm$ 0.2%



Figure 23 - Stiffness method 1 test set-up

Determination of stress

Equation 5.2 may be used to calculate the applied stress to the wood specimen. In this equation, σ represents the stress, F the force, w the width of the sample at the strain gauge site, and t the thickness of the sample at the strain gauge location.

$$\sigma[\text{MPa}] = \frac{F[\text{N}]}{w[\text{mm}] \cdot t[\text{mm}]} \quad 5.2$$

Determination of stiffness

The stiffness may be determined using Equation 5.3, where ε is the nondimensional strain derived with the strain gauge.

$$E[\text{GPa}] = \frac{\Delta\sigma[\text{MPa}]}{\Delta\varepsilon[-]} \cdot 10^{-3} \quad 5.3$$

The delta symbol indicates that the analysis is performed across a segment of the strain-stress curve generated from the test result. To provide a consistent method of calculation, the points for this period were selected according to the ASTM D3039/D3039M standard. This indicates that the positions at which $\varepsilon = 0.001$ and $\varepsilon = 0.003$ were used in this calculation.

Determination of Poisson's Ratio

Poisson's Ratio was also calculated using the ASTM D3039/D3039M standard. The formula in the standard can be seen in Equation 5.4.

$$\nu = \frac{\Delta\varepsilon_t[-]}{\Delta\varepsilon_l[-]} \cdot 10^{-3} \quad 5.4$$

In this Equation, ν is the material's Poisson's ratio, $\Delta\varepsilon_t$ is the difference in lateral strain between the two longitudinal strain points selected and $\Delta\varepsilon_l$ is difference between the two longitudinal strain points selected. These values are taken from the two strain gauges perpendicularly placed in the same sample.

Stiffness method 2

The second method was applied to wood samples according to ISO 13061-7 (perpendicular to grain direction) and ISO 13061-6 (parallel to grain direction). Compared to the standards, the sample sizes differed. A length of 100 mm was used, although ISO 13061-7 specifies a maximum length of 50 mm. The choice to use longer test samples was made

following Roest [4], who analysed tonewoods and since there was no standard that expressly included tonewoods.

A secondary objective of this analysis is to identify whether or not there is a significant variation in performance across distinct areas of the evaluated wood plate. The samples' locations in the plate are chosen to offer information on the plate's consistency. In doing so, new scientific information is added to the knowledge of fundamental wood materials.

The samples were tested using a 300 kN Instron 5900R tensile testing equipment with a 100 kN load cell. Instead of strain gauges, DIC (described in Chapter 5.2) was used to monitor the strain. Equations 5.2 and 5.3 were also used in the computation process.

5.4 Flexural analysis method

While tensile testing works for single layup materials, for sandwich materials, they do not work as intended due to the presence of different materials in the layup. For the determination of sandwich materials' elastic properties, flexural analysis has to be done.

The flexural testing was done following the ASTM D7249/D7249M – 12 standard using 100 kN-capable Instron 5900R tensile testing equipment. A non-standard configuration was used with a support span of 500mm and a load span of 100 mm for the 4-point configuration.

Both the 4-point and 3-point configurations were used for this method. The difference is in the loading bars. In the 4-point configuration, two points are in contact with the sample at the load span distance. This results on a more distributed force on the sample. On the other hand, the 3-point configuration only has one line of contact which makes a more uneven force distribution. Figures 24 and 25 show the setup for the 3- and 4-point configurations.



Figure 24 - 4-point flexural test setup



Figure 25 - 3-point flexural test setup

While, for the 4-point configuration, a cylindrical pivot of 12mm was used, for the 3-point configuration a lower cylindrical pivot diameter of 8 mm was used.

The stress analysis was done using the equation 5.6.

$$\sigma[\text{MPa}] = \frac{M[\text{N} \cdot \text{mm}] \cdot y[\text{mm}]}{I_s[\text{kg}/\text{m}^2]} \quad 5.5$$

$$\sigma[\text{MPa}] = \frac{L[\text{mm}] \cdot P[\text{N}] \cdot y[\text{mm}]}{2 \cdot (2 \cdot I_{of}[\text{kg}/\text{m}^2] + I_{if}[\text{kg}/\text{m}^2] + 2 \cdot I_c[\text{kg}/\text{m}^2])} \quad 5.6$$

σ = Bending Stress

M = Moment of force

L = Length

P = Force

y = distance from sandwich centroid to outer face centroid

I_s = Sandwich's 2nd moment of inertia

I_{of} = Outer face's 2nd moment of inertia

I_{if} = Inner face's 2nd moment of inertia

I_c = Core's 2nd moment of inertia

5.5 Modal and damping analysis

Experiments were conducted to identify the resonant frequencies and damping coefficients of the wood and composite plates.

An impact hammer technique (TAP Testing) was used, which is an experimental method used to excite the system in order to collect its harmonic information, including natural frequencies, modal masses, modal damping ratios, and mode shapes.

In the Laboratory of Vibrations at Faculdade de Engenharia da Universidade do Porto (FEUP), after hitting the plate with a hammer fitted with a force transducer, an accelerometer was used to measure the frequency response of that plate. Both the excitation signal and the response signal are provided to separate channels of an analyser, which analyses the data to identify the distinct FRFs corresponding to the different impact points. The setup with the accelerometer in place can be seen in Figure 26.

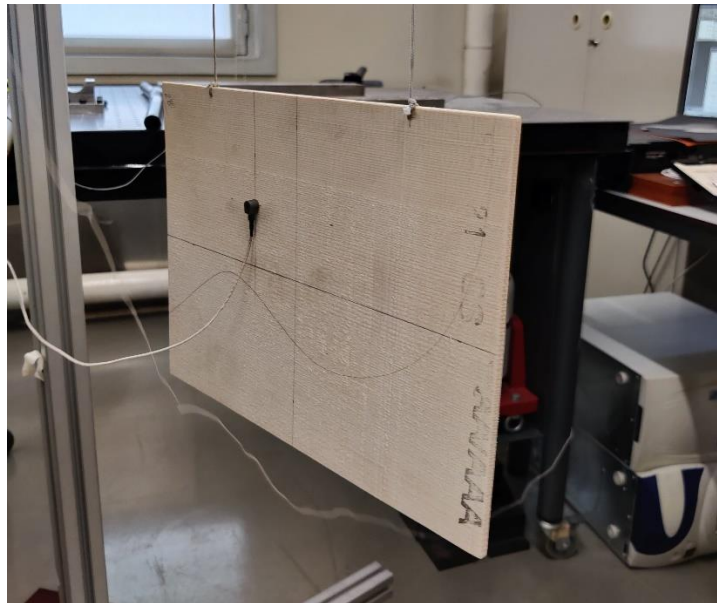


Figure 26 - Accelerometer setup for modal analysis

The used accelerometer was an Endevco 27A11 and the hammer was a Dytran 5800SL. Table 4 has both of the specs. The data processing software was Brüel & Kjaer Pulse, version 6.

Table 4 - Sensitivity of accelerometer and hammer used in the dynamic test

Model	Sensitivity
Endevco 27A11	9.859 mVg ⁻¹ @ 100 Hz
Dytran 5800SL	106.40 mV (LbF) ⁻¹

All plates were manufactured with the same dimensions, hence results could be compared. The measurements selected were 218 mm by 290 mm, since the hardwood plates were about 436 mm by 290 mm apiece, and so only needed to be split in half. In addition, the dimensions of an A4 sheet (210 mm x 297 mm) were deemed suitable for this testing, so the 218 mm x 290 mm were deemed suitable.

An example of the three dots drawn on all the plates to test can be seen in Figure 27. These three points were the points of impact for each plate. At Point 1, on the side opposite to the collision, the accelerometer was installed. As for the boundary conditions, two 3 mm holes were drilled 5 mm from the top and 60 mm from the closest side to replicate the free regime.

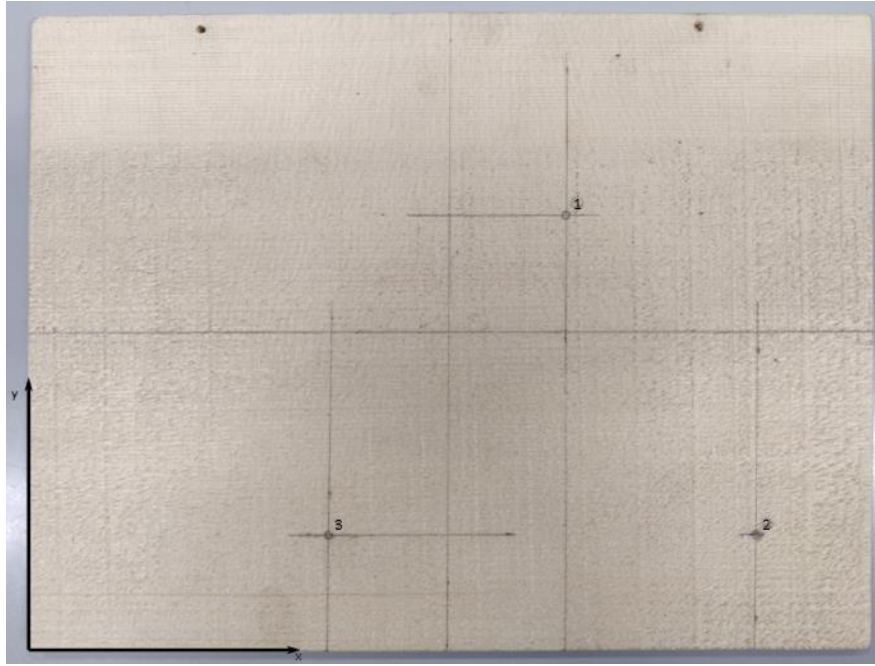


Figure 27 - Points used for the dynamic tests

In Table 5, the coordinates of the three points tested can be seen.

Table 5 - Coordinates of the points used in the dynamic tests

	Point 1	Point 2	Point 3
x	185	250	105
y	149	40	40

These points were computed based on the first mode forms for plates with the above-mentioned dimensions so that they would not be on a node line and hence not vibrate. There were three measurements collected for each spot.

In parallel with this analysis, a finite element method was employed to simulate the first natural frequencies of the material. Altair ESAComp was used since it is a powerful tool for composite analysis and has a finite element system. The software can export the model to ABAQUS and ANSYS, allowing for more in-depth FE (finite element) analysis of more intricate structures. In addition, the use of this software ensured that no mistake was caused by misapplication of the laminate theory's formulae and that, despite the possibility of error owing to the limited number of mesh elements, the FE simulations were appropriately built and produced accurate results.

A panel analysis of natural frequencies was performed to determine the first few natural frequencies. The software permits a maximum of 10 natural frequencies. However, since the analysis was performed with free boundary conditions, the first six natural frequencies are not of use. Therefore, only the top four frequencies may be identified using this approach.

While ESAComp supports a maximum of 200 elements per mesh, a few experiments showed that the difference in results between 40 and 200 elements was insufficient to justify the additional simulation time. So, a 40-element mesh was used for each case, and a 200-element mesh simulation was used for the best-case scenarios to get more accurate results.

5.6 Composite analysis

Prior to the experimental creation of the sandwich materials, it was decided to use numerical finite element analysis simulation and composite analysis to restrict composite possibilities and to, afterwards, compare the results with those of the experimental method. A preliminary analysis was undertaken to anticipate the outcomes and suggest some possible solutions for the sandwich layups.

First, the materials are added and information about them is supplied to the system. Some of the data entry choices in the ESAComp software are seen in Figures 28 and 29.

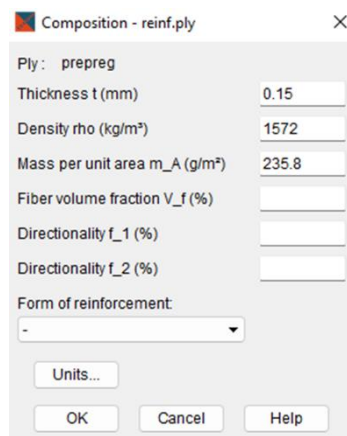


Figure 28 - ESAComp material's composition menu

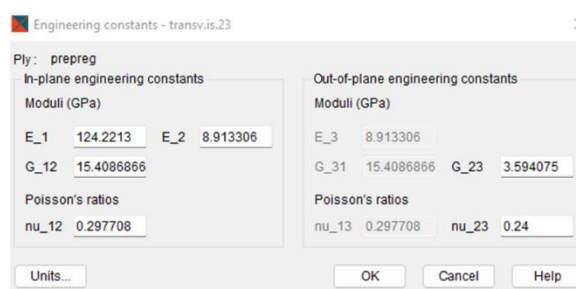


Figure 29 - ESAComp material's Engineering constants menu

Using the input materials, the sandwich laminate materials are then simulated. Figure 30 shows the inputs required by ESAComp (material and layer orientation) to define the layup.

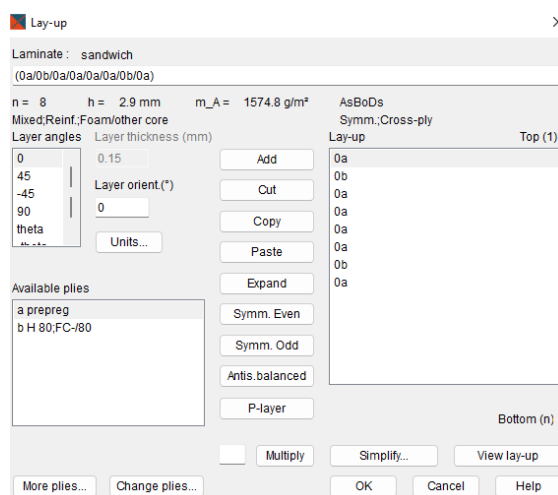


Figure 30 - ESAComp's layup menu

After the material is designed, a 2.5D behaviour analysis (using Classical Laminate Theory incorporated inside the software) was performed to determine the engineering constants of the laminate. Predominantly, the in-plane and flexural moduli and Poisson's ratios were considered the most important.

In the beginning of the thesis, two options were proposed for a FEM (Finite element method) analysis. The first was the use of the Abaqus software since it has a powerful

simulation capacity and it would lead to more accurate results. The second was the use of ESAComp since it included a finite element analysis system in addition to the composite simulation system.

In the end, due to software access limitations, ESAComp was chosen for both the composite and FEM analysis.

5.7 Sample manufacturing

In this section, the different methods of sample manufacturing will be detailed. These samples include both the tensile testing samples, the flexural testing samples and the modal analysis samples. Each test has its own size specifications according to the relevant standards and manufacturing process.

Wood samples

Wood was examined for its stiffness and natural frequencies. This required a 218 mm by 290 mm plate, as stated in section 5.5. In addition, adhering to the section 5.3 standards required the manufacture of samples for stiffness testing.

The wood for this dissertation was acquired from Tonewood (a company specialising in woods for musical instruments in Switzerland). To give mechanical and vibrational characteristics for analysis, AA/AAA grade wood was selected as a quality material.

Using a band saw, the correct dimensions of wood were cut for the dynamic plate. However, due to a lack of laboratory space, wood samples for the stiffness testing were manually cut using a utility knife. This was possible due to the ductility of the wood. However, due to the cutting process, dimension variations are present. In order to find a rectangular equivalent that would be as close as possible to the sample's dimensions, five random measurements were taken for each dimension. The samples are presented on Figures 31 and 32.



Figure 31 - Transversal wood samples



Figure 32 - Longitudinal wood samples

Moreover, it can be seen in Figures 31 and 32 that the samples possessed a large difference in terms of grain dimension. As mentioned before, this was done for the results to better reflect the wooden plate.

Carbon fibre composite samples

Using hand layup, test specimens were built in order to characterise the material. This characterization enabled the input of values into ESAComp, and better choose the parameters of the sandwich materials to study. The curing was done using a vacuum bag and an oven at a temperature of 110°C for six hours.

The stiffness test samples in both longitudinal and transverse directions are shown in Figure 34. The plate for the dynamic testing was done similarly, only without the machining.

The Prepreg HS 150 ET 445 (38%) T700 24K 60CM was used. This was chosen because the partner company uses this unidirectional prepreg, so the material supply was guaranteed, and because this material is also used in some of their electric composite guitar models.

Table 6 - Carbon prepreg information

MATERIAL	HS 150 ET 445 (38%) T700 24K 60CM
FIBRE	T 700 24K
FIBRE WEIGHT	150 g/m ²
RESIN PERCENTAGE	38% +/-3%



Figure 33 - Vacuum bag before curing

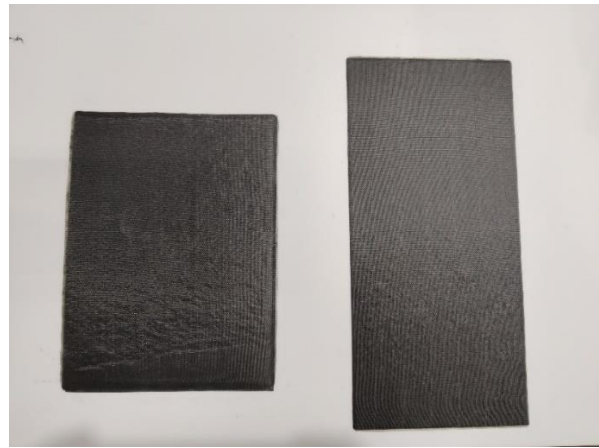


Figure 34 - Test Specimens after curing

After being manufactured, the specimens were machined to have the right dimensions for testing. These dimensions, along with the thickness, are in accordance with ASTM D3039/D3039M shown in Table 7.

Table 7 - Tensile Specimen Geometry Recommendations in ASTM D3039/D3039M [55]

Fibre Orientation	Width [mm]	Overall Length [mm]	Thickness [mm]	Tab Length [mm]	Tab Thickness [mm]	Tab Bevel Angle [°]
0° unidirectional	15	250	1.0	56	1.5	7 or 90
90° unidirectional	25	175	2.0	25	1.5	90



Figure 35 - Prepreg samples in the final dimensions

After the machining of samples, the tabs and strain gauges were attached. The tabs used were made from aluminium, and the strain gauge information can be seen in Table 8.

Table 8 - Strain gauge information

MODEL	C4A-06-060SL-350-39P
Grid resistance	350.0 $\pm$ 0.3%
Gage factor @ 24°C	2.09
Transverse sensibility	+1.8 $\pm$ 0.2%

Sandwich samples

Four materials were used to make the sandwich materials. One of the materials has previously been addressed in the “Carbon fibre composite samples” section. In the Chapters 7 and 8, more properties will be introduced as needed. Nevertheless, Table 9 displays an overview of all four.

The NTPT T800 prepreg material is presented as two distinct materials since material availability demanded using both as opposed to just one. However, as the only variation between the two is in their areal weight, their properties are equivalent.

Table 9 - Sandwich material overview

Material	HS 150 ET 445 (38%) T700 24K 60CM	NTPT T800 prepreg (50 g/m ²)	NTPT T800 prepreg (100 g/m ²)	PVC Foam
Fibre/Foam name	Toray® T700 24K	Toray® T800	Toray® T800	MILLIFOAM® DIV80H
Areal weight	235.8 g/m ²	50 g/m ²	100 g/m ²	-
Density	-	-	-	80 kg/m ³
Resin percentage	38% +/-3%	-	-	-
Epoxy		ThinPreg™80EP- 736	ThinPreg™80EP- 736	-
Thickness	0.15 mm	0.05 mm	0.1 mm	1 mm

PVC was layered with thin-ply (NTPT T800 prepreg) and standard-ply (HS 150) to create two sandwich materials. The combination of thin-ply and PVC will henceforth be referred to as "CarbonT-1," whereas the combination of standard-ply and PVC will be referred to as "CarbonS-1."

The hand layup technique was employed for both materials. The layups will be discussed in more detail in Chapters 7 and 8.

Since the core of both sandwich materials was PVC, the same procedure was employed for both layups. Due to the high porosity of PVC, it was difficult for the carbon fibre composite layer to adhere to it. The solution employed was that once all the carbon layers were assembled independently, the full layup with PVC in the middle layers was constructed.

After the CarbonS-1 layering process was completed, the samples were put in a vacuum bag and cured in an oven. The curing time was approximately six hours at 110°C under vacuum.

The CarbonT-1 was cured in an autoclave at a pressure of 6 bar and with a temperature cycle as shown in Figure 36.

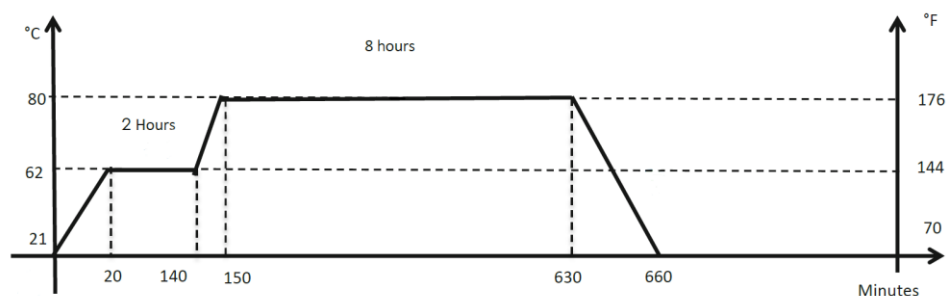


Figure 36 - Curing conditions in autoclave [56]

Once the curing was done, the CarbonS-1 plate was ready for dynamic testing since the prepreg was cut before curing. However, for the CarbonT-1 plate, due to the low thickness of the prepreg, the plate had to be machined after curing.

In line with the ASTM D7249/D7249M standard, the samples for the flexural testing were machined. Table 10 depicts a conventional setup with a span of 560 mm. However, the greatest support span available was only 500 mm, so this was used. The dimensions selected for each sample were 550 mm by 16 mm.

Table 10 - ASTM D7249/D7249M Loading Configurations [57]

Configuration		Support span (S)	Load span (L)
Standard	4-Point	560 mm	100 mm

6 Baseline of wood

ESAComp was used to simulate the properties and analyse its viability to compute natural frequencies for a defined material.

Furthermore, using the methods presented in Chapter 4, a baseline for wood may be established. In this chapter, wood acquired from Tonewoods will be tested to find its elastic and dynamic properties which will be the baseline for the rest of the thesis.

This baseline serves as the fundamental reference point for the construction and comparison of composites hereafter.

6.1 Initial baseline ESAComp analysis

Michael Greenfield, widely recognised as one of the best acoustic guitar luthiers working today, supplied the wood properties he often uses in his instruments. Since these values are the result of years of experience, they may be used as a starting point, in theory. The supplied properties were:

- Density: 0.38 – 0.42 g/cm³
- Modulus long: 13.5 – 15 GPa
- Modulus cross: 0.8 – 1.25 GPa
- Velocity Long: 5700 – 5950 m/s
- Velocity cross 1600 – 1800 m/s

In addition, Roest [4] identified the boundaries within which major guitar properties should fall for the best sound quality:

- Longitudinal stiffness: 12GPa - 16GPa
- Transverse stiffness: 0.8 - 1.2 GPa
- Anisotropy ratio: 10-12
- Density: 400-500 kg /m³

For the first analysis, the average of the previously provided data was used. In addition, as the material must be completely described in ESAComp, several attributes, such as ν_{21} and ν_{21} were arbitrated.

The shear modulus was computed using the formula presented in Equation 6.1 [24].

$$G_{xy} = \frac{\sqrt{E_x E_y}}{2(1 + \sqrt{\nu_x \nu_y})} \quad 6.1$$

Table 11 - First ESAComp analysis wood values

MECHANICAL PROPERTIES	WOOD
ρ	0.4 g/cm ³
E_x	14.25 GPa
E_y	1.025 GPa
ν_{12}	0.38
ν_{21}	0.03
G_{xy}	1.73 GPa
Geometry	
L_x	0.290 m
L_y	0.218 m
h	5.3 mm

The data in Table 11 was entered into ESAComp so that the natural frequencies could be calculated (see Table 12). Then, the results were used to determine the thickness of the carbon prepreg that best matched the natural frequencies of the wood.

Table 12 - Calculated wood natural frequencies

	FREQUENCY (Hz)
1 st natural frequency	183.00
2 nd natural frequency	190.09
3 rd natural frequency	402.61
4 th natural frequency	414.84

6.2 Tensile testing

Wood samples were subjected to tensile testing using the method described in chapter 5.3 (The sample manufacturing process is described in Chapter 5.7). The dimensions of the longitudinal samples were 5 mm x 10 mm x 100 mm and the transverse samples' dimensions were 5 mm x 25 mm x 100 mm. The average of the five measurements of the wood sample dimensions is shown in Table 13.

Table 13 - Overview of wood sample dimensions, weight and density

Sample	t [mm]	w [mm]	l [mm]	volume [mm ³]	mass [g]	ρ [kg/m ³]
W-L-1	5.29	10.39	99.43	5468.10	1.9	347.47
W-L-2	5.32	10.55	99.19	5575.87	2.0	358.68

W-L-3	5.21	10.53	99.39	5463.22	2.0	366.08
W-L-4	5.14	10.13	99.47	5187.39	2.0	385.55
W-L-5	5.14	10.23	99.42	5236.29	2.0	381.95
W-L-6	5.28	9.79	99.52	5148.77	1.8	349.59
W-L-7	5.32	10.05	100.07	5351.84	1.9	355.01
W-L-8	4.59	9.90	99.73	4537.61	1.9	418.72
W-L-9	5.22	9.98	99.79	5204.79	1.8	345.83
W-L-10	5.17	9.91	99.91	5126.14	1.8	351.14
W-T-1	5.61	24.68	99.85	13830.47	5.2	375.98
W-T-2	5.56	24.83	99.98	13806.05	5.3	383.89
W-T-3	5.53	25.28	99.99	13984.06	5.3	379.00
W-T-4	5.44	24.63	99.95	13414.70	5.1	380.18
W-T-5	5.43	25.87	100.06	14059.38	5.2	369.86
W-T-6	5.60	25.38	100.91	14353.52	5.1	355.31
W-T-7	5.56	25.01	99.65	13880.99	5.0	360.20
W-T-8	5.47	25.30	99.80	13834.64	4.9	354.18
W-T-9	5.47	24.88	99.74	13587.18	4.8	353.27
W-T-10	5.37	25.92	99.48	13869.71	5.0	360.49

After manufacturing the samples, the tests were undertaken at 2 mm/min. Due to problems with the load cell (which led to a lot of data noise), the test results were deemed not valid (the stress-strain curves can be seen in Appendixes A4 and A5 and the resulting Young's moduli and Poisson's ratios are presented in Appendix A7).

6.3 Dynamic testing

As described in Chapter 5.5, an Impact Hammer Test (TAP Testing) was performed to evaluate the dynamic response of the wood. The plate examined measured 290 mm x 218 mm, and three impact locations were evaluated (see Table 5).

The data was analysed using MATLAB to get the natural frequencies and damping coefficients (the MATLAB code used are shown in appendixes D1 and D2). The test outcomes are shown in Figures 37 and 38 and in Table 14.

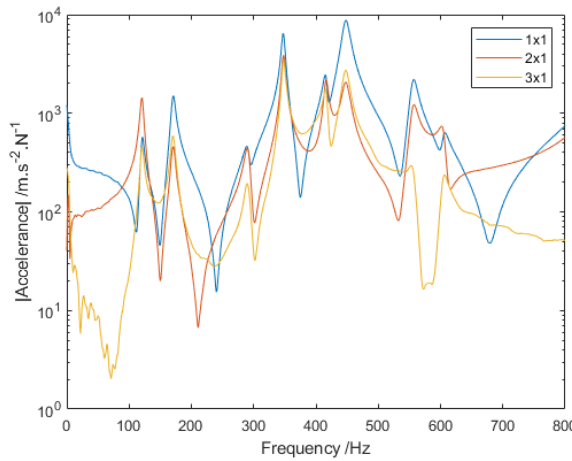


Figure 37 - FRFs obtained from wood dynamic testing

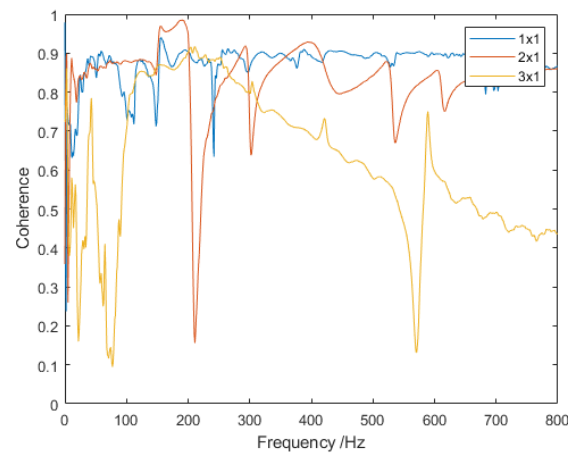


Figure 38 - Coherence plot of wood dynamic testing

Table 14 - Wood plate natural frequencies and damping

	FREQUENCY (Hz)	DAMPING
1st Natural frequency	120.86	0.023
2nd Natural frequency	170.56	0.019
3rd Natural frequency	290.10	0.027
4th Natural frequency	347.81	0.0079
5th Natural frequency	414.36	0.0087
6th Natural frequency	447.66	0.013
7th Natural frequency	556.08	0.0097
8th Natural frequency	607.13	0.011

Comparing the natural frequency values from the first ESAComp iteration (Table 12) to the experimentally determined values in Table 14, the first four modes have an average relative difference of 30% and the first mode has a relative difference of 51%. This is the result of a disparity in mechanical properties between the reference values in Table 11 and the elastic properties of the wood plate tested dynamically.

Now that the wood baseline has been established, alternative materials may be produced to replace it. In the following two chapters, two alternatives to wood in guitar applications will be developed and assessed.

7 Development of a CarbonS-1 alternative

The goal is to produce a material that is as close to wood as possible in terms of natural frequencies and damping, and yet still being able to endure the stresses inherent in a guitar. As the basis for the early development of the material, a carbon-based material was chosen. As indicated in the literature review, this was due to the excellent outcomes of prior studies published in the literature.

Initially, an investigation was conducted to determine the thickness that, without a core material, would most closely resemble the natural frequency of wood, but it was quickly deemed unreliable and was abandoned and a sandwich material was pursued.

As was done with the wood samples in chapter 6, an initial analysis of the sandwich material is performed once the material has been selected in order to assess the feasibility of the composite simulations performed using ESAComp.

The sandwich layups are simulated in ESAComp to determine the optimal layup possibilities, and the most promising layup was produced and tested. The results were then compared to the established baseline.

7.1 Prepreg HS 150 analysis

The Prepreg HS 150 ET 445 (38%) T700 24K 60CM was used due to the fact that the partner company employs this unidirectional prepreg, hence guaranteeing the material supply.

This to-be-used unidirectional prepreg was investigated to determine its actual mechanical and vibrational properties.

The first step was to determine the material thickness that would approach the natural thickness of the prepreg with that of the wood. This research was done since, if the prepreg was able to simulate wood relatively well, the price of another material and the problems that sandwich manufacturing processes could bring would be unjustifiable. However, this was judged unpromising based on early simulations, and a sandwich material was sought.

Using the same method as with the wood samples, an initial analytical analysis was conducted to get a preliminary understanding of the results, compare them with the experimental results, and establish if the analytical method is practical.

ESACOMP was used to forecast the properties of the prepreg based on the data sheet of the prepreg, the fibre and matrix, and the fibre volume of the prepreg. The known properties of the fibre and matrix are detailed in Table 15. In addition, given the number of unknown properties, some properties were obtained through the T700S properties provided by Composite Oracle [58]. These properties are denoted with "*" below.

Table 15 - Fibre and matrix properties of HS 150 prepreg

	Fibre (T700S)	Matrix (ET445)
Density	1.80 g/cm ³	1.2 g/cm ³
Tensile strength	4900MPa	--
Tensile Modulus	230GPa	--
Poisson's Ratio (estimated)*	0.298	--
Shear modulus*	37 GPa	--
Strain at Failure	2.1%	
T_g		135°C
Curing Temperature		120-130°C
Curing Time		60-30 min

The process was deemed unreliable due to the scarcity of information on the matrix and fibre.

The material data sheet also included the composite properties for a 60 percent fibre volume laminate, in addition to the fibre properties. This is close to the fibre volume fraction of the prepreg, 62%, thus these numbers were employed for the initial iteration. However, the matrix used in this laminate is distinct from that of the prepreg under investigation, and so some error will be associated with it.

The same holds true for the matrix's material sheet. However, there are properties for a prepreg laminate with just one property different from the prepreg under investigation: the weight per area. This allows for more precise values in theory.

Table 16 contains the values for the two laminates available in ESAComp. Yet, for the ESAComp simulations, some properties were arbitrated. They are marked in the table with “*”. The density was calculated considering a 60% fibre volume and considering the T700S fibre density and ET445 cured density.

Table 16 - T700S Composite and HS 300 ET445 38% properties

MATERIAL	T700S FIBRE COMPOSITE (T700S FIBRE AND EPOXY MATRIX)	HS 300 ET445 38%
Tensile strength [MPa]	2860	2489
Tensile modulus [GPa]	134	131.1
90° Tensile modulus [GPa]	8*	8*
Density [kg/m³]	1572	1572
Tensile strain [%]	2.02	--
Poisson's ratio [-]	--	0.35
Transverse Poisson's ratio		0.24*
Compressive strength [MPa]	1.450	1254
Compressive modulus [GPa]	--	115.6
Flexural strength [MPa]	1.690	---
Flexural modulus [GPa]	120	---
Interlaminar shear strength [MPa]	86.9	83.5
In plain shear strength [MPa]	136	63.3
In plain shear modulus [GPa]	--	3.93
90° tensile strength [MPa]	81	--

Using the above numbers, equation 7.1 was used to determine the thickness of the plate with natural frequencies similar to the wood plate.

$$h_c = h_w * \frac{\left[c_x^w * \left(\frac{1}{L_x} \right)^2 + c_y^w * \left(\frac{1}{L_y} \right)^2 \right]}{\left[c_x^c * \left(\frac{1}{L_x} \right)^2 + c_y^c * \left(\frac{1}{L_y} \right)^2 \right]} \quad 7.1$$

$$c_x = \sqrt{\frac{E_x}{\rho \cdot (1 - v_{xy} \cdot v_{yx})}} \quad 7.2$$

$$c_y = \sqrt{\frac{E_y}{\rho \cdot (1 - v_{xy} \cdot v_{yx})}} \quad 7.3$$

h_w = wood thickness

E_x = Young's Modulus in the x direction

E_y = Young's Modulus in the y direction

L_x = length in the x direction

L_y = length in the y direction

ν_{xy} and ν_{yx} = Poisson's ratio

Equation 7.1 determines the thickness at which the first frequency of both materials is the same. The equation is derived from the rectangular wooden plate formula in "Physics of Musical Instruments" [24]. Since wood is likewise an orthotropic material, the formula was deemed suitable for carbon composite as well. The resulting frequency distributions are shown in Table 17. Nevertheless, this equation was deduced considering a simply supported boundary condition. Since those are not the conditions the wood was analysed, these values can serve only as a rough guideline.

For the ESAComp simulation, since both materials had similar properties, only the HS 300 was used since it had more properties defined and should be closer to the prepreg ultimately chosen.

Table 17 - HS 300 ESAComp calculated natural frequencies

	WOOD	HS 300 ET445 38%	RELATIVE DIFFERENCE [%]
THICKNESS [mm]	5.38	3.731	--
1 st frequency [Hz]	120.87	99.30	18%
2 nd frequency [Hz]	170.56	182.3	7%
3 rd frequency [Hz]	290.11	271.98	6%
4 th frequency [Hz]	347.82	416.58	20%
Average	--	--	13%

The wood frequency values correlate to Table 14. The results showed an average relative error of 13 percent and an 18 percent error in the first natural frequency, which was deemed unreliable, thus the plate was not manufactured and tested.

Using equation 7.1, with some mathematical adjustments, when calculating the natural frequencies, it is found that anisotropy is the most critical element; thus, if the formula is valid, the same anisotropy must be obtained to match the natural frequencies.

It is still necessary to investigate the HS 150 material to determine its actual properties. This will provide a better idea of the formula's accuracy and also a stronger foundation for future iterations and for making the sandwich material.

Tensile Testing

As described in Chapter 5, the unidirectional prepreg laminate was examined using a stiffness study. Following the ASTM D3039/D3039M–14 standard, the longitudinal samples were tested at 1 mm/min and the transverse samples were tested at 0.5 mm/min. The 100 kN load cell was used for longitudinal samples, whereas the 10 kN load cell was used for transverse samples. The stress-strain curves are shown in Figures 39 and 40.

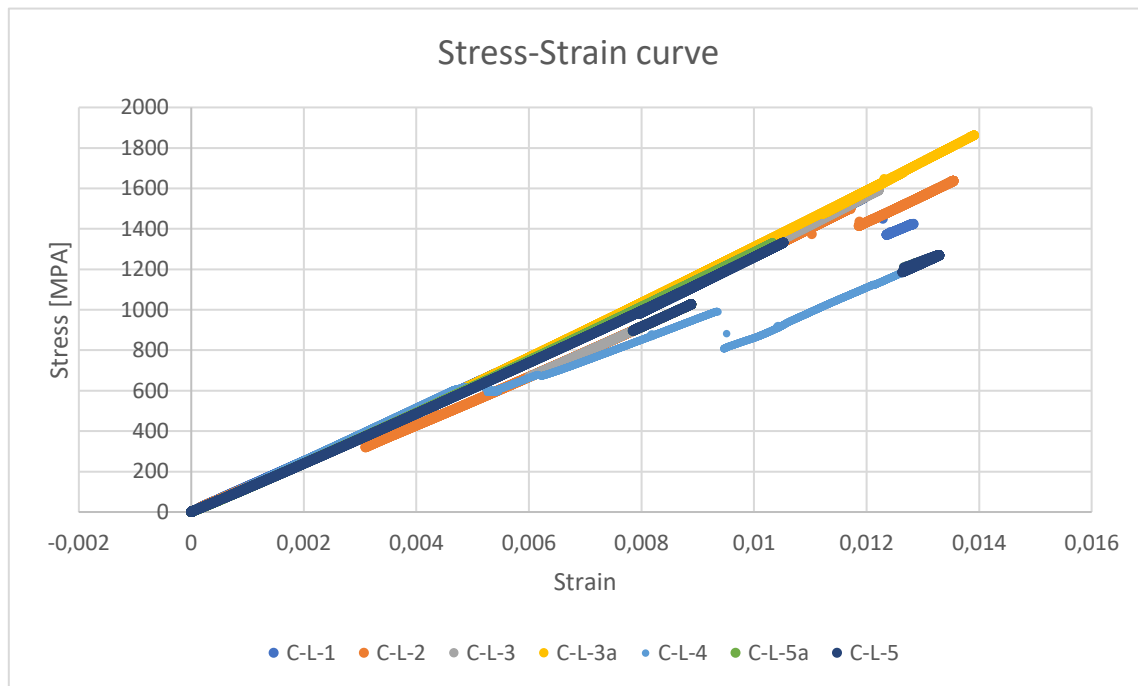


Figure 39 - Stress-strain curves for the longitudinal carbon samples.

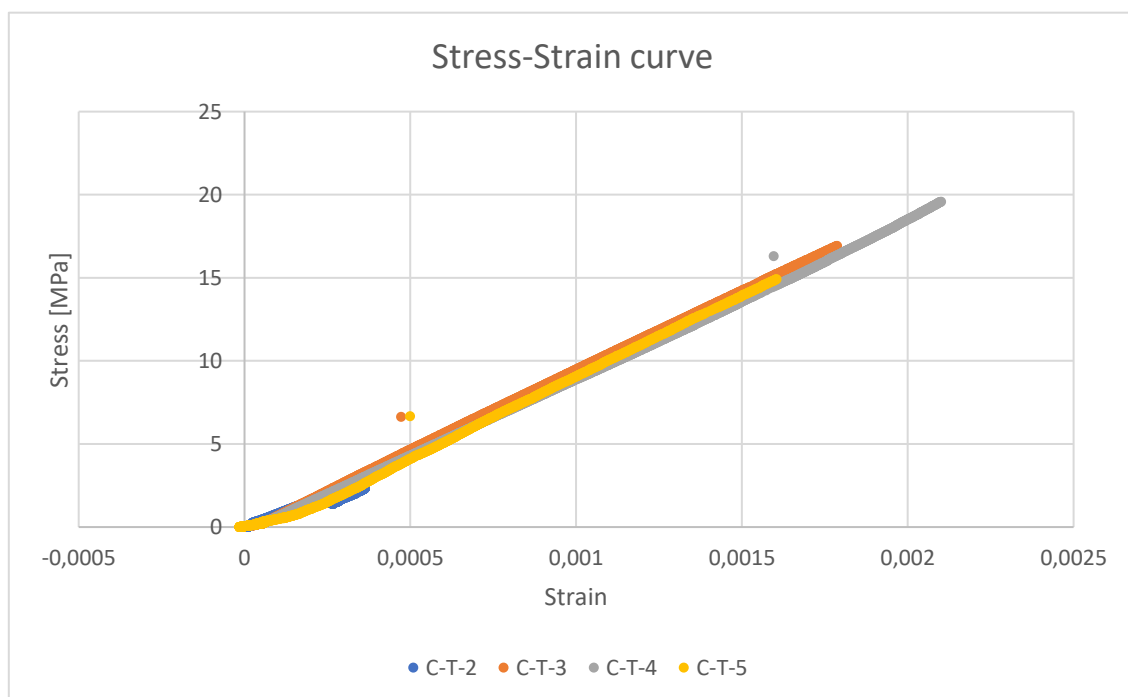


Figure 40 - Stress-strain curves for the transverse carbon samples

In the longitudinal testing, there were several slips. The tab was detached from the sample on the C-L-2 which was attributed to the existence of moment forces, thus the configuration was altered to avoid them.

The C-L-3 test failed at 30 kN, thus it was rerun with the designation C-L-3a. This time, the test sample slipped. However, cracking was audible throughout the test, so no more attempts were made with this sample.

The C-L-4 sample's tabs were involved with sandpaper to reduce slippage. However, the tabs were not aligned with the sample, so the sample began to crack along the sides.

The same happened with C-L-5 and C-L-3. At 27 kN, slippage occurred, therefore the test was redone and renamed C-L-5a.

The C-T-1 was used to determine whether the load cell was adequate for the transverse samples. The, 100 kN load cell was firstly used. The results showed that a more sensitive load cell was required. The 10 kN load cell was used for the remainder of the transverse samples.

These tests allowed determining the Young's modulus and the Poisson's ratio, as shown in Table 18.

Table 18 - Poisson's ratio and Young's modulus of carbon samples

SPECIMEN	POISSON'S RATIO	YOUNG'S MODULUS [GPA]
C-L-1	0.27	124.83
C-L-2	0.31	121.29
C-L-3	0.31	123.95
C-L-3a	0.32	125.71
C-L-4	0.29	129.39
C-L-5	0.27	121.62
C-L-5a	0.28	122.73
C-L-AVERAGE	0.30	124.22
C-T-2	--	6.91
C-T-3	--	10.01
C-T-4	--	9.14
C-T-5	--	7.57
C-T-AVERAGE	--	8.91

The results showed that there was a 6% difference of Young's modulus, a 10% difference in the 90° Young's modulus and an 18% difference of Poisson's ratio compared to the values in the matrix data sheet (HS 300 ET445 38%).

The same ESAComp analysis was done with the real values, meaning that E_1 , E_2 and ν_{12} were changed. Furthermore, the shear modulus was computed using the formula presented in Equation 6.1. Since the prepreg has a thickness of around 0.15 mm, the thickness was approximated to the nearest possible value (3.75mm).

Table 19 - HS 150 ESAComp calculated natural frequencies

	WOOD	HS 150 ET445 38%	RELATIVE DIFFERENCE [%]
THICKNESS [mm]	5.38	3.75	--
1st frequency [Hz]	120.87	189.66	56.92%
2nd frequency [Hz]	170.56	193.1	13.21%
3rd frequency [Hz]	290.11	408.23	40.72%
4th frequency [Hz]	347.82	427.44	22.89%
Average	--	--	33.43%

The average difference of 33.43 percent was judged unsatisfactory, thus testing and production were cancelled.

However, this study took into account the thickness derived using equation 7.1, which pertains to a rectangular wood plate with simple support. The use of a different thickness may resemble the natural frequencies of wood more closely.

7.2 ESAComp composite simulations

With the elastic properties determined, ESAComp simulations are now more accurate. Instead of seeking the material thickness that would resemble the natural frequencies as nearly as possible, it was decided to design a new sandwich material that would be more similar to wood in terms of natural frequencies and damping.

The core material chosen was a PVC material (MILLIFOAM® DIV80H) due to its easy access. The properties can be seen in Table 20.

Changes to the layups of the laminates were simulated, followed by a 2.5D behaviour analysis and natural frequency simulation for each to determine the most promising. The potential layups were looked at in more depth to figure out which ones would be chosen for production and testing.

A symmetrical lay-up with layers of carbon fibre on the exterior and PVC material on the inside was analysed first. Nonetheless, the concept of simulating multi-layered layups (carbon layers between PVC layers) was also considered. This new concept was to include carbon fibre layers between the PVC layers, expanding the possibilities for property modification and maybe enhancing their sensitivity. The multi-layered option also contained the other options when the number of carbon layers in the centre was 0.

Table 20 - MILLIFOAM® DIV80H properties

Material	PVC Foam
Name	MILLIFOAM® DIV80H
Density	80 kg/m ³
Thickness	1 mm
Density	80 g/cm ³
Compressive Strength	1.4 MPa
Compressive Modulus	90 MPa
Tensile Strength	2.5 MPa
Tensile Modulus	95 MPa
Shear Strength	1.15 MPa
Shear Modulus	27 MPa
Coefficient of Thermal Expansion	4.0 1/K*10E-5
Thermoforming Temperature	90-120°C (194-248°F)

Table 21 suggests that the first layers are comprised of carbon fibre composites in the quantity shown in the "Carbon Layers 1" column, followed by the number of PVC layers shown in the "PVC Layers 1" column, and so on. Figures 41 and 42 depict these configurations to facilitate understanding. Figure 41 displays the arrangement of a simple layup where there is only one layer of PVC without carbon in the middle (depicted in the table as "Carbon Layers 2" is equal to zero). Figure 42 depicts an example of a multi-layered composite where:

- Carbon Layers 1 = 3
- PVC Layers 1 = 1
- Carbon Layers 2 = 1
- PVC Layers 2 = 1
- Carbon Layers 3 = 3

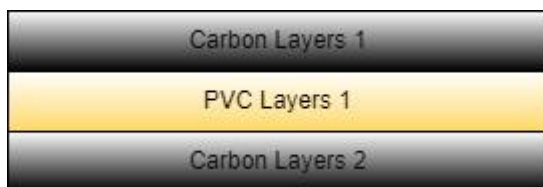


Figure 41 - Simple Layup configuration

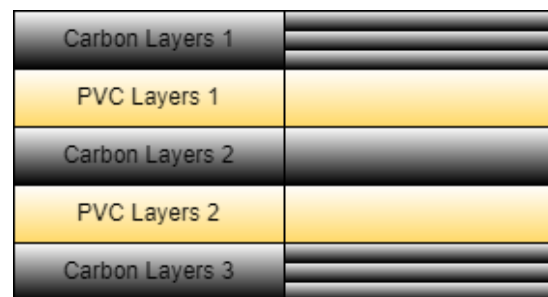


Figure 42 - Multi-layer layup configuration

Three analyses were conducted to minimise the average inaccuracy of the first four natural frequencies, the longitudinal Young's modulus (E_1), and the sound radiation coefficient (R). Natural frequency analysis was chosen to determine the most promising layup. In order to reduce all errors as much as possible, a further in-depth study of each layup's first natural frequency (f_1) error, longitudinal Young's modulus error, and sound radiation coefficient error was performed.

Table 21 contains just frequency error analyses, since these are the most promising. Appendix B4 contains the complete list of outcomes.

In this investigation, it was determined that the relative placement of the PVC layers inside the sandwich material had no influence on the laminate. For instance, the properties and dynamic responsiveness of the layups 1-2-1-1-1 and 1-1-1-2-1 are identical (layup sequence as depicted in Figure 42).

The numbers 8 and 11 from Table 21 were the most promising. They had the lowest R error values, and the rise in natural frequency error was comparable to that of the best cases. The Young's modulus error was not considered since, as previously shown, only anisotropy should be significant. The anisotropy error was insufficient to reevaluate these possibilities for those with lower anisotropy error values, and other examples with lower anisotropies did not have lower sound radiation coefficient errors.

With smaller errors in sound radiation coefficient, anisotropy, and the first natural frequency, the number 11 was the more attractive of these two alternatives.

In order to analyse the material mechanically and dynamically, as was done with wood, samples were created once the layup was determined. Since sandwich samples can't be put through a tensile test, flexural tests were done to find out the elastic properties of the material.

Table 21 - Frequency error analysis overview for simulated CarbonS-1 layups

Option	f_{1-4} error [%]	f_1 error [%]	R error [%]	Anisotropy error [%]	Carbon fibre composite layers 1	PVC layers 1	Carbon fibre composite layers 2	PVC layers 2	Carbon fibre composite layers 3
1	10.39	12.10	29.67	1.16	1	1	9	1	1
2	10.42	17.75	44.87	0.49	5	1	0	0	5
3	10.68	15.00	32.39	1.03	1	1	10	1	1
4	10.73	11.44	19.23	3.43	1	1	2	1	1
5	10.85	17.63	39.59	4.32	1	1	1	1	1
6	11.26	9.63	26.45	1.21	1	1	8	1	1
7	11.89	28.72	72.38	1.83	1	2	0	0	1
8	11.93	7.97	5.42	2.74	1	1	3	1	1
9	11.96	7.70	22.60	1.25	1	1	7	1	1
10	12.43	6.39	17.90	1.62	1	1	6	1	1
11	12.51	6.28	4.54	2.21	1	1	4	1	1
12	12.64	5.85	12.05	1.91	1	1	5	1	1
13	12.77	7.55	40.10	0.68	4	1	0	0	4
14	13.87	34.35	12.05	1.91	2	1	3	1	2
15	15.09	35.82	4.56	2.21	2	1	2	1	2

For a better understanding of the vibration modes investigated, Figures 43, 44, 45 and 46 depict the modes for the first four natural frequencies of the selected layup (case 11 from

Table 21). These modes are the same for all plates with the same dimensions, so they apply to both the wooden plate and all sandwich plates.

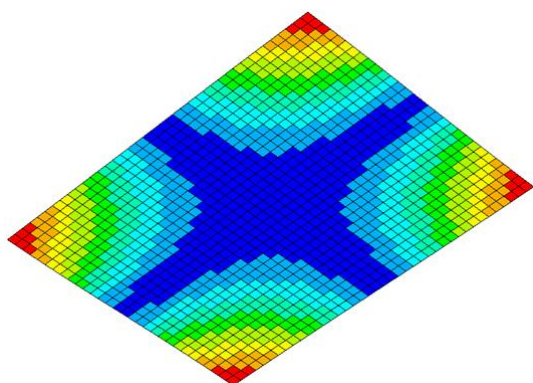


Figure 43 - 1st vibration mode

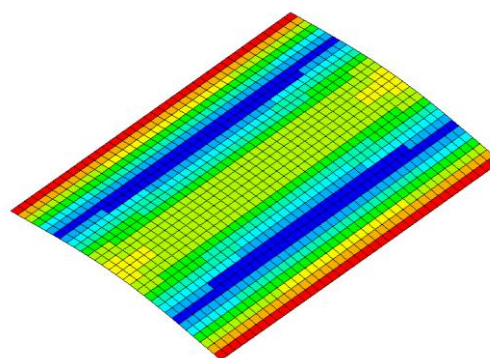


Figure 44 - 2nd vibration mode

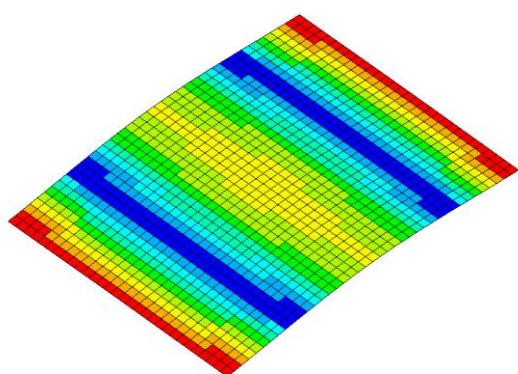


Figure 45 - 3rd vibration mode

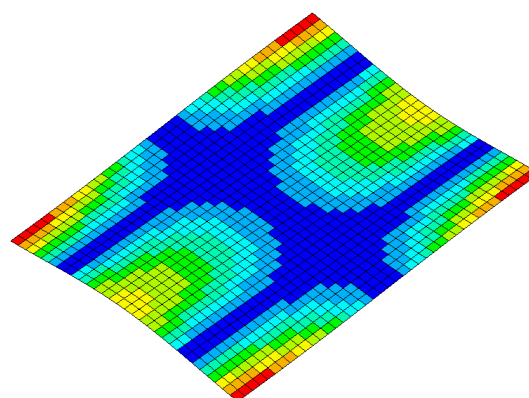


Figure 46 - 4th vibration mode

7.3 CarbonS-1 flexural testing

Flexural testing was conducted using the method described in Chapter 5.4.

Initially, the ASTM D7249/D7249M-12 standard's standard configuration for the 4-point test was attempted. Therefore, despite the fact that the samples were not standard, testing was conducted as closely as possible to the standard.

Table 22 shows the average of the five dimensions measured for the CarbonS-1 sample.

Table 22 - Overview of CarbonS-1 sample dimensions, weight and density

Sample	t [mm]	w [mm]	l [mm]	volume [mm ³]	mass [g]	ρ [kg/m ³]
CarbonS-1_L_1	2.76	16.72	552.6	25559.44	14.1	551.65
CarbonS-1_L_2	2.78	16.90	552.2	26008.68	14.9	572.88
CarbonS-1_L_3	2.81	16.86	552.0	26232.56	15.2	579.43
CarbonS-1_L_4	2.79	16.07	552.0	24769.91	14.3	577.31
CarbonS-1_L_5	2.79	15.15	552.2	23343.75	13.2	565.46
CarbonS-1_T_1	2.80	16.08	552.0	23268.92	14.0	601.66
CarbonS-1_T_2	2.87	16.81	552.0	24193.51	14.6	603.46
CarbonS-1_T_3	2.79	16.16	552.0	24929.54	13.8	553.56
CarbonS-1_T_4	2.79	15.69	552.0	24193.51	13.5	558.00
CarbonS-1_T_5	2.76	15.24	552.0	23268.92	13.1	562.98

However, testing of the CarbonS-1_L_1 sample at 5 mm/min with this arrangement revealed that the sample did not break, despite exhibiting audible evidence of cracking. This data is not shown because a computer error prevented it from being captured. Manually, it was determined that the sample began to exhibit cracking at around 9 N and 25 mm of displacement. In addition, the exam lasted more than 15 minutes.

The setup was altered to a 3-point configuration and the testing speed was raised to 10 mm/min after this sample testing since the standard advises the use of a testing speed to produce failure within 3 to 6 min. This setup was applied to the same sample as it had not yet failed.

The stress-strain curve for longitudinal samples is shown in Figure 47. The same curve is shown in Figure 48 for transverse samples.

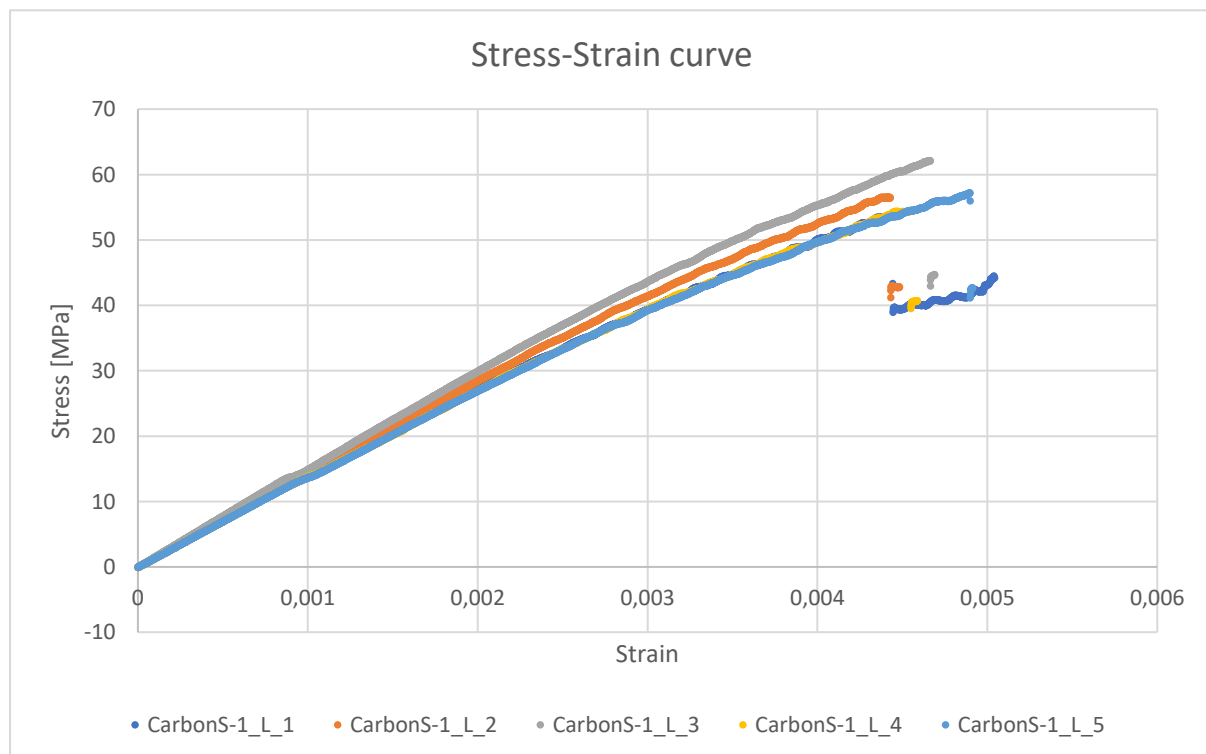


Figure 47 - Stress-strain curves for the longitudinal CarbonS-1 samples

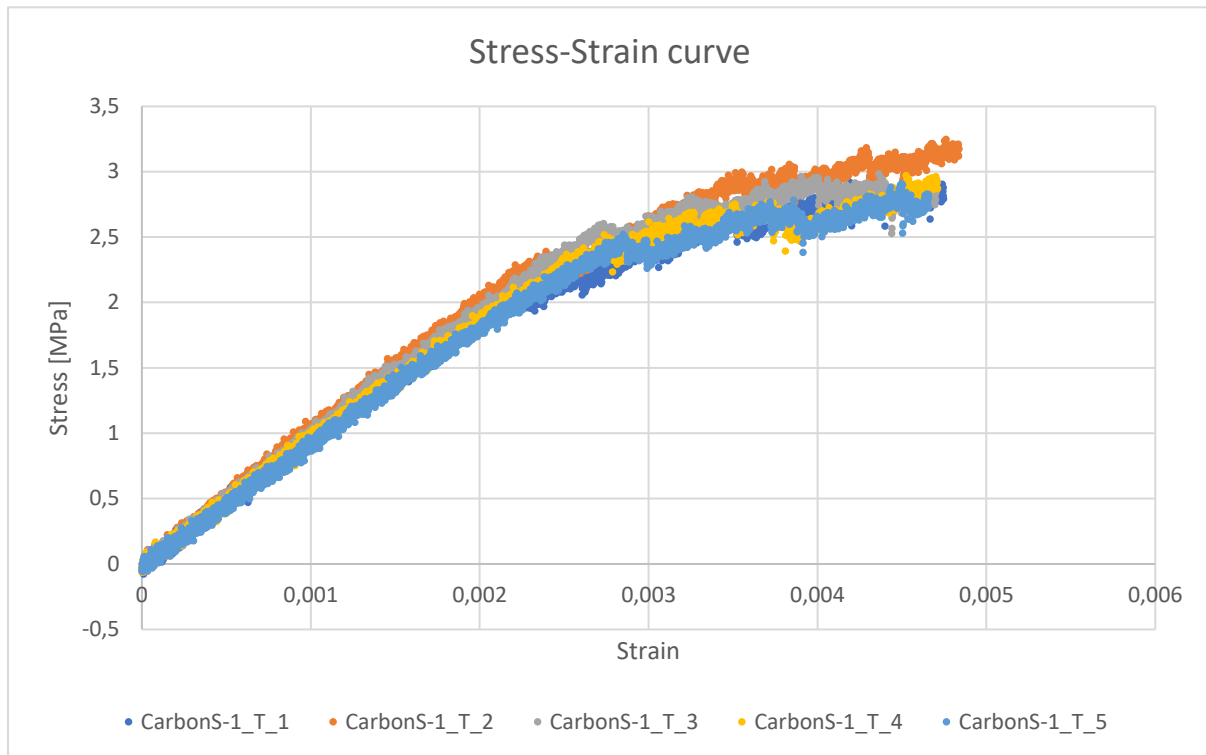


Figure 48 - Stress-strain curves for the transverse CarbonS-1 samples

Compared to the two curves, the transversal samples exhibit a greater degree of data noise. This is probably owing to the samples' uneven thickness, which prevented the cylindrical pivot from touching the whole width of the sample. In addition, the transversal samples did not break due to the non-visible cracking that can be observed in the curves when the tension rapidly drops and was also audible.

The existence of these cracks enabled the material to bend, preventing it from breaking. This indicates that in the fibre direction, there is a larger strength, but it breaks fairly immediately, but in the transverse direction, there is a lesser strength, but it did not break at the same strain.

In the elastic portion of both curves, each sample exhibited identical behaviour and findings, as well as a comparable maximum force before breaking. Each sample exhibits cracking in the same area of strain values on the transverse curve. This shows that the samples had extremely comparable behaviour, which increases the credibility of the results.

The data was smoothed (for the cross-sectional samples) and analysed in Excel. Table 23 displays the values for the Facing ultimate strength and Young's modulus.

Table 23 - Facing ultimate strength and Young's modulus of CarbonS-1 samples

SPECIMEN	FACING ULTIMATE STRENGTH [MPA]	YOUNG'S MODULUS [GPA]
CarbonS-1_L_1	462.69	12.83
CarbonS-1_L_2	472.17	13.54
CarbonS-1_L_3	506.22	14.41
CarbonS-1_L_4	475.54	12.81
CarbonS-1_L_5	530.96	12.82
Average	489.52	13.28
CarbonS-1_T_1	25.57	0.81
CarbonS-1_T_2	25.57	0.82
CarbonS-1_T_3	26.02	0.95
CarbonS-1_T_4	26.72	0.85
CarbonS-1_T_5	26.43	0.88
Average	26.06	0.87

The Young's Modulus results can be compared to the simulation results, but the ultimate tensile strength cannot since, in order to do a strength analysis in ESAComp, the initial failure stresses and strains of the prepreg must be determined, and these values were unavailable.

In terms of the Young's modulus, there is an inaccuracy of 190,6% in the longitudinal direction and 228,0% in the transverse direction when comparing the measured values to the simulated values. Nevertheless, the anisotropy is 15,34 which means an error of only 11%.

7.4 CarbonS-1 dynamic testing

The Impact Hammer Test (TAP Testing) was done to evaluate the dynamic response of the CarbonS-1 material. The examined plate measurements can be seen in Table 24. The impact points were the same as in chapter 6.3.

Table 24 - Overview of CarbonS-1 plate dimensions, weight and density

Sample	t [mm]	w [mm]	l [mm]	volume [mm ³]	mass [g]	ρ [kg/m ³]
CarbonS-1	2.78	290	218	175751.60	100.9	573.99

The data was analysed using MATLAB to get the natural frequencies and damping coefficients (the MATLAB code used are shown in appendixes D1 and D2). The test outcomes are shown in Figures 49 and 50 and in Table 25.

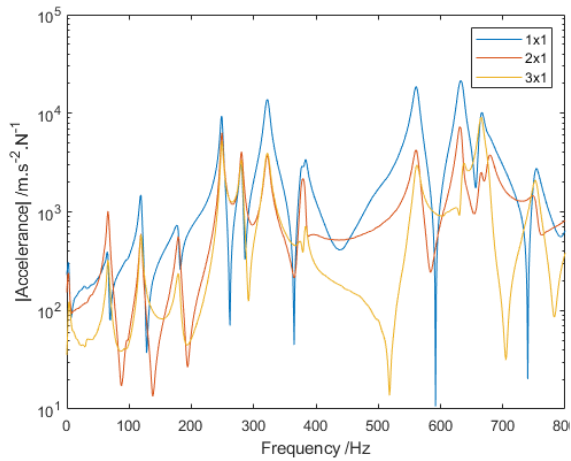


Figure 49 - FRF's obtained from CarbonS-1 dynamic testing

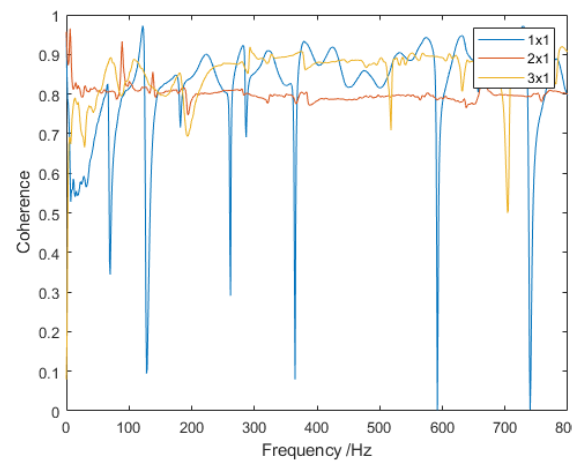


Figure 50 - Coherence plot of CarbonS-1 dynamic testing

When comparing the results of Table 25 to those in Table 14, an average difference of 16% is observed for the first eight natural frequencies. However, the relative difference in the first four frequencies is greater (19%). However, the mid-range frequencies, which are regarded as the most challenging to mimic, are close to the target wood frequencies.

When comparing the first four frequencies with those simulated, the average difference is 22%, while the difference for the first frequency is 55%. In chapter 6.3, the error between the simulated and experimental initial frequency is similar to that seen above. This error may have occurred because the material was not fully described and some of its properties were coarsely estimated.

Table 25 - CarbonS-1 plate natural frequencies and damping

	FREQUENCY [HZ]	RELATIVE DIFFERENCE [%]	DAMPING
1st Natural frequency	82.63	32	0.028
2nd Natural frequency	162.00	5	0.011
3rd Natural frequency	234.71	19	0.0093
4th Natural frequency	283.74	18	0.0087
5th Natural frequency	326.83	21	0.010
6th Natural frequency	361.47	19	0.0075
7th Natural frequency	501.73	10	0.010
8th Natural frequency	605.94	0	0.0066
9th Natural frequency	644.25	--	0.0087
10th Natural frequency	669.52	--	0.0072
11th Natural frequency	753.91	--	0.010

8 Development of a CarbonT-1 alternative

The thin-ply prepreg is the second material chosen to be the carbon base for another sandwich material. This was chosen owing to the material's reduced thickness, which would allow for a more effective layup choice.

A thin-ply composite of T800 fibres and ThinPreg™ 80EP-736 toughened epoxy resin by North Thin Ply Technology (NTPT) was used. Due to material limitations on the NTPT T800 prepreg with a fibre areal weight (FAW) of 50 g/m², two rolls with different fibre areal weights were used. One of the prepreg unidirectional rolls has a fibre areal weight (FAW) of 50 g/m² and was used for the dynamic testing, and the other of 100 g/m² was used for the flexural testing (both with a weight resin composition of 38%). This was possible because the rolls are equivalent in terms of properties.

In contrast to Chapter 7, this prepreg was not studied to identify its real mechanical characteristics since Danzi et al. [59] had previously exhaustively characterised the material in prior studies (properties in Table 26). Additional actions consisted of selecting the layup configurations, choose the layup, manufacture the samples, and study its elastic and dynamic properties to compare them to the wood baseline done in Chapter 6.

Table 26 - T800 thin-ply properties [59]

PROPERTIES	T800 THIN-PLY
E_1 [GPa]	148.36 (± 6.37)
E_2 [GPa]	8.01 (± 0.35)
Anisotropy [-]	18.52
ν_{12} [-]	0.38 (± 0.06)
G_{12} [GPa]	4.73 (± 0.39)
X_T [MPa]	2923.8 (± 97.4)
Y_T [MPa]	63.76 (± 8.24)
S_{12} [MPa]	145.74 (± 2.39)

8.1 ESAComp composite simulations

Composite frequency simulations were performed since the material had already been characterized. Similarly to Chapter 6.2, the layups of the laminates were simulated, followed by a 2.5D behaviour analysis and natural frequency simulation to select the most promising layup. Additionally, the potential layups were examined in greater detail to determine which ones would be picked for manufacturing and testing.

The frequency analyses for the most promising layups using the 50 g/m² layers are shown in Table 27.

Table 27 - Frequency error analysis overview for simulated CarbonT-1 layups

Option	f_{1-4} error [%]	f_1 error [%]	R error [%]	Anisotropy error [%]	Carbon fibre composite layers 1	PVC layers 1	Carbon fibre composite layers 2	PVC layers 2	Carbon fibre composite layers 3
1	10.25	18.76	260.32	10.75	1	2	2	1	1
2	10.31	17.69	158.65	26.78	3	1	3	1	3
3	10.51	16.00	171.63	25.62	3	1	2	1	3
4	10.52	10.68	422.08	27.41	4	1	3	1	4
5	10.64	15.78	274.17	7.59	1	2	1	1	1
6	10.76	13.96	186.32	24.58	3	1	1	1	3
7	10.77	21.40	242.23	14.01	1	2	3	1	1
8	10.79	19.38	242.00	18.95	2	2	0	0	2
9	11.04	12.73	273.52	2.69	1	3	0	0	1
10	11.05	8.72	72.23	30.26	5	1	12	1	5
11	11.05	8.67	75.93	30.42	5	1	11	1	5
12	11.06	8.54	79.91	29.97	5	1	10	1	5
13	11.06	8.71	68.79	30.44	5	1	13	1	5
14	11.07	11.50	202.90	23.62	3	2	0	0	3
15	11.07	8.64	65.59	30.48	5	1	14	1	5
16	11.08	8.35	84.21	29.83	5	1	9	1	5
17	11.10	8.51	62.58	30.83	5	1	15	1	5

An issue emerged in these simulations, since the sound radiation coefficient and anisotropy errors were very high. However, the three most promising scenarios were identified. The 5-1-X-1-5 layups, where X is greater than 10, had the lowest sound radiation coefficient and around 30% anisotropy differences. Since all layups with lower anisotropy differences also had large R differences, they were disregarded. However, for the layups analysed, where X was less than 13, the difference of the sound radiation coefficient was more than 70 percent, which was regarded as too high, and those instances were excluded.

As the number of mid-carbon layers increased for the investigated examples (marked yellow and green in Table 27), the R difference decreased with an increase in the anisotropy difference. As a result, the number 17 in Table 27 was selected as a compromise between the sound radiation coefficient and anisotropy.

8.2 CarbonT-1 flexural testing

Due to material limitations on the NTPT T800 prepreg with an areal weight of 50 g/m², the NTPT T800 prepreg with an areal weight of 100 g/m² was tested. Since the composite simulations were done with the 50 g/m², the tested layup was simulated with the new areal weight (100 g/m²). The simulation results are shown in Table 28.

Nevertheless, the two materials are equivalent, so the test results can be also considered for the NTPT T800 prepreg with an areal weight of 50 g/m².

Table 28 - 100 g/m² CarbonT-1 composite simulation

E_{f1} [GPa]	E_{f2} [GPa]	ρ [kg/m ³]	Carbon fibre composite layers 1	PVC layers 1	Carbon fibre composite layers 2	PVC layers 2	Carbon fibre composite layers 3
84.09	4.58	591.11	5	1	15	1	5

Flexural testing was conducted using the method described in chapter 5.4. Table 29 shows the average of the five dimensions measured for the CarbonT-1 sample.

Table 29 - Overview of CarbonS-1 sample dimensions, weight and density

Sample	t [mm]	w [mm]	l [mm]	volume [mm ³]	mass [g]	ρ [kg/m ³]
CarbonT-1_1	3.78	15.53	536.0	31497.89	34.8	1105.78
CarbonT-1_2	3.73	15.44	535.5	30877.16	33.5	1084.62
CarbonT-1_3	3.73	15.23	533.6	30366.58	33.5	1103.84
CarbonT-1_4	3.74	15.17	535.0	30386.12	33.6	1104.78
CarbonT-1_5	3.76	15.13	535.0	30471.91	33.5	1098.71

The setup was a 3-point configuration and the testing speed used was 10 mm/min to be the same used in chapter 7.3. The stress-strain curves of the samples are shown in Figure 51.

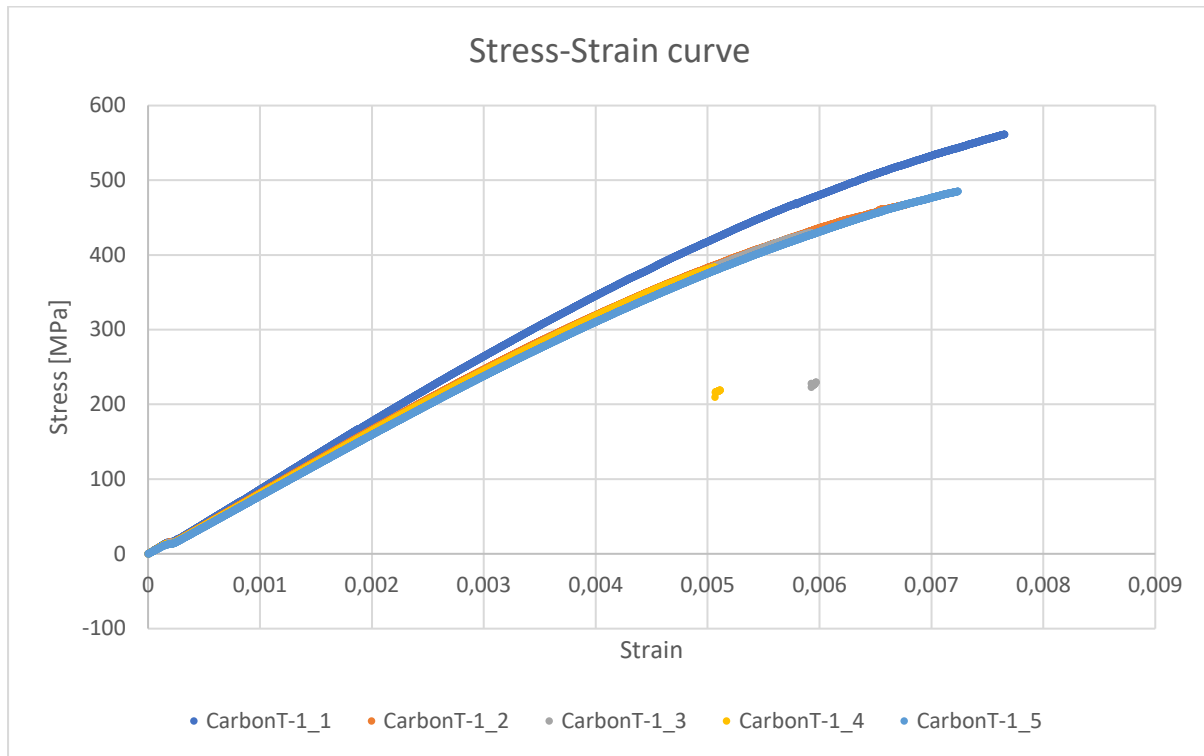


Figure 51 - Stress-strain curves for the CarbonT-1 samples

Table 30 - Facing ultimate strength and Young's modulus of CarbonT-1 samples

SPECIMEN	Facing ultimate strength [MPa]	Young's modulus [GPa]
CarbonT-1_1	1262.82	89.08
CarbonT-1_2	1107.52	82.67
CarbonT-1_3	1088.06	81.45
CarbonT-1_4	968.712	82.36
CarbonT-1_5	1182.40	80.31
Average	1121.90	83.17

Comparing the values from Table 28 and Table 30 an error of 1% can be observed. However, due to material limitations, it was not possible to analyse the transverse direction which made it impossible to determine the anisotropy.

8.3 CarbonT-1 dynamic testing

The Impact Hammer Test (TAP Testing) was done to evaluate the dynamic response of the CarbonT-1 material. The examined plate measurements can be seen in Table 31. The impact points were the same as in chapter 6.3.

For this experimental part, the material used was the NTPT T800 with an areal weight of 50 g/m².

Table 31 - Overview of CarbonT-1 plate dimensions, weight and density

Sample	t [mm]	w [mm]	l [mm]	volume [mm ³]	mass [g]	ρ [kg/m ³]
CarbonT-1	1.97	283.60	217.0	121113.08	138.8	1145.62

The data was analysed using MATLAB to get the natural frequencies and damping coefficients (the MATLAB code used are shown in appendixes D1 and D2). The test outcomes are shown in Figures 52 and 53 and in Table 32.

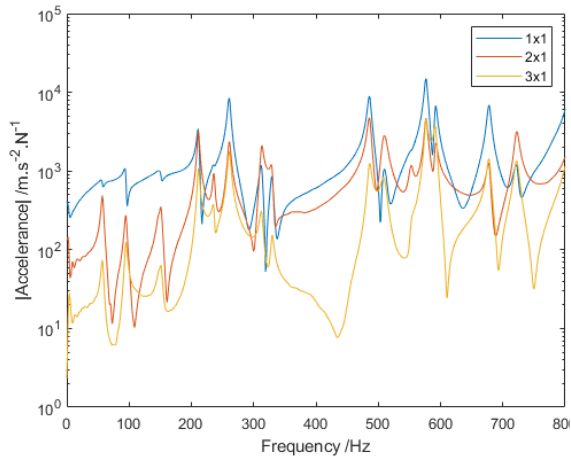


Figure 52 - FRFs obtained from CarbonT-1 dynamic testing

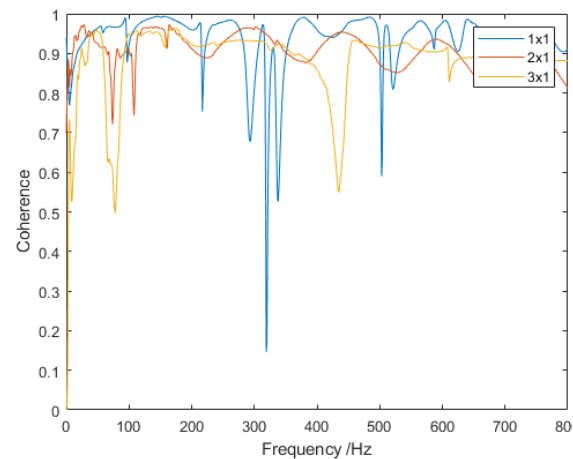


Figure 53 - Coherence plot of CarbonT-1 dynamic testing

When comparing the results of Table 32 with those in Table 14, an average difference of 15% is observed for the first eight natural frequencies. However, the difference in the first four frequencies is greater (22%). However, just like the CarbonS-1 material, the mid-range frequencies are close to the reference wood frequencies.

Table 32 - CarbonT-1 plate natural frequencies and damping

	FREQUENCY (HZ)	RELATIVE DIFFERENCE [%]	DAMPING
1st Natural frequency	170.64	41%	0.015
2nd Natural frequency	212.62	25%	0.040
3rd Natural frequency	261.60	10%	0.0069
4th Natural frequency	300.97	13%	0.0084
5th Natural frequency	375.68	9%	0.0053
6th Natural frequency	494.01	10%	0.0065
7th Natural frequency	524.09	6%	0.0076
8th Natural frequency	576.89	5%	0.0039
9th Natural frequency	592.67	--	0.0058
10th Natural frequency	677.59	--	0.0040
11th Natural frequency	722.12	--	0.0038

9 Analysis of the results

After completing the study, it is possible to compare the natural frequencies and damping of the newly produced materials and the wood baseline. In Tables 34 and 35, these analyses are conducted, and a large variation is seen between the two materials and the wood baseline. For an easier analysis, the natural frequencies and damping are also shown in Figures 54 and 55.

The anisotropy of CarbonS-1 is much higher than that of wood. Nevertheless, since the literature values for this material property range from 10 to 15, the results may be regarded as typical. When compared to the wood baseline, the Young's modulus has a large percent error. However, this was expected because the Young's modulus of carbon fibre composites is much higher. Moreover, the objective was to mimic the anisotropy and not the Young's modulus, with the sole criterion being that the material not be excessively stiff so that it could bend and vibrate more effectively.

Table 33 - Frequency comparison between wood, CarbonS-1 and CarbonT-1

	WOOD	CARBONS-1	CARBONT-1
E_1 [GPa]	12-16	13.28	83.17
E_2 [GPa]	0.8-1.25	0.86	--
Anisotropy	10-12	15.34	--
f_1 [Hz]	120.86	82.63	170.64
f_2 [Hz]	170.56	162.01	212.62
f_3 [Hz]	290.10	234.71	261.60
f_4 [Hz]	347.81	283.74	300.97
f_5 [Hz]	414.36	326.83	375.68
f_6 [Hz]	447.66	361.47	494.01
f_7 [Hz]	556.08	501.73	524.09
f_8 [Hz]	607.13	605.94	576.89

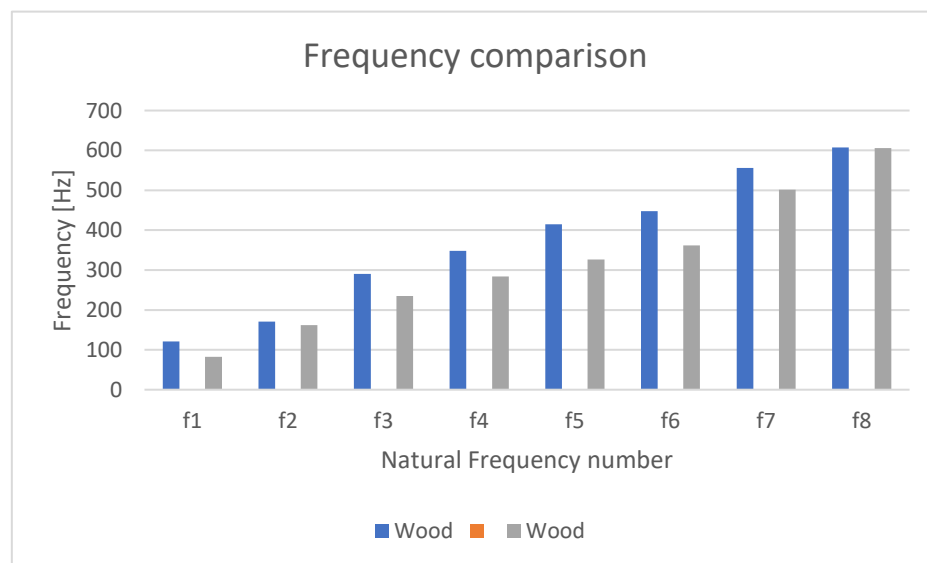


Figure 54 - Frequency comparison between wood, CarbonS-1 and CarbonT-1

In terms of natural frequencies, CarbonT-1 showed a lower average difference of 15% compared to the 16% average difference of CarbonS-1. However, both CarbonS-1 and CarbonT-1 frequencies are very variable, and only a more complete baseline might give more insights into those results.

Table 34 - Damping comparison between wood, CarbonS-1 and CarbonT-1

	WOOD	CARBONS-1	CARBONT-1
E_1 [GPa]	4.02	13.28	83.17
E_2 [GPa]	0.40	0.86	--
Anisotropy	9.82	15.34	--
ζ_1	0.023	0.028	0.014
ζ_2	0.019	0.011	0.04
ζ_3	0.027	0.0093	0.0070
ζ_4	0.0079	0.0087	0.0084
ζ_5	0.0087	0.010	0.0054
ζ_6	0.013	0.0075	0.0065
ζ_7	0.0097	0.010	0.0076
ζ_8	0.011	0.0067	0.0040

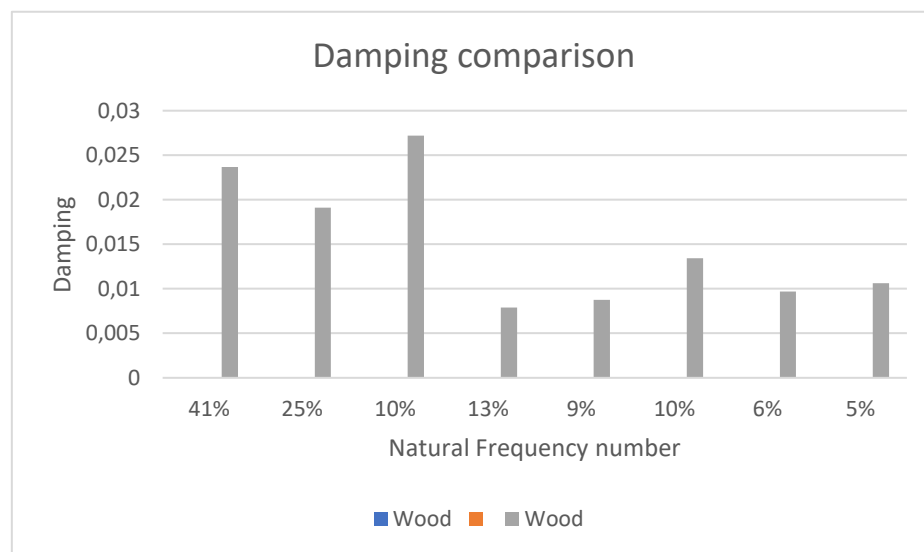


Figure 55 - Damping comparison between wood, CarbonS-1 and CarbonT-1

Regarding damping, the reverse holds true. CarbonS-1 more closely resembles the examined wood. Especially in the early modes, the CarbonT-1 plate exhibited very significant differences. CarbonT-1 showed an average difference of 50% and CarbonS-1 of 30%.

Overall, the CarbonS-1 sandwich structure presented more promising results, even though the relative differences in natural frequencies are a little higher than in CarbonT-1. However, the damping is closer to the wood baseline, while CarbonT-1 turned out being too stiff. In addition, the density of CarbonT-1 was too high due to apparent crushing of the PVC foam during processing.

10 Conclusions and recommendations

The research target of developing two new composite materials that might replace wood in the soundboard of a guitar, the most important component in the instrument's sound production, was not met. In terms of natural frequencies and damping, both new materials deviated significantly from the established wood baseline.

The CarbonS-1 solution demonstrated more promising results, and it is recommended that this newly produced composite is incorporated into a composite guitar soundboard and that additional research is conducted.

Several observations might be made while evaluating the research critically:

First, the baseline for wood is derived from a single wooden plate, resulting in a set of values rather than a range of values. In addition, the wood is evaluated based on the regularity of its grain, not its acoustic qualities, rendering the conclusions of a single plate inconclusive. In addition, the absence of other wood data makes it hard to link mechanical properties with acoustic properties since the analysed wood may represent an exception to the norm. A more extensive investigation into the guitar qualities of tonewood would be advantageous in order to have more data to compare and a range of values for the material, as opposed to simply one set of results.

Second, the finite element analysis performed was limited, leading to bad predictions; hence, the usage of more robust software is recommended.

It is expected that the composite will become more economically viable in the future due to the current trends in the price of high-quality wood.

Several suggestions for future efforts can be recommended. First, it is suggested to develop a composite guitar soundboard using the CarbonS-1 solution and to perform modal and psychoacoustic research. It is also recommended to further explore the design of laminates with multidirectional stacking sequences using the CarbonS-1 and CarbonT-1 material systems. In addition, a thorough investigation of the mechanical and dynamic properties of tonewoods is suggested to provide a more solid foundation for future composite advancements.

The last suggestion for future study is to examine acoustic metamaterials and their possible uses for musical instruments in more depth. Using additive manufacturing and advanced modelling tools, a material that more closely resembles the acoustic response of wood might be generated.

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Appendixes

A1. Wood sample width measurements

	w[mm]					Average
W-L-1	10,33	9,97	10,47	10,65	10,54	10,392
W-L-2	10,45	10,45	10,93	10,56	10,38	10,554
W-L-3	10,41	10,39	10,61	10,59	10,67	10,534
W-L-4	9,61	9,69	10,60	10,62	9,94	10,130
W-L-5	10,42	10,48	10,13	10,00	10,14	10,234
W-L-6	10,10	10,36	9,44	9,76	9,31	9,794
W-L-7	9,94	9,89	10,38	9,85	10,20	10,052
W-L-8	10,04	9,72	9,86	9,95	9,95	9,904
W-L-9	10,04	10,25	10,00	9,99	9,64	9,984
W-L-10	9,70	9,97	10,33	9,74	9,82	9,912
W-T-1	24,29	24,99	25,01	24,24	24,87	24,680
W-T-2	24,83	24,75	24,89	24,89	24,81	24,834
W-T-3	25,24	25,21	25,29	25,29	25,37	25,280
W-T-4	24,49	24,68	24,57	24,64	24,79	24,634
W-T-5	25,60	25,69	26,21	26,11	25,77	25,876
W-T-6	25,12	25,71	25,56	25,13	25,38	25,380
W-T-7	24,89	24,89	24,98	25,13	25,19	25,016
W-T-8	25,05	25,36	25,53	25,18	25,40	25,304
W-T-9	24,77	24,77	24,88	24,97	25,03	24,884
W-T-10	25,43	25,79	26,06	26,14	26,20	25,924

A2. Wood sample length measurements

	l[mm]					Average
W-L-1	99,32	99,53	99,51	99,52	99,27	99,430
W-L-2	99,18	99,27	99,05	99,19	99,29	99,196
W-L-3	99,47	99,27	99,41	99,40	99,41	99,392
W-L-4	99,61	99,40	99,42	99,43	99,50	99,472
W-L-5	99,40	99,36	99,50	99,27	99,61	99,428
W-L-6	99,37	99,70	99,74	99,55	99,28	99,528
W-L-7	100,13	100,09	100,08	99,97	100,12	100,078
W-L-8	99,82	99,72	99,70	99,66	99,75	99,730

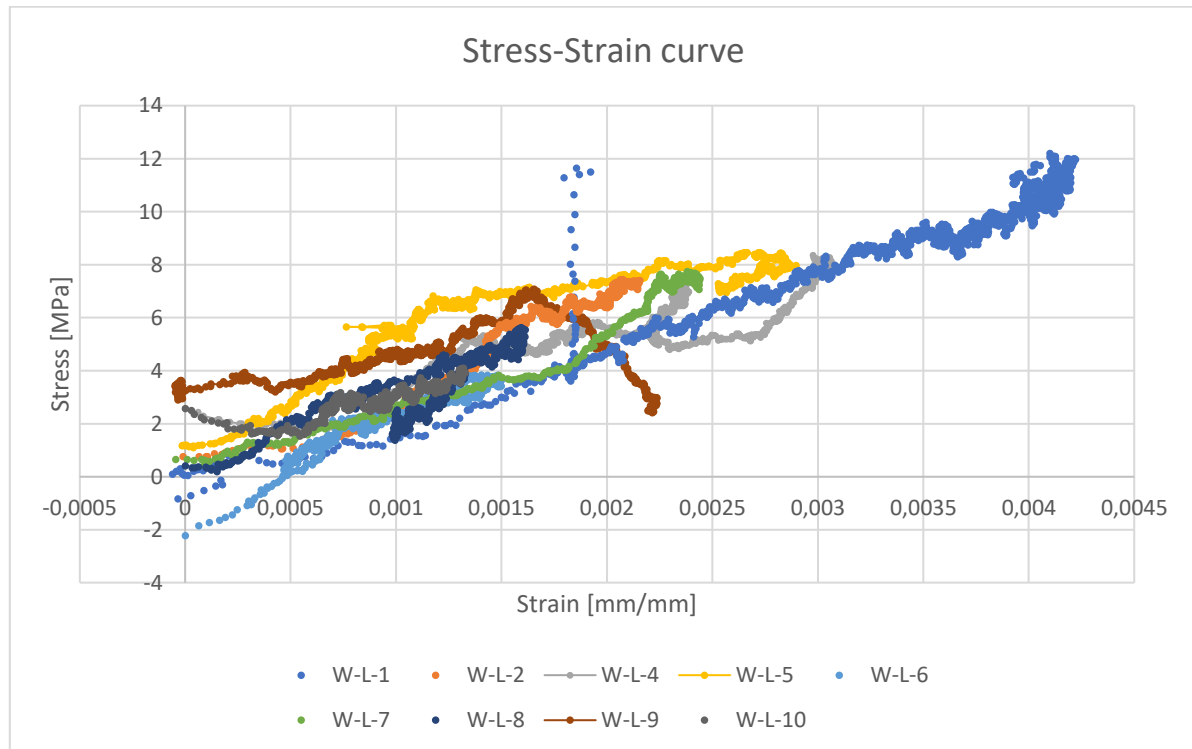
W-L-9	99,76	99,84	99,76	99,70	99,90	99,792
W-L-10	99,80	100,01	99,99	99,90	99,88	99,916
W-T-1	99,84	99,78	99,88	99,80	99,98	99,856
W-T-2	100,27	99,87	99,85	100,01	99,94	99,988
W-T-3	100,29	99,94	99,95	99,96	99,83	99,994
W-T-4	100,11	99,97	99,81	99,94	99,95	99,956
W-T-5	100,04	100,13	100,01	99,98	100,15	100,062
W-T-6	100,84	101,07	100,69	101,03	100,96	100,918
W-T-7	99,60	99,73	99,66	99,65	99,64	99,656
W-T-8	99,77	99,80	99,68	99,87	99,91	99,806
W-T-9	100,04	99,58	99,60	99,96	99,56	99,748
W-T-10	99,48	99,36	99,65	99,49	99,43	99,482

A3. Wood sample thickness measurements

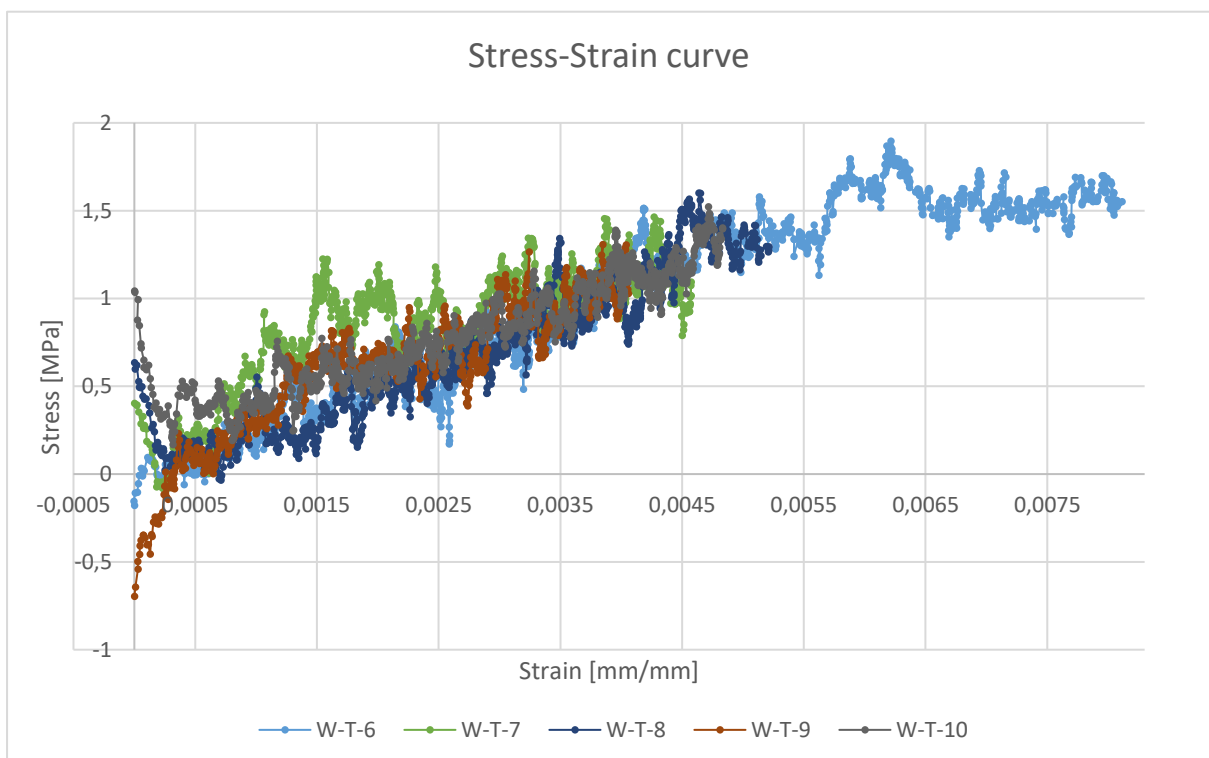
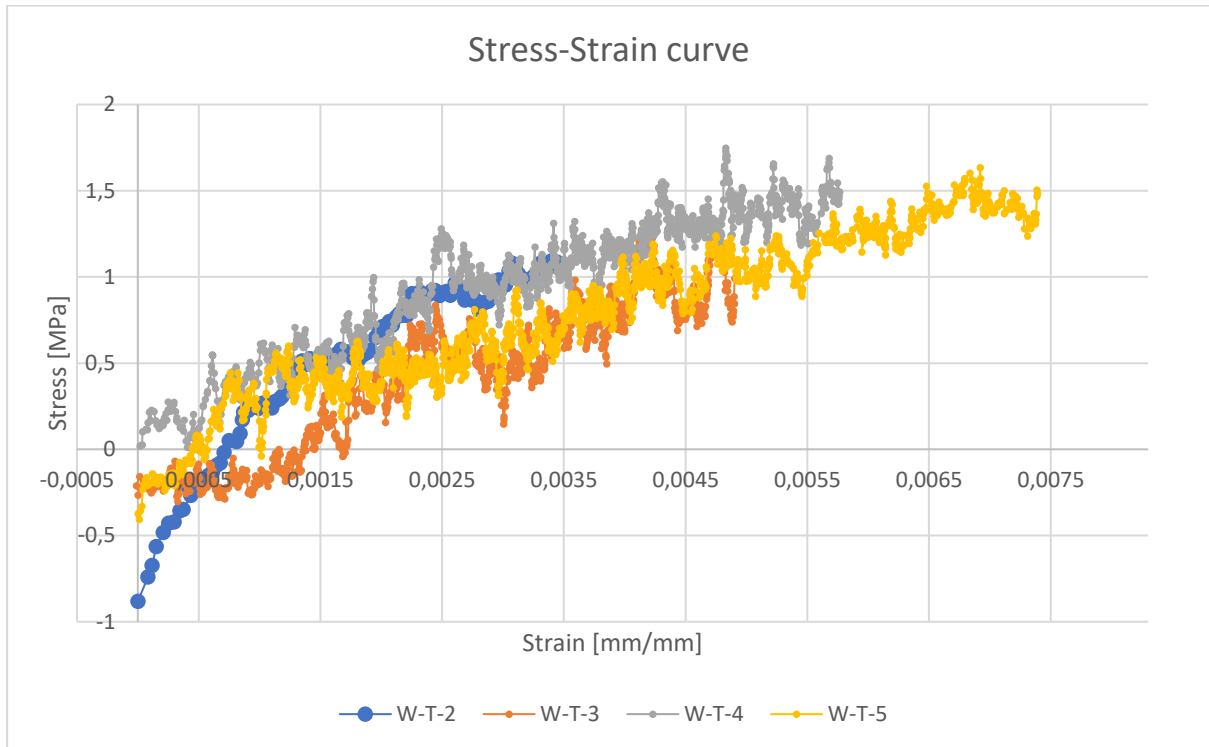
	t[mm]					Average
W-L-1	5,35	5,29	5,25	5,28	5,29	5,292
W-L-2	5,25	5,35	5,33	5,41	5,29	5,326
W-L-3	5,08	5,18	5,14	5,5	5,19	5,218
W-L-4	5,09	5,21	5,13	5,17	5,14	5,148
W-L-5	5,1	5,2	5,15	5,14	5,14	5,146
W-L-6	5,27	5,29	5,27	5,31	5,27	5,282
W-L-7	5,24	5,37	5,34	5,27	5,38	5,320
W-L-8	5,16	5,24	5,17	2,23	5,17	4,594
W-L-9	5,13	5,28	5,22	5,23	5,26	5,224
W-L-10	5,25	5,17	5,13	5,17	5,16	5,176
W-T-1	5,51	5,65	5,55	5,7	5,65	5,612
W-T-2	5,52	5,53	5,63	5,5	5,62	5,560
W-T-3	5,59	5,4	5,59	5,53	5,55	5,532
W-T-4	5,4	5,51	5,36	5,53	5,44	5,448
W-T-5	5,42	5,33	5,43	5,5	5,47	5,430
W-T-6	5,51	5,65	5,65	5,58	5,63	5,604
W-T-7	5,44	5,62	5,6	5,52	5,66	5,568
W-T-8	5,46	5,51	5,54	5,43	5,45	5,478
W-T-9	5,49	5,44	5,47	5,47	5,5	5,474

W-T-10	5,33	5,31	5,46	5,44	5,35	5,378
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A4. Stress-strain curves for the longitudinal wood samples



A5. Stress-strain curves for the transverse wood samples



A6. Wood tensile test results

	Pmax [N]	Ultimate tensile strength [MPa]	ϵ_1	ϵ_2	F1	F2	σ_1	σ_2	E1
W-L-1	889,8684	16,18105	0,0010 16	0,0030 02	81,457 28	427,45 21	1,4811 91	7,7726 39	3,1693 52
W-L-2	1102,894 3	19,62075	0,0005 12	0,0015 03	60,381 53	317,13 34	1,0742 02	5,6418 78	4,6090 24
W-L-3	737,7421	13,42169	0,0005	0,0009 98	218,57 5	342,09 96	3,9765 18	6,2237 94	4,5075 96
W-L-4	661,2247	12,67947	0,0008 06	0,0011 01	115,21 31	210,26 46	2,2092 95	4,0319 78	6,1847 08
W-L-5	628,3756	11,93175	0,0005 01	0,0010 01	159,96 21	309,65 46	3,0374	5,8797 98	5,6855 47
W-L-6	449,4411	8,687889	0,0007	0,001	77,339 43	126,25 74	1,4950 04	2,4406 09	3,1530 15
W-L-7	644,3289	12,04879	0,0004 92	0,0015 03	67,966 13	200,63 27	1,2709 5	3,7517 83	2,4543 55
W-L-8	376,4601	8,274035	0,0003 02	0,0009 94	35,763 11	163,20 17	0,7860 2	3,5869 31	4,0491 75
W-L-9	518,6571	9,944263	0,0004 99	0,0009 99	186,06 56	237,91 69	3,5674 54	4,5616 03	1,9888 66
W-L-10	640,4645	12,48359	0,0006 02	0,0010 01	98,857 09	158,28 14	1,9268 69	3,0851 36	2,8992 7
Average	730,5535 857	13,5102	0,0006 47	0,0014 44	111,55 64	276,21 35	2,0777 94	5,1060 68	4,0255 56

A7. Wood tensile test Young's modulus and Poisson's ratio

SPECIMEN	POISSON'S RATIO	YOUNG'S MODULUS [GPa]
W-L-1	0.281892509	3.169352
W-L-2	-0.275468528	4.609024
W-L-3	0.576167429	4.507596
W-L-4	0.191874669	6.184708
W-L-5	-0.178589974	5.685547
W-L-6	0.96140111	3.153015

W-L-7	-0.155291713	2.454355
W-L-8	-0.141031105	4.049175
W-L-9	0.791384336	1.988866
W-L-10	1.218829396	2.89927
W-L-AVERAGE	0.327116813	4.025556
W-T-1	---	---
W-T-2	-0.05763	0.466326906
W-T-3	-0.02814	0.563527183
W-T-4	-0.08598	0.198253511
W-T-5	-0.05593	0.320247655
W-T-6	-0.02987	0.314315954
W-T-7	-0.04928	0.61664744
W-T-8	-0.03232	0.43214604
W-T-9	0.008833	0.52082925
W-T-10	-0.05888	0.255236343
W-T-AVERAGE	-0.04324	0.409725587

A8. Wood TAP testing frequency results

f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	Average
121,3061	120,627	120,6675	120,8669
170,6178	170,693	170,3764	170,5624
290,2314	289,981	290,1162	290,1096
347,3613	347,900	348,1879	347,8164
412,927	416,151	414,0295	414,369
447,918	447,383	447,683	447,6615
556,3692	556,957	554,9367	556,0876
610,6597	604,924	605,81	607,1313

A9. Wood TAP testing damping results

d_1	d_2	d_3	Average
0,0281	0,019	0,0235	0,0237
0,0196	0,020	0,0181	0,0191
0,0439	0,020	0,0182	0,0272
0,0082	0,0079	0,0076	0,0079

0,0081	0,0085	0,0097	0,0088
0,0134	0,0135	0,0134	0,0134
0,0101	0,0094	0,0096	0,0097
0,0104	0,014	0,0075	0,0106

B1. CarbonS-1 flexural samples width measurements

	w[mm]					Average
CARBONS-1_1	15,72	17,63	17,21	16,75	16,30	16,722
CARBONS-1_2	18,02	17,36	16,96	16,34	15,85	16,906
CARBONS-1_3	17,68	17,33	17,06	16,45	15,80	16,864
CARBONS-1_4	15,75	16,21	16,46	16,15	15,79	16,072
CARBONS-1_5	13,71	14,97	15,78	15,75	15,55	15,152
CARBONS-1_T_1	15,83	15,89	15,96	16,03	16,73	16,088
CARBONS-1_T_2	15,55	16,04	16,76	17,60	18,12	16,814
CARBONS-1_T_3	15,74	15,99	16,18	16,65	16,26	16,164
CARBONS-1_T_4	15,82	15,57	15,70	15,73	15,67	15,698
CARBONS-1_T_5	15,36	15,49	15,51	15,09	14,75	15,240

B2. CarbonS-1 flexural samples length measurements

	l[mm]					Average
CARBONS-1_1	552,00	553,00	553,00	553,00	552,00	552,6
CARBONS-1_2	553,00	552,00	552,00	552,00	552,00	552,2
CARBONS-1_3	552,00	552,00	552,00	552,00	552,00	552,0
CARBONS-1_4	552,00	552,00	552,00	552,00	552,00	552,0
CARBONS-1_5	552,00	552,00	552,00	553,00	552,00	552,2
CARBONS-1_T_1	552,00	552,00	552,00	552,00	552,00	552,0

CARBONS-1_T_2	552,00	552,00	552,00	552,00	552,00	552,0
CARBONS-1_T_3	552,00	552,00	552,00	552,00	552,00	552,0
CARBONS-1_T_4	552,00	552,00	552,00	552,00	552,00	552,0
CARBONS-1_T_5	552,00	552,00	552,00	552,00	552,00	552,0

B3. CarbonS-1 flexural samples thickness measurements

	t[mm]					Average
CARBONS-1_1	2,77	2,78	2,78	2,74	2,76	2,766
CARBONS-1_2	2,72	2,79	2,81	2,8	2,81	2,786
CARBONS-1_3	2,75	2,78	2,78	2,95	2,83	2,818
CARBONS-1_4	2,74	2,78	2,81	2,81	2,82	2,792
CARBONS-1_5	2,77	2,81	2,75	2,82	2,8	2,790
CARBONS-1_T_1	2,8	2,8	2,8	2,81	2,79	2,800
CARBONS-1_T_2	2,82	3,12	2,78	2,82	2,81	2,870
CARBONS-1_T_3	2,81	2,79	2,76	2,78	2,83	2,794
CARBONS-1_T_4	2,83	2,79	2,75	2,76	2,83	2,792
CARBONS-1_T_5	2,78	2,75	2,76	2,79	2,75	2,766

B4. CarbonS-1 composite simulations

f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]	E_1 [GPa]	E_2 [GPa]	ρ [kg/m ³]	Carbon fibre layers 1	PVC layers 1	Carbon fibre layers 2	PVC layers 2	Carbon fibre layers 3
76,39	77,4	163,55	172,42	124,22	8,91	1572,00	5	0	0	0	5
142,32	155,76	295,84	301,7	74,57	5,39	975,20	5	1	0	0	5
205,79	233,2	409,64	421,38	53,29	3,88	719,43	5	2	0	0	5
207,35	234,94	412,88	424,69	56,2	4,09	754,52	5	1	1	1	5
209,22	237,03	416,74	428,63	58,89	4,28	786,74	5	1	2	1	5

211,37	239,43	421,18	433,16	61,37	4,45	816,46	5	1	3	1	5
263,96	307,01	506,35	527,19	41,46	3,04	577,33	5	3	0	0	5
263,26	306,4	504,57	525,51	44,11	3,23	609,46	5	2	1	1	5
262,94	306,21	503,61	524,67	46,54	3,4	639,58	5	2	2	1	5
263,01	306,43	503,46	524,64	48,8	3,56	667,68	5	2	3	1	5
263,26	306,4	504,57	525,51	44,11	3,23	609,46	5	1	1	2	5
262,94	306,21	503,61	524,67	46,54	3,4	639,58	5	1	2	2	5
263,01	306,43	503,46	524,64	48,8	3,56	667,68	5	1	3	2	5
61,13	61,92	130,85	137,98	124,22	8,91	1572,00	4	0	0	0	4
129,99	141,27	272,25	277,57	67,8	4,91	893,82	4	1	0	0	4
195,79	219,4	395,91	405,7	46,64	3,41	639,50	4	2	0	0	4
196,03	219,63	396,58	406,37	50,11	3,65	681,25	4	1	1	1	4
196,83	220,49	398,37	408,19	53,29	3,88	719,43	4	1	2	1	4
198,11	221,87	401,15	411,01	56,2	4,09	754,52	4	1	3	1	4
255,93	293,63	501,52	518,54	35,55	2,62	506,29	4	3	0	0	4
253,6	291,17	496,5	513,52	38,57	2,83	543,03	4	2	1	1	4
251,93	289,44	492,86	509,9	41,3	3,03	577,33	4	2	2	1	4
250,85	288,35	490,51	507,58	43,87	3,21	609,42	4	2	3	1	4
45,86	46,44	98,14	103,51	124,22	8,91	1572,00	3	0	0	0	3
117,49	126,68	247,99	252,95	58,89	4,28	786,74	3	1	0	0	3
185,19	204,89	380,91	389,18	38,61	2,84	543,03	3	2	0	0	3
183,32	202,77	377,26	385,45	42,82	3,14	593,64	3	1	1	1	3
182,52	201,83	375,8	383,96	46,64	3,41	639,50	3	1	2	1	3
182,55	201,82	376,07	384,23	50,11	3,65	681,25	3	1	3	1	3
246,75	278,7	495,13	508,68	28,73	2,14	424,31	3	3	0	0	3
241,91	273,47	484,92	498,35	32,21	2,38	466,81	3	2	1	1	3
238,24	269,52	0	477,21	35,35	2,61	116,80	3	2	2	1	3
235,58	266,67	471,65	484,94	38,2	2,81	543,03	3	2	3	1	3
30,58	30,96	65,43	69,02	124,22	8,91	1572,00	2	0	0	0	2
104,62	111,74	222,64	227,49	46,64	3,41	639,50	2	1	0	0	2
173,14	188,7	362,64	370,15	28,73	2,14	424,31	2	2	0	0	2
167,51	182,54	351,04	358,36	33,94	2,51	944,73	2	1	1	1	2
164,16	178,86	344,2	351,42	38,61	2,84	543,10	2	1	2	1	2
162,39	176,88	340,67	347,85	42,82	3,14	593,64	2	1	3	1	2
234,66	260,28	483,32	494,36	20,77	1,57	328,67	2	3	0	0	2
225,61	250,52	464,15	474,87	24,81	1,86	378,40	2	2	1	1	2
218,87	243,28	449,94	460,46	28,38	2,11	424,31	2	2	2	1	2

213,95	237,98	439,65	450,02	31,57	2,34	466,81	2	2	3	1	2
15,29	15,48	32,71	34,52	124,22	8,91	1572,00	1	0	0	0	1
90,26	95,26	193,68	198,96	28,73	2,14	424,31	1	1	0	0	1
155,58	166,68	331,79	340,22	16,28	1,15	274,61	1	2	0	0	1
142,18	152,35	303,3	311,15	22,88	1,72	354,04	1	1	1	1	1
134,69	144,34	287,41	294,96	28,73	2,14	424,31	1	1	2	1	1
130,5	139,84	278,56	286	33,94	2,51	486,91	1	1	3	1	1
212,15	230,68	448,91	460,14	11,37	0,9	215,64	1	3	0	0	1
195,28	212,73	412,73	423,09	16,04	1,24	274,61	1	2	1	1	1
183,77	200,51	388,17	398,02	19,98	1,52	328,67	1	2	2	1	1
175,91	192,13	371,46	381,01	23,38	1,76	378,40	1	2	3	1	1
0	0	0	0	0	0	0,00	0	0	0	0	0
9,66	12,2	23,54	24,35	0,08	0,08	80,00	0	1	0	0	0
19,31	24,4	47,03	48,69	0,08	0,08	80,00	0	2	0	0	0
14,98	21,18	35,55	37,69	8,74	0,72	184,09	0	1	1	1	0
18,06	29,84	35,8	48,8	16,28	1,25	274,61	0	1	2	1	0
23,82	34,8	47,43	59,67	22,88	1,72	354,04	0	1	3	1	0
28,93	36,6	70,45	73,01	0,08	0,08	80,00	0	3	0	0	0
25,7	33,75	62,81	63,17	0,37	0,25	151,05	0	2	1	1	0
25,31	37,73	57,33	64,75	0,68	0,33	215,64	0	2	2	1	0
28,5	46,85	57,54	76,28	1,38	0,42	274,61	0	2	3	1	0
128,46	137,61	274,3	281,74	38,61	2,84	543,03	1	1	4	1	1
127,94	136,98	273,33	280,86	42,82	3,14	593,64	1	1	5	1	1
128,59	137,58	274,88	282,56	46,64	3,41	639,50	1	1	6	1	1
130,17	139,13	278,43	286,32	50,11	3,65	681,25	1	1	7	1	1
132,51	141,47	283,61	291,76	53,29	3,88	719,43	1	1	8	1	1
135,49	144,47	290,16	298,62	56,2	4,09	754,47	1	1	9	1	1
139	148,01	297,87	306,66	58,89	4,28	786,74	1	1	10	1	1

B5. CarbonS-1 TAP testing frequency results

f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	Average
62,7642	66,109	119,0446	82,63933
118,3348	118,851	248,8356	162,007
174,8583	248,805	280,4899	234,7178

248,7099	280,475	322,0501	283,7449
280,4633	321,937	378,0947	326,8316
321,9991	378,969	383,4441	361,4706
382,9587	560,443	561,7891	501,7301
560,6716	631,494	625,6729	605,9463
632,2377	664,087	636,4393	644,2548
665,0692	678,210	665,2948	669,5248
754,0205	755,6866	752,0457	753,9176

B6. CarbonS-1 TAP testing damping results

d_1	d_2	d_3	Average
0,0389	0,029	0,017	0,028333
0,0111	0,016	0,0073	0,011333
0,0129	0,007	0,0079	0,009367
0,0065	0,0075	0,0121	0,0087
0,0084	0,0113	0,0113	0,010333
0,0119	0,0087	0,0019	0,0075
0,0134	0,0082	0,009	0,0102
0,008	0,0052	0,0068	0,006667
0,0073	0,0151	0,0038	0,008733
0,0062	0,0101	0,0054	0,007233
0,0081	0,0145	0,0076	0,010067

C1. CarbonT-1 flexural samples width measurements

	w[mm]					Average
CARBONT-1_1	14,89	15,20	15,49	16,39	15,72	15,538
CARBONT-1_2	14,58	15,17	15,61	16,16	15,69	15,442
CARBONT-1_3	14,87	15,01	15,41	15,43	15,45	15,234
CARBONT-1_4	14,76	14,69	15,22	15,61	15,57	15,170
CARBONT-1_5	16,30	15,63	15,24	15,16	13,33	15,132

C2. CarbonT-1 flexural samples length measurements

	l[mm]					Average
CARBONT-1_1	536,00	536,00	536,00	536,00	536,00	536,0
CARBONT-1_2	535,50	535,50	535,50	535,50	535,50	535,5
CARBONT-1_3	533,55	533,55	533,55	533,55	533,55	533,6
CARBONT-1_4	535,00	535,00	535,00	535,00	535,00	535,0
CARBONT-1_5	535,00	535,00	535,00	535,00	535,00	535,0

C3. CarbonT-1 flexural samples thickness measurements

	t[mm]					Average
CARBONT-1_1	3,87	3,7	3,74	3,77	3,83	3,782
CARBONT-1_2	3,81	3,69	3,7	3,79	3,68	3,734
CARBONT-1_3	3,81	3,69	3,71	3,75	3,72	3,736
CARBONT-1_4	3,78	3,7	3,71	3,82	3,71	3,744
CARBONT-1_5	3,86	3,7	3,72	3,73	3,81	3,764

C4. CarbonT-1 composite simulations

f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]	E_1 [GPa]	E_2 [GPa]	ρ [kg/m ³]	Carbon fibre layers 1	PVC layers 1	Carbon fibre layers 2	PVC layers 2	Carbon fibre layers 3
18,30	30,66	48,26	74,63	148,36	8,01	1000,00	5	0	0	0	5
71,61	123,56	187,49	282,15	49,51	2,74	386,67	5	1	0	0	5
119,05	207,48	310,52	456,57	29,74	1,68	264,00	5	2	0	0	5
117,35	204,52	306,12	450,18	32,06	1,81	278,43	5	1	1	1	5
115,91	202,02	302,41	444,79	34,30	1,93	292,31	5	1	2	1	5
114,70	199,91	299,28	440,25	36,45	2,04	305,66	5	1	3	1	5
160,78	282,60	417,77	599,83	21,27	1,23	211,43	5	3	0	0	5
158,62	278,86	412,10	591,27	23,04	1,33	222,54	5	2	1	1	5
156,63	275,42	406,89	583,41	24,72	1,42	233,33	5	2	2	1	5
154,81	272,28	402,13	576,23	26,33	1,50	243,84	5	2	3	1	5
158,62	278,86	412,10	591,27	23,04	1,33	222,54	5	1	1	2	5
156,63	275,42	406,89	583,41	24,72	1,42	233,33	5	1	2	2	5
154,81	272,28	402,13	576,23	26,33	1,50	243,84	5	1	3	2	5

14,64	24,53	38,61	59,71	148,36	8,01	1000,00	4	0	0	0	4
67,73	116,63	177,59	268,54	42,45	2,36	342,86	4	1	0	0	4
113,70	197,67	297,40	441,31	24,80	1,42	233,33	4	2	0	0	4
111,44	193,75	291,53	432,64	27,32	1,55	248,98	4	1	1	1	4
109,55	190,46	286,61	425,38	29,74	1,68	264,00	4	1	2	1	4
107,96	187,70	282,70	282,48	32,06	1,81	164,43	4	1	3	1	4
153,51	269,15	400,44	582,30	17,53	1,03	188,24	4	3	0	0	4
150,90	264,63	393,57	571,89	19,40	1,13	200,00	4	2	1	1	4
148,50	260,50	387,28	562,34	21,17	1,23	211,43	4	2	2	1	4
146,31	256,75	381,57	553,68	22,85	1,32	222,54	4	2	3	1	4
10,98	18,40	29,96	44,78	148,36	8,01	1000,00	3	0	0	0	3
63,38	108,90	166,49	252,94	34,30	1,93	292,31	3	1	0	0	3
106,97	185,51	280,69	420,10	19,42	1,13	200,00	3	2	0	0	3
103,99	180,34	272,89	408,43	22,17	1,28	217,02	3	1	1	1	3
101,53	176,09	266,47	398,83	24,80	1,42	233,33	3	1	2	1	3
99,49	172,57	261,16	390,88	27,32	1,55	248,98	3	1	3	1	3
143,92	251,77	377,10	554,96	13,56	0,82	163,64	3	3	0	0	3
140,79	246,38	368,86	542,42	15,54	0,93	176,12	3	2	1	1	3
137,93	241,46	361,34	530,93	17,39	1,03	188,24	3	2	2	1	3
135,34	237,02	354,56	520,58	19,14	1,12	200,00	3	2	3	1	3
7,32	12,26	19,30	29,85	148,36	8,01	1000,00	2	0	0	0	2
57,99	99,41	152,66	232,85	24,80	1,42	233,33	2	1	0	0	2
97,44	168,68	256,72	386,71	13,56	0,82	163,64	2	2	0	0	2
93,52	161,91	246,42	371,13	16,56	0,98	182,22	2	1	1	1	2
90,39	156,52	238,20	358,71	19,42	1,13	200,00	2	1	2	1	2
87,86	152,16	231,57	348,67	22,17	1,28	217,02	2	1	3	1	2
129,90	227,04	342,33	508,36	9,35	0,60	137,50	2	3	0	0	2
126,28	220,81	332,75	493,74	11,43	0,71	150,77	2	2	1	1	2
122,94	215,10	323,95	480,23	13,35	0,81	163,64	2	2	2	1	2
119,95	209,99	316,10	468,16	15,14	0,91	176,12	2	2	3	1	2
3,66	6,13	9,65	14,93	148,36	8,01	1000,00	1	0	0	0	1
49,37	84,59	130,49	198,94	13,56	0,82	163,64	1	1	0	0	1
80,67	140,06	214,02	321,53	7,14	0,48	123,81	1	2	0	0	1
75,73	131,53	200,95	301,73	10,43	0,65	144,19	1	1	1	1	1
72,01	125,12	191,13	286,83	13,56	0,82	163,64	1	1	2	1	1
69,14	120,18	18,55	275,31	16,56	0,98	182,22	1	1	3	1	1
105,48	185,57	280,76	415,33	4,87	0,36	109,68	1	3	0	0	1

101,79	179,19	270,91	400,40	7,03	0,47	123,81	1	2	1	1	1
98,19	173,07	261,42	385,72	8,93	0,58	137,50	1	2	2	1	1
95,00	167,64	253,01	372,75	10,62	0,67	150,77	1	2	3	1	1
0,00	0,00	0,00	0,00	0,00	0,00	0,00	0	0	0	0	0
9,66	12,20	23,54	24,35	0,08	0,08	80,00	0	1	0	0	0
19,31	24,40	47,03	48,69	0,08	0,08	80,00	0	2	0	0	0
17,52	22,39	42,80	44,17	3,70	0,29	102,44	0	1	1	1	0
16,49	22,47	41,05	41,54	7,14	0,48	123,81	0	1	2	1	0
16,01	24,66	40,18	41,55	10,43	0,65	144,19	0	1	3	1	0
28,93	36,60	70,45	73,01	0,08	0,08	80,00	0	3	0	0	0
30,02	39,14	73,65	74,30	0,31	0,17	95,08	0	2	1	1	0
28,77	37,71	70,71	71,61	0,34	0,21	109,68	0	2	2	1	0
27,75	37,66	68,91	69,25	0,38	0,24	123,81	0	2	3	1	0
21,96	36,79	57,90	89,55	148,36	8,01	1000,00	6	0	0	0	6
75,25	130,07	196,76	294,70	55,69	3,07	425,00	6	1	0	0	6
123,61	215,95	321,61	468,53	34,30	1,93	292,31	6	2	0	0	6
122,35	213,75	318,37	463,89	36,45	2,04	305,66	6	1	1	1	6
121,29	211,89	315,63	459,98	38,53	2,15	318,52	6	1	2	1	6
120,39	210,32	313,33	456,71	40,52	2,26	330,91	6	1	3	1	6
119,64	209,02	311,41	454,00	42,45	2,36	342,86	6	1	4	1	6
119,03	207,94	309,84	451,79	44,31	2,46	354,39	6	1	5	1	6
118,53	207,08	308,58	450,03	46,10	2,56	365,52	6	1	6	1	6
166,68	293,68	431,55	611,76	24,80	1,42	233,33	6	3	0	0	6
164,90	290,60	426,90	604,77	26,47	1,51	243,84	6	2	1	1	6
163,26	287,77	422,61	598,32	28,08	1,60	254,05	6	2	2	1	6
166,29	293,46	429,71	604,47	29,73	1,68	264,00	6	2	3	1	6
165,13	291,47	426,63	599,63	31,30	1,77	273,68	6	2	4	1	6
164,05	289,32	423,78	595,14	32,81	1,85	283,12	6	2	5	1	6
163,06	287,92	421,15	591,02	34,26	1,92	292,31	6	2	6	1	6
113,68	198,14	296,65	436,45	38,53	2,15	318,52	5	1	4	1	5
112,83	196,66	294,47	433,30	40,52	2,26	330,91	5	1	5	1	5
112,13	195,45	292,67	430,72	42,45	2,36	342,86	5	1	6	1	5
111,57	194,46	291,22	428,66	44,31	2,46	354,39	5	1	7	1	5
111,12	193,68	290,08	427,06	46,10	2,56	365,52	5	1	8	1	5
110,78	193,09	289,23	425,89	47,83	2,65	376,27	5	1	9	1	5
110,54	192,67	288,64	425,10	49,51	2,74	386,67	5	1	10	1	5
110,39	192,40	288,28	424,67	51,13	2,82	396,72	5	1	11	1	5

110,33	192,28	288,14	424,57	52,70	2,91	406,45	5	1	12	1	5
110,34	192,30	288,21	424,78	54,22	2,99	415,87	5	1	13	1	5
110,43	192,44	288,46	425,27	55,69	3,07	425,00	5	1	14	1	5
110,58	192,70	288,90	426,04	57,11	3,14	433,85	5	1	15	1	5
110,80	193,06	289,50	427,05	58,50	3,22	442,42	5	1	16	1	5
111,07	193,53	290,25	428,31	59,84	3,29	450,75	5	1	17	1	5
111,41	194,09	291,15	429,79	61,14	3,36	458,82	5	1	18	1	5
111,79	194,74	292,19	431,49	62,40	3,43	466,67	5	1	19	1	5
112,23	195,48	293,37	433,38	63,63	3,49	474,29	5	1	20	1	5

C5. CarbonT-1 TAP testing results

f_1	f_2	f_3	Average
89,3745	211,200	211,366	170,6469
143,294	260,804	233,7896	212,6292
211,0439	312,985	260,7927	261,6071
260,7265	329,644	312,5519	300,974
312,3898	485,146	329,5111	375,6821
485,547	510,113	486,3721	494,0106
510,3722	552,599	509,2999	524,0904
576,4378	576,732	577,5112	576,8936
592,9982	593,920	591,1132	592,677
677,8514	677,768	677,1641	677,5946
721,846	722,4567	722,0651	722,1226

C6. CarbonS-1 TAP testing damping results

d_1	d_2	d_3	Average
0,0273	0,008	0,0088	0,014633
0,1076	0,009	0,0038	0,04
0,0059	0,007	0,0084	0,006967
0,0084	0,0092	0,0076	0,0084
0,0062	0,0054	0,0045	0,005367
0,0057	0,0092	0,0047	0,006533
0,0059	0,0077	0,0092	0,0076
0,0037	0,0042	0,004	0,003967

0,0049	0,0075	0,005	0,0058
0,0037	0,0045	0,0039	0,004033
0,0024	0,0045	0,0047	0,003867

D1. MATLAB code for plots

```
close all;clearvars;clc

%%

load('FRFs ');

figure()

semilogy(FRFs.FREQ,abs(FRFs.FRF1(:,1)));

hold on

semilogy(FRFs.FREQ,abs(FRFs.FRF2(:,1)));

semilogy(FRFs.FREQ,abs(FRFs.FRF3(:,1)));

legend('1x1','2x1','3x1')

xlabel('Frequency /Hz')

ylabel('Acceleration | /g .N^{-1}')
```



```
figure()

plot(FRFs.FREQ,FRFs.COHERENCE1(:,1))

hold on

plot(FRFs.FREQ,FRFs.COHERENCE2(:,1))

plot(FRFs.FREQ,FRFs.COHERENCE3(:,1))

legend('1x1','2x1','3x1')

xlabel('Frequency /Hz')

ylabel('Coherence')
```

D2. MATLAB code for obtaining frequencies and damping

Depending on the number of natural frequencies the value of “X” is changed. In this these the values of 8 and 11 were used.

```
load('FRFs.mat')

[f r1, dr1, ms1] = modalfit(FRFs.FRF1, FRFs.FREQ, 1,X,"FitMethod ","pp")

[f r2, dr2, ms2] = modalfit(FRFs.FRF2, FRFs.FREQ, 1,X,"FitMethod ","pp")

[f r3, dr3, ms3] = modalfit(FRFs.FRF3, FRFs.FREQ, 1,X,"FitMethod ","pp")

[f r] = ([ f r 1 ] + [ f r 2 ] + [ f r 3 ]) / 3

[dr3] = ([ dr1 ]+[ dr2 ]+[ dr3 ]) / 3
```