# UNDERSTANDING THE ACOUSTIC BEHAVIOUR OF NATURAL FIBER COMPOSITES AND THE EFFECTS OF TEMPERATURE AND HUMIDITY

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*Dedicated*

*to*

*My Parents*

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(Left to Right: Dr Larry Lessard (Supervisor), Arun Duraisamy (Author) and Adam Smith (PhD. Student)

# ABSTRACT

Natural fibre composites are currently replacing wood and glass fibre secondary structures in aerospace and automobile industries. With many kinds of traditional wood listed as endangered, the music instrument manufacturing sector has started looking for alternate materials. This new endeavour resulted in many carbon fibre instruments, now seen in the market. Carbon fibre proved to be excellent in certain aspects such as environment resistance and weight reduction but had less success with achieving good acoustic behaviour. In this research, flax fibre composites, made from the fibres of the flax plant, grown in large quantities in countries like Canada, are examined to see if they can be a better replacement. Fretboards in guitars are the subject of interest, usually made from Brazilian Rosewood. First, Taguchi's Design of Experiments method is used to identify the hierarchy among five different parameters ($E_1$, $E_2$, $E_f$, thickness and density) on the acoustic behaviour. Second, the effect of temperature and humidity on the natural frequency and damping is studied for different fretboard samples (flax composite of 2 different grades, bamboo) keeping the Rosewood as the baseline.

**Keywords:** Flax fibre composites, Natural Frequency, Damping ratio, Taguchi's method, humidity and temperature effects.

# RÉSUMÉ

Les fibres en composites naturelles sont graduellement en train de remplacer les fibres de bois et de verre dans les industries automobiles et aérospatiales. Étant donné que divers bois traditionnels sont en voie de disparition, les fabricants des instruments de musique se sont déjà mis à la recherche de substituts, ce qui a engendré l'apparition sur le marché d'instruments musicaux faits à partir de fibre de carbone. Bien que ce matériau prouva être excellent dans certains aspects tel que sa résistance environnementale et la réduction du poids, il eut par contre moins de succès dans l'aboutissement d'un bon comportement acoustique. Cette recherche examine la fibre de lin en tant que meilleur remplaçant à la fibre de carbone. La fibre de lin est faite à partir de la plante de lin, cultivée en grande quantité dans des pays tels que le Canada. La touche dans les guitares, habituellement fabriquée à partir de palissandre du Brésil, est le sujet abordé. Premièrement, la méthode expérimentale de Taguchi permettra d'identifier la hiérarchie de cinq paramètres ($E_1$, $E_2$, $E_f$, épaisseur et densité) vis-à-vis du comportement acoustique. Deuxièmement, les effets de la température et de l'humidité sur la fréquence naturelle et l'amortissement seront étudiés pour divers échantillons de touche (composite de lin de deux différents grades, bambou) gardant le palissandre comme ligne de base.

**Mot clés :** Composites en fibre de lin, fréquence naturelle, rapport d'amortissement, méthode de Taguchi, effets de l'humidité et de la température.

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# LIST OF SYMBOLS

| ***Symbol*** | ***Meaning*** |
|---|---|
| $c$ | Speed of sound in a material |
| $E$ | Modulus along the grain direction of the wood |
| $P$ | Density of a material |
| $z$ | Impedance of a material |
| $R$ | Sound radiation coefficient of a material |
| $\delta$ | Damping Ratio |
| $X$ | Amplitude of each oscillation |
| $\omega_n$ | Natural frequency |
| $\omega_1, \omega_2$ | Frequency |
| $f_T$ | Total degree of freedom of the problem |
| $f_{factor}$ | Degree of freedom of each factor |
| $f_e$ | Degree of freedom of error |
| $S_T$ | Sum of Square of the analysis |
| $Y_i$ | Result of the $i^{th}$ trial |
| $\bar{Y}$ | Average of $Y_i$ terms |
| $S_e$ | Sum of Square of error |
| $S_{factor}$ | Sum of Square of each factor |
| V | Variance |
| $V_{factor}$ | Variance of each factor |
| $V_e$ | Variance of error |
| $F_{factor}$ | Variance ratio of each factor |
| $S'_{factor}$ | Pure sum of square of each factor |

| | |
|---|---|
| $P_{factor}$ | Percentage contribution of each factor |
| $E_x$ | Modulus along the fibre of the prepreg |
| $E_y$ | Modulus perpendicular to the fibre of the prepreg |
| $\vartheta_{xy}$ | Poisson's ratio in the XY plane |
| $h_o$ | Ply thickness |
| $X_T$ | Strength of the prepreg under tension along the fibre |
| $X_C$ | Strength of the prepreg under compression along the fibre |
| $Y_T$ | Strength of the prepreg under tension perpendicular to the fibre |
| $Y_C$ | Strength of the prepreg under compression perpendicular to the fibre |
| $S_C$ | Shear strength of the prepreg |
| $\vartheta_{xz}$ | Poisson's ratio in xz plane |
| $\vartheta_{yz}$ | Poisson's ratio in yz plane |
| $G_{xy}$ | Shear modulus in xy plane |
| $G_{yz}$ | Shear modulus in yz plane |
| $T_g$ | Glass transition temperature |
| $l$ | Length of the fretboard |
| $E_1$ | Effective modulus of the laminate in 1-direction |
| $E_2$ | Effective modulus of the laminate in 2-direction |
| $E_f$ | Flexural modulus of the laminate |

# INTRODUCTION 1

Acoustics, derived from a Greek word *akouein* meaning to hear, is the science of sound [1]. The sound is a result of vibration of matter around us. When the matter around us vibrates within the frequency range of *20Hz* to *20kHz*, we hear them [2]. Since the invention of musical instruments vibrations became a topic of human interest. The first musical instrument dates to *67,000* years when a Slovenian archaeologist Ivan Turk discovered a piece of bear thigh bone with holes [3] as shown in Figure 1. Until then the discovery of musical instruments was traced back only up to *4,000* years. The Hindus, Japanese, Chinese and the Egyptians were the first to develop music and musical instruments and maintained a record of it in the form of texts. Later great minds such as Pythagoras studied sound from a scientific perspective and were subsequently followed by Galileo to present day scientists [4].

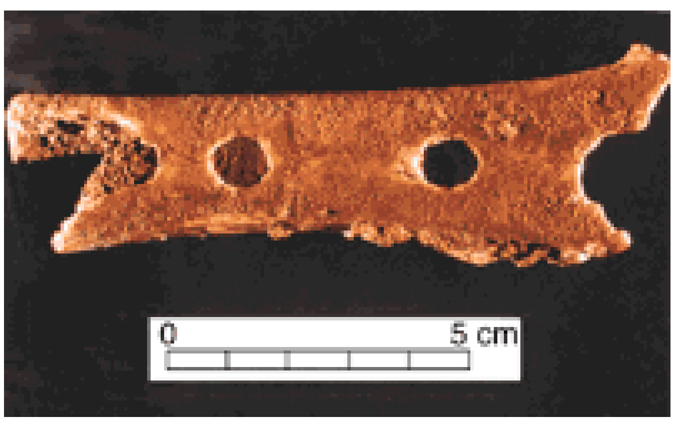



**FIGURE 1: CAVEMAN'S PIPE. [3]**

Musical instruments can be broadly classified into string instruments, woodwinds, brass and percussion [5]. In the literature, we can see that these instruments were made from animal bones and skin during the early periods, then followed by wood, metal and finally to present day advanced materials like carbon fibre composites. With the continuous development of material science, the material used in these instruments has also evolved. The musical instruments evolved more on a hit or miss basis by trying different options from the full range of available material. In the literature, we can also see that the authors consider these instruments as continuously evolving where the maker makes their tweaks to improve the sound or comfort of use. Recent advancement in materials has resulted in systematic scientific studies to understand the qualities of the materials that are being used for many centuries in these instruments.

The most known and bought musical instruments of the present day are guitars. They belong to the string instrument family. Guitars have been in existence since the Baroque period. They have been continuously evolving since then, and they began to take their modern form in the $19^{th}$ century. The popularity of the instrument was mainly concentrated around Italy, and Spain then spread to Europe by the great musician Fernando Sor and more followed later [6]. The most commonly known form of the guitar is the acoustic guitar. A typical acoustic guitar is shown in Figure 2. They mainly consist of the sound box, strings, frets, neck, tuning system and bridge. The sound box is made of a vibrating top plate, sound hole, back plate and ring structure. When a string of the guitar is plucked, the vibration is transferred to the air inside the sound box, and due to the vibration of this air inside, musical sounds are produced. Many factors play a significant role in the final sound quality, the size of the hole, the material, room temperature and humidity conditions, the pattern of the support rods attached to the back of the top plate.

Acoustic guitars have traditionally been made with several endangered wood types, including Rosewood (for the fingerboard, sides, back and bridge), Mahogany (for the neck), and Ebony (for the fingerboard and/or bridge). Over the last few decades, these have become rare, and some have been banned from import into the EU and Canada. For example, Brazilian Rosewood has been an endangered species since 1992, when it was added to the CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) list.

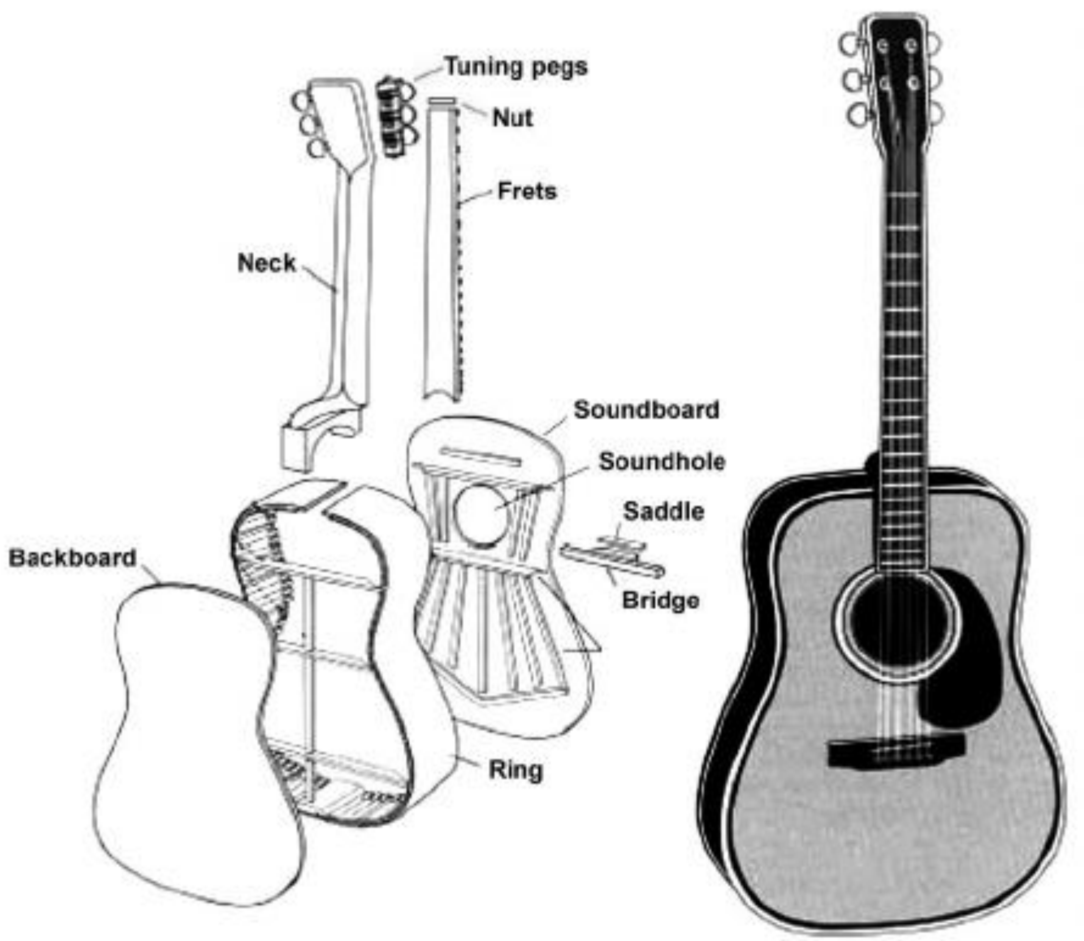



**FIGURE 2: A TYPICAL ACOUSTIC GUITAR. [7]**

## 1.1 Motivation

The need for replacement material for musical instruments due to the endangerment of wood species, as seen in the case of the acoustic guitar, has resulted in the use of present day advanced materials. Another important factor that fuels this need is the deterioration effect of the environment on these instruments. The sound quality varies with a change in temperature and humidity conditions of the surroundings. Also, the process of choosing raw material is still a task well executed only out of years of experience and not something that is entirely quantified, resulting in the inconsistency of the quality of musical instruments. The idea of using bio-based composite material is explored as they are still close to natural materials and they have the possibility of being recycled when used with bio-based resin systems.

## 1.2 Objectives

The primary aim of this thesis is to understand the relevant parameters that are required to mimic the acoustic behaviour of Rosewood using flax fibre composites. Natural frequency and damping ratio were considered as the main acoustic parameters to be studied. The moduli, thickness and density were the parameters that were investigated to rank them according to their influence to the acoustic properties. Secondly, as both the material, Rosewood and the material under consideration as a replacement are susceptible to temperature and humidity, the effect of these factors was also studied in detail.

## 1.3 Thesis Organization

The thesis has been divided into seven chapters. The first chapter is the introduction where the motivation and objective of the thesis are discussed. The second chapter provides a review of the work that has been carried out in the past. The third chapter gives a detailed explanation of the approach taken and the methods employed to accomplish the objectives. The fourth, fifth and sixth chapter details the manufacturing procedure used, different experiments that were conducted and discussion of the results. Finally, the conclusion and future work chapter. Appendices are included to detail auxiliary information and present more results.

# Literature Review 2

Music has been a part of human life for a long time. It is also reported in the literature that babies can differentiate inharmonious from the harmonious combination of notes [3]. The long history can also be seen with the evolution of raw materials that have been used to make these instruments. Bones of animals were used as a material for making flutes and intestine was used as strings during the early period of humanity. With the development of human skills to shape wood, wood became the most prominent raw material for musical instruments. Later with modern day processes, metals were used and finally, now we see composite materials being explored as possible options in many instruments. Though there has been much development in the materials field, wood has until now managed to be the first choice for an instrument manufacturer and musicians.

## 2.1 Dominance of wood in musical instruments

Wood, due to its wide range of properties, abundance and ease of machinability, is being used in a multitude of applications. Wegst, [8] in his papers details the criteria that need to be satisfied for a material to be chosen as a raw material for musical instruments and discusses why wood has always been the most preferred choice of raw material. In the paper, he talks about some of the acoustic properties: the speed of sound ($c$) in the material, impedance ($z$), sound radiation coefficient ($R$) and loss coefficient, which is a measure of the rate at which the material loses energy due to internal friction. These are given by,

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

**EQUATION 1: SPEED OF SOUND IN A MATERIAL.**

$$z = \sqrt{E\rho}$$

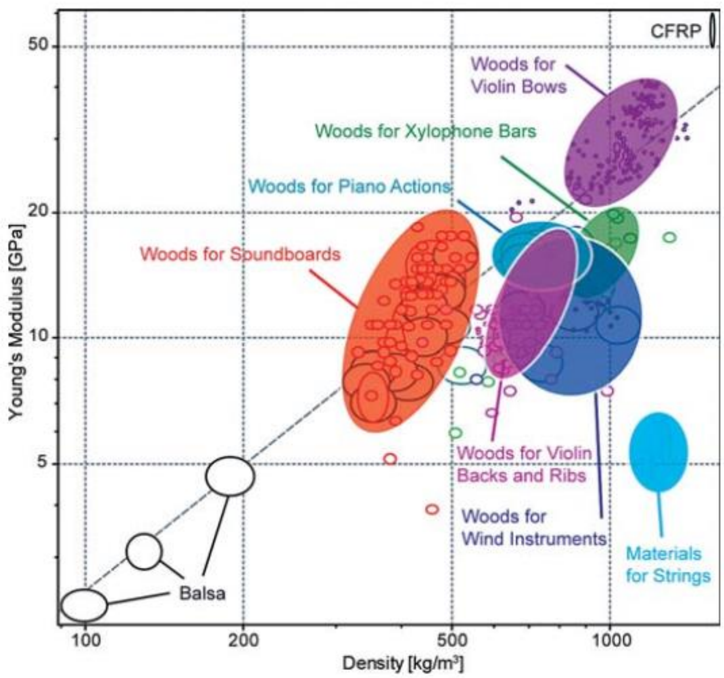
**EQUATION 2: IMPEDANCE OF MATERIAL.**

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

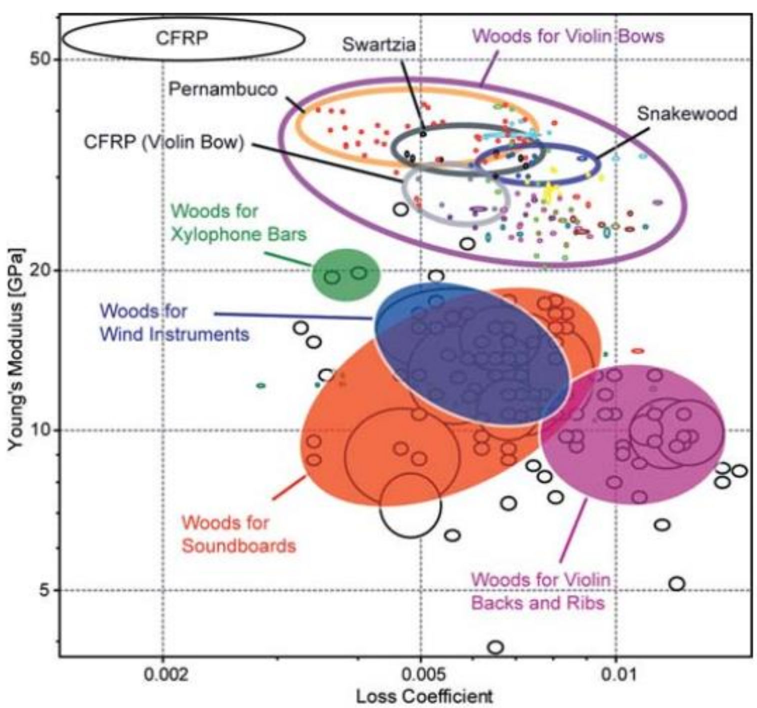
**EQUATION 3: SOUND RADIATION COEFFICIENT OF A MATERIAL.**

In the equations given above, $E$ is the modulus along the grain direction of the wood and $\rho$ is the density. Here we can note that finally, it comes down to the modulus, density and loss coefficient of the material. He uses material selection charts where he organises material according to their density, Young's modulus, loss coefficient, the speed of sound and radiation coefficient and details the advantage of using a particular wood species. Two of these graphs are shown in Figure 3.

It is believed in the musical industry that ageing of these wooden musical instruments has a positive influence on the acoustic properties [9,10]. In the literature, it is reported that humidity and creep are the primary factors for this positive impact and experiments have been conducted to prove the hypothesis. Various research has been carried out to better understand the effect of ageing of the musical instruments [9-14]. Though all these factors play a role in choosing a raw material for an instrument, finally the appearance of these wood plays a significant role.




(a)




(b)

**FIGURE 3: MATERIAL SELECTION CHART; (A) YOUNG'S MODULUS AGAINST DENSITY AND (B) YOUNG'S MODULUS AGAINST LOSS COEFFICIENT. [8]**

## 2.2 Composite Materials

Composite materials are a combination of two or more constituent materials combined in a certain configuration to form a new material at the macro level. The resultant material has superior properties in comparison to the individual constituents. Realisation of composite materials in structures was first noted from the Egyptian period where they used straw in clay as reinforcements to make bricks [15]. Modern day advanced composite materials were developed in the 1940s. Composite materials can be classified based on the reinforcement material and the type of matrix used. Depending on the size and shape of the reinforcement they can be categorised as fibre reinforced composites, particle reinforced composites and flake-reinforced composites. Based on the matrix chosen, they can be categorised as polymer matrix composites, ceramic matrix composites or metal matrix composites [16, 17].

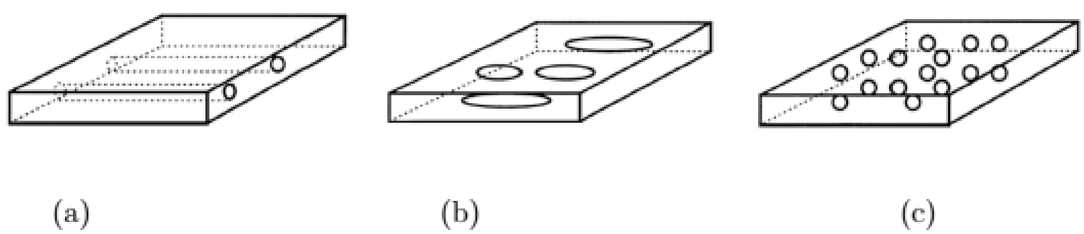



**FIGURE 4: CLASSIFICATION OF COMPOSITE BASED ON REINFORCEMENTS. (A) FIBRE REINFORCED, (B) FLAKE REINFORCED AND (C) PARTICLE REINFORCED. [16]**

Fiber-reinforced polymer matrix composites are the most commonly used composite material. They are used in wide range of applications from sporting equipment to aerospace industries. These composites materials can be further classified based on the type of polymer matrix, such as thermoplastic composite material and thermoset composite material. The fibre can be categorised based on the size of the fibre as long or continuous fibre composite material and short fibre composite material. Depending on the nature of the fibre they are classified as either natural fibre composite material or synthetic fibre composites. Synthetic fibres include carbon fibre, glass fibre and other polymer based fibres. Natural fibres include flax, hemp, jute, banana. In the literature, we can find banana fibre, and coconut fibres are also being studied for practical applications [18, 19].

With the endangerment of wood species and inconsistency of the quality of musical instruments made of wood, the availability of composite materials sparked research and development of the composite musical instrument. RainSong was the first company to manufacture carbon fibre guitars at a large scale [20]. The company tried to promote the excellent environment resistance of these guitars, so they advertised the guitars by a person using it to pedal a boat.

Probert [20] studied the use of carbon fibre composite as a replacement material for the sound box for an acoustic guitar. He performed finite element analysis to develop a simplified guitar model. He then manufactured a carbon fibre sound box and compared that with a Yamaha FG403S guitar by performing the psychoacoustic analysis. From the studies, it was found that the first ten natural frequencies could be matched with an error of *0.9%* to *15.7%*. Regarding performance, it was reported that the composite guitar performed well but was still not as good as the wood instrument, and further design improvement was needed.

A similar study that used carbon fibre composites was done by Dominy et al. [21] to replace wood in a violin for improvement of the sound quality, but a good result was not achieved, and it was still a work in progress. There are other studies where only the top plate of a guitar was examined using carbon fibre composites. Different core materials were investigated such as polypropylene, polystyrene, balsa and even cardboard was experimented with [21 – 25]. They did not satisfy the damping properties of Sitka spruce that they were trying to mimic though they could meet the Haines et al. [26] criteria. According to this criterion based on a *2.5 mm* thick spruce soundboard, the modulus ratio in the two directions should be at least a *12*; the ratio of stiffness to areal density must be at least $12x10^6\ m^2/s^2$; the areal density must be between *1.1 to 1.4* $kg/m^2$, and finally the damping should increase with increasing frequency.

The use of natural fibre composite as a replacement for current wood materials has not been explored much. Possible natural fibres that are recommended in literature are bast fibres (which include flax fibres) [27]. In the market, a hemp fibre composite guitar is manufactured and sold by Canadian Hemp Guitars, but the quality of the instruments is not well known. Phillips [28] developed a one-piece ukulele using flax fibre composite with balsa and foam as core materials. The Haines et al. criteria were met, and a new manufacturing procedure for a one-piece ukulele was developed. Similar studies were done by Marcadet et al. [29] for a violin top plate, and they proposed to use a layer of carbon fibre to improve the attenuation capacity of the top layer of the structure.

In literature, we also find that researchers have considered other species of wood material as a replacement for conventional materials that are being used at present. The option of bamboo as a raw material was explored in many of musical instruments, and it was found that they are suitable for cases where the required density is high and the damping is low. Materials such as Japanese cedar were considered to see if they can be used as a guitar back plate and balsa as a top plate [29 – 33].

From the literature review, it is clear that the possibility of using natural fibre composite is not well explored. Different parameters are reported to be important factors that need to be considered while designing using an alternative material and it becomes difficult to match all the parameters while designing a composite laminate for the same purpose. Thus, it is important to find a weighted balance of these factors that will help us to quantify and design better. Another point that can be noted is that in the case of carbon fibre composites, the damping was always either higher than the required value or lower. Though in literature there are damping prediction models for composite materials [34,35], these models cannot be entirely relied upon as damping is a sensitive property to measure. It is susceptible to the boundary conditions and the testing environment. Suggesting the use of natural fibre composites also requires an understanding of the acoustic behaviour of natural fibres subjected to temperature and humidity. For addressing these concerns, the fretboard is taken as an example, and studies were performed.

# APPROACH AND METHODOLOGY 3

The objective of the thesis was to find the critical parameters that influence acoustic behaviour and secondly to understand the effect of temperature and humidity. For achieving these goals, Taguchi's Design of Experiment (DOE) method was employed in the first study, and the influence was calculated using the Analysis of Variance (ANOVA) procedure. All the acoustic measurements were done by performing vibration testing of the samples that were prepared as part of the project. In this chapter, we shall discuss the concepts that were used and detailed the difficulties that one might come across while performing these tests.

## 3.1 Experimental Modal Analysis

Testing of a system or sample for identifying its vibrational properties such as natural frequency, damping ratio and mode shapes is called experimental modal analysis [4]. It is also referred to simply as modal analysis or modal testing. The test can be classified depending on the type of sensors used, the system excitement technique employed and the boundary conditions. In simple words, the system under study, subjected to boundary conditions, is excited by applying an external force. The force can either be impulsive or a waveform. Measuring devices are used to read the response of the system. The response is post-processed to obtain the natural frequency, damping and mode shapes.

***Boundary Condition:*** For performing the modal testing, many aspects need to be addressed. The foremost is the type of boundary condition that is employed to carry out the test. The most commonly used boundary conditions are the free-free boundary conditions and the cantilever boundary conditions. For the case of free-free boundary conditions, the system is completely isolated from the environment, achieved by hanging the sample with the help of light strings. As it is not restricted from any movement, the system can vibrate in all its modes. Care must be taken to have the string attachments at the points where it does not affect any of the modes. Another factor that needs to be considered is the string length: if the string is too short, the modes of the system get damped, or if it is too long then it takes a longer time to get the system to a ground state, and it can start oscillating even by the slightest air disturbance.

For the case of cantilever boundary conditions, the system is fixed at one end and usually excited at the other end. It is immune to air disturbance effects to a certain extent. However, there are many disadvantages to this type of boundary condition as it requires more energy for the system to be excited to its resonant frequency. Some of the modes might not be identified due to the fixed end; additional damping is induced into the system and repetition with reliable results is difficult to achieve because of clamping force variations. Practical boundary conditions or conditions similar to the application of the system under consideration is employed when its behaviour under working conditions need to be recorded. For basic characterization purposes, free-free boundary conditions are preferred if the sample is heavy enough. If the sample is too small and light, where it might get easily disturbed by external factors, then cantilever conditions should be used.

***Excitation Force:*** The vibration of a system can be classified as either forced vibration or free vibration. In the case of free vibration, the system is excited by an impulsive force, and the system vibrates until it dissipates all the energy. A hammer excitation method is usually employed for this purpose. For forced vibration, a constant force signal is applied to the system and the vibration thus induced is called forced vibration. A shaker is employed for this purpose. The method of excitation is again dependent on the system under study. If the system is light in weight, then it is preferred to use the free vibration method as it would not add mass to the system under study, which will alter the natural frequency significantly. Forced vibration is preferred when the system is hefty or has high damping in which case it would require more energy for the complete excitation of the system.

***Sensors and Exciters:*** Both responses measuring sensor and exciters can be classified as contact and non-contact based. It is always preferred to use a non-contact method over a contact based method as it does not affect the system. Thus the pure response of the system without any environmental errors can be recorded. Contact based sensors include strain gauges, accelerometers and velocimeters; and exciters include hammers and electromagnetic shakers. Non-contact based sensing would make use of a laser vibrometer and loudspeaker as a non-contact based excitation device.

Again, the size and weight of the system under study determines the type and number of sensors and exciters used. Though the loudspeaker is a non-contact based method that would not add to the response of the system, if the system is heavy, it might not be able to transfer enough energy to excite the system. Another important factor is the distance from the sample to a loudspeaker; it needs to be not too close where the air between the two might not only transfer energy but also dampen the system. Keeping the loudspeaker away to counter this effect might result in the inefficient transfer of energy. In the case of contact based, there is a wide variety of sensors and exciters that are available in the market. The sensor's physical parameters at times play a greater role than their sensitivity. Since they are in contact with the system, even the weight of the wire that is connected to the sensor might affect the recorded response. The wires must be long enough and light enough that they do not influence the oscillation of the system and do not add any damping.

Overall modal testing is a very sensitive experimental study. We can also note that the most important parameter that determines the details mentioned above is the system itself. Other things to watch out for a while performing such test are the room and table where the experiment is conducted. In the market, there are vibration isolation tables that are used to do such experiments. If the sample is too large, then fixtures are designed to perform the tests. It is important to make sure that the room where the test is conducted is enclosed to reduce any air flow, which will affect the response of the system. Care should be taken to support the system at the points of nodes where the displacement is zero. Such supports will not alter the mode shape or the damping of the system in the case of free-free boundary conditions. Another parameter is the force of excitation, which is crucial when measuring damping. If the amplitude of vibration increases, it reduces the damping of the system [36]. For this purpose, if the sample is a simple structure then a commercial software can be used to identify the nodal regions of the structure before performing the experimental tests.

## 3.2 Post-processing of Modal Testing

The next important step in the experimental modal analysis is the processing of the recorded response to obtain the required results. All the responses that are recorded are in the time domain, that is, the displacement of the system is recorded against time. For identifying the natural modes, the response is converted to the frequency domain, where the response is plotted against frequency. This kind of plot is called the frequency response function (FRF). The time domain results are converted to frequency domain results applying the Fast Fourier Transform (FFT) method. The peaks on the FRF graph indicate the natural frequencies of the system and the corresponding amplitude of the force applied to excite the system.

For plotting the mode shape of the system, the system response is measured at multiple locations, and the peak amplitude for each resonant frequency are plotted to get the mode shapes. This step can be done either by having multiple sensors at all these locations and measuring the response or by using fewer sensors and repeating the process. At these levels, the non-contact sensors are much easier to use regarding taking measurements at multiple locations whereas in the case of contact-based sensors, the sensor should be moved around the system and care must be taken not to damage the sensor and the system. Many commercial software is available to process these results and provide us with the final mode shapes, for example, MEScope and LMS Technologies.

***Damping Measurement***: Damping is the loss in energy of the system due to internal friction. It is tough to measure damping for a system without having any added influence from the surroundings. The system damping measured can be a sum of the pure system damping in addition to damping due to the boundary conditions, air circulation and the sensors that are attached [36, 37]. There are mainly two different methods to calculate the damping ratio experimentally. The first method is called the logarithmic decrement method, and the other is known as the half-power bandwidth method. The logarithmic decrement method is employed when the natural modes of the system are very close to each other in the FRF plot. If the resonant frequencies are very close to each other, the damping at one mode is influenced by the nearby modes. The half-power bandwidth method is used when the resonant frequencies are well-spaced apart. Here the system is assumed to be a single-degree-of-freedom system, and according to this assumption, in the vicinity of resonance, the FRF is dominated by that mode and the other resonant frequencies have negligible influence. The accuracy of the half power bandwidth is lower in comparison.

- *Logarithmic Decrement Method:* in this case, the system is excited to one resonant frequency and once steady state is achieved, the excitation is stopped, and the system is allowed to come back to ground state and decay is measured. The natural logarithm of this decay in amplitude within a certain interval of time gives the measure of the damping of the system.

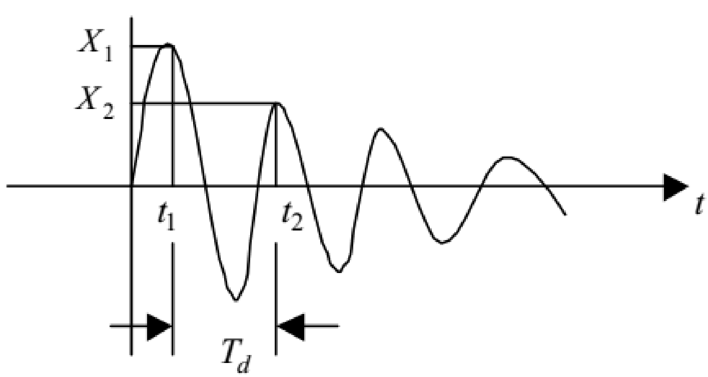



**FIGURE 5: DAMPED FREE VIBRATION RESPONSE.**

Two successive cycles are considered to calculate the damping ratio, and it is given by,

$$Damping\ Ratio, \delta = \frac{1}{n} \ln \frac{X_1}{X_{n+1}}$$

$$where, n\ is\ the\ number\ of\ oscillations,$$
$$X\ is\ the\ amplitude\ at\ each\ oscillation.$$

**EQUATION 4: DAMPING RATIO USING LOGARITHMIC DECREMENT METHOD.**

- *Half power bandwidth method:* in this approach, as mentioned earlier, the system is considered to be a single degree of freedom system. The excitation of the system can be done by any means discussed before. The FRF graph is taken to perform the calculations.

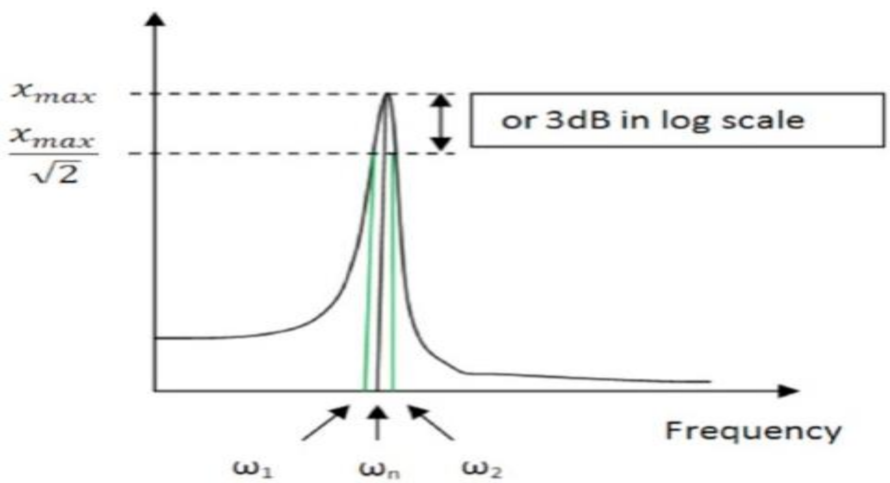



**FIGURE 6: HALF POWER BANDWIDTH METHOD ILLUSTRATION.**

$$\delta = \frac{\omega_2 - \omega_1}{2\omega_n}$$

**EQUATION 5: DAMPING RATIO USING HALF-POWER BANDWIDTH METHOD.**

## 3.3 Taguchi's Design of Experiments

The procedure to identify and study all possible conditions experimentally, involving many factors is known as design of experiments [38]. It is also referred to as the factorial design method. The technique has been in use since the 1920s, mainly employed in the chemical and pharmaceutical industries. According to the procedure, if we identify two factors that might be responsible for the outcome for a certain problem and we take two levels for each of these factors, then we would have to perform four trials, which is a combination of all these four values. The results are analysed using standard statistical analysis technique, ANOVA procedure. The method will be explained in detail later. Upon performing the post-processing, the most influential parameters can be found. So, in general, for $L$ levels of each parameter and $n$ number of parameters, we would have to perform $L^n$ number of trials. Now, when the number of factors and levels considered are small, this is not such a bad way to approach a problem. However, when many factors might influence the result and the cost and time involved to perform these trials are high, then it becomes a not so affordable method to use.

The fractional factorial method developed by Dr Genichi Taguchi addresses the problem involved in using the factorial method. The fractional, or also called a partial factorial approach, chooses some out of the many trials in the factorial method that would give the maximum information and only those tests are conducted. For example, if the number of factors studied in the case of a problem is *15* at *2* levels each, then the number of trials that need to be performed to do ANOVA is *32768* tests. However, with the fractional factorial method, the number of tests reduces to only *16*. The number of tests that is required to perform the array of experiments is labelled as $L_n$, where $n$ is the number of trials, so an *8* trial experiment is called $L_8$ and so on. To better understand the procedure, the table for $L_8$ is provided in Table 1.

**TABLE 1: EXPERIMENT LAYOUTS USING AN L8 ARRAY [37]**

(a) Experiment Structure

| Full Factorial Experiments | | | | $A_1$ | | | | $A_2$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $B_1$ | | $B_2$ | | $B_1$ | | $B_2$ | |
| | | | | $C_1$ | $C_2$ | $C_1$ | $C_2$ | $C_1$ | $C_2$ | $C_1$ | $C_2$ |
| $D_1$ | $E_1$ | $F_1$ | $G_1$ | T1 | | | | | | | |
| | | | $G_2$ | | | | | | | | |
| | | $F_2$ | $G_1$ | | | | | | | | |
| | | | $G_2$ | | | | T3 | | | | |
| | $E_2$ | $F_1$ | $G_1$ | | | | | | | | |
| | | | $G_2$ | | | | | | T5 | | |
| | | $F_2$ | $G_1$ | | | | | | | T7 | |
| | | | $G_2$ | | | | | | | | |
| $D_2$ | $E_1$ | $F_1$ | $G_1$ | | | | | | | | |
| | | | $G_2$ | | | | | | | T8 | |
| | | $F_2$ | $G_1$ | | | | | | T6 | | |
| | | | $G_2$ | | | | | | | | |
| | $E_2$ | $F_1$ | $G_1$ | | | | T4 | | | | |
| | | | $G_2$ | | | | | | | | |
| | | $F_2$ | $G_1$ | | | | | | | | |
| | | | $G_2$ | T2 | | | | | | | |

(b) Trial runs and conditions

| Column | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Factor<br><br>Trial | A | B | C | D | E | F | G |
| T1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| T2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
| T3 | 1 | 2 | 2 | 1 | 1 | 2 | 2 |
| T4 | 1 | 2 | 2 | 2 | 2 | 1 | 1 |
| T5 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| T6 | 2 | 1 | 2 | 2 | 1 | 2 | 1 |
| T7 | 2 | 2 | 1 | 1 | 2 | 2 | 1 |
| T8 | 2 | 2 | 1 | 2 | 1 | 1 | 2 |

In Table 1(a), factors (A, B, …, G) with two levels, ($A_1$, $A_2$, $B_1$, $B_2$, …, $G_1$, $G_2$) are shown. Each box indicates a trial according to the factorial method with a particular combination of these factors at either one of their levels. Entire table covers all possible combinations. We notice that the total trails come to *128*. With Taguchi's method of $L_8$, we choose only *8* (T1, T2, …, T8) of these *128* trials which provides with maximum information. The combination of different levels of each factor for these eight tests are listed in Table 1(b).

***ANOVA:*** Once the trials according to Taguchi's DOE is conducted, the results are post-processed using ANOVA which is a statistical technique used to study the variance in the results caused due to the variation in the factors. Hence it gives a numerical value of the influence of these factors on the effect. If there is one factor under study, it is called one-way ANOVA, and if there is more than one factor, then it is called two-way ANOVA. Many quantities are calculated in the ANOVA procedure. These quantities will be explained and the associated equations that follow.

***Total number of trials (n):*** This includes the total number of trials that are conducted as part of the analysis. The total number of trials for each factor is named, $n_{factor}$.

***Degree-of-freedom (DOF) (f):*** it is a quantity that gives a measure of the amount of information that can be uniquely obtained from the data. There are three different DOFs, the total DOF, $f_T$; DOF of each factor, $f_{factor}$; and DOF of the error, $f_e$.

$$Total\ DOF\ (f_T) = n * r - 1$$

$$where, \qquad n = trials, r = repititions$$

$$DOF\ of\ factors, (f_{factor}) = n_{factor} * r - 1$$

$$DOF\ of\ Error\ (f_e) = f_T - f_B - f_C - f_D - f_{E\ldots\ldots}$$

**EQUATION 6: DOF CALCULATION FOR THE ANALYSIS, FACTOR AND ERROR.**

***Sum of Squares (S):*** is a measure of the deviation of the results from the mean value. It gives an estimation of the sum of variation of the individual observation about the average.

$$Sum\ of\ Squares\ (S_T) = \sum_{i=1}^{n} (Y_i - \bar{Y})^2$$

$$where, \quad \bar{Y}\ is\ the\ average\ of\ Y_i$$

$$Error\ Sum\ of\ Square\ (S_e) = S_T - S_{factor}$$

**EQUATION 7: SUM OF SQUARE IN TOTAL AND THE ERROR.**

***Variance (V):*** it gives the distribution of the results about the mean value as it is only a representation of a part of the possible results. The DOF of the analysis is used in this calculation.

$$Variance\ (V) = \frac{S_T}{f}$$

**EQUATION 8: VARIANCE FORMULA.**

***Variance Ratio (F):*** also, known as the F statistic, is the ratio of the variance because of the factor and the variance because of the error term. It is a measure of the significance of the factor under study. The F factor computed is compared to the F factor from the standard table at certain confidence level, and if the calculated value is more than or equal to the standard for a particular confidence level, then the factor has a significant influence on the result or else it can be omitted.

$$Variance\ Ratio\ (F_{factor}) = \frac{V_{factor}}{V_e}$$

**EQUATION 9: F STATISTIC FORMULA.**

***Pure Sum of Squares (S'):*** when the sum of squares of each factor is subtracted by the product of the DOF of that factor and the error variance term, the resulting value is called the pure sum of squares.

$$Pure\ Sum\ of\ Squares\ (S'_{factor}) = S_{factor} - f_{factor} * V_e$$

**EQUATION 10: PURE SUM OF SQUARES FORMULA.**

***Percentage Contribution (P):*** this gives the percentage influence of each parameter that is studied. It is calculated by dividing the pure sum of squares of a factor by the total sum of squares.

$$Precentage\ contribution\ (P_{factor}) = S'_{factor} * \frac{100}{S_T}$$

**EQUATION 11: PERCENTAGE CONTRIBUTION FORMULA.**

The error percentage, which is calculated from the analysis signifies the error that is involved in conducting the experiments and might be an indication that other parameters have not been identified or considered as part of the study. The confidence of the F statistic from the standard gives the measure of the reliability of the results. For the factor whose F statistic is below the standard, and if the percentage influence is negative, the sum of squares and their DOF is added to the sum of square and DOF of the error and the rest of the calculation is redone to redistribute the contribution.

In the next chapters, we will see how the above discussed concepts and experimental methods are applied to the current problem under study to achieve the desired objectives.

# MANUACTURING 4

Manufacturing plays a very significant role in the final behaviour of the components and a pivotal role in the life span of the parts. Thus, choosing an optimised manufacturing procedure and curing temperature is paramount to exploit the capabilities of the raw materials used. In this thesis, all the samples that were manufactured used the materials and procedure that is illustrated in this chapter.

## 4.1 Materials

***Prepreg*** is a material where the resin system is pre-impregnated into the fibre and stored in the frozen state to prevent it from curing. FLAXPREG UD 180 (*180g flax per* $m^2$) [39] from Lineo was used as the base material. It is an out-of-autoclave prepreg material, which means that the material can be processed using a regular oven. As the name indicates, flax is the fibre and epoxy resin system is the matrix utilised in the prepreg with a fibre content of *50%* by weight. The properties of the flax/epoxy layer are shown in Table 2.

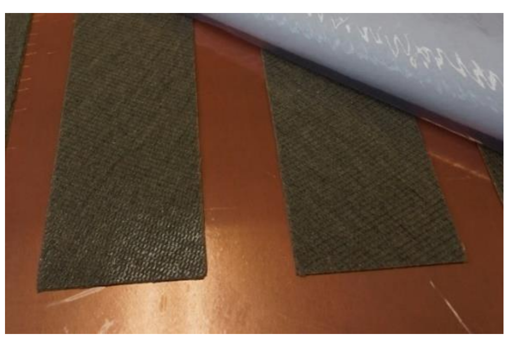


**FIGURE 7: FLAXPREG UD 180 PREPREG FROM LINEO.**

**TABLE 2: PROPERTIES OF FLAXPREG UD 180 [39]**

| Modulus | | Strength | | Other | |
|---|---|---|---|---|---|
| $E_x$ (MPa) | 28200 | $X_t$ (MPa) | 286 | $h_o$ (m) | $3.03 \times 10^{-4}$ |
| $E_y$ (MPa) | 3310 | $X_c$ (MPa) | 96 | | |
| $E_s$ (MPa) | 5200 | $Y_t$ (MPa) | 12 | $\rho$ (kg/m$^3$) | 1330 |
| $\nu_{xy}$ | 0.34 | $Y_c$ (MPa) | 41 | | |
| | | $S_c$ (MPa) | 27 | | |

***Core:*** is a material that is used to increase the thickness with only a small effect on the density and the in-plane mechanical properties of the laminate that is manufactured. A large bank of core materials is available on the market, which can be used in a laminate. In our studies, since we are looking at acoustic properties of the final product, it is necessary for us to choose the right core material as it would affect these properties. Due to relatively low damping property of Balsa, it was used as the core material. Also, it is very light, which means that one can lower the overall average density of the laminate. Balsa is very cheap and readily available at various thicknesses, making it the first choice. Some of the properties of Balsa are listed in Table 3.

**TABLE 3: PROPERTIES OF BALSA [40]**

| Modulus | | Poisson's Ratio | | Other | |
|---|---|---|---|---|---|
| $E_x$ (MPa) | 3900 | $\nu_{xy}$ | 0.40 | | |
| $E_y$ (MPa) | 600 | | | | |
| $G_{xy}$ (MPa) | 500 | $\nu_{yz}$ | 0.23 | $\rho$ (kg/m$^3$) | 170 |
| $G_{yz}$ (MPa) | 300 | $\nu_{xz}$ | 0.23 | | |
| $G_{xz}$ (MPa) | 300 | | | | |

***Mould and consumables***: A mould is a tool where we lay our prepreg, and it conforms to the shape of the mould before curing. The final finish greatly depends on the finish of the mould surface. Hence it is vital to have a mould surface that is very smooth and free from scratches. As only flat laminates were made in the study, we used an aluminium flat tool plate. It was polished to obtain a mirror finish and treated to protect the mould from the chemicals of the prepreg and to provide a non-stick release surface. The detailed procedure for polishing the mould is given in Appendix A.

Consumables are the materials that are used as part of the manufacturing process and are discarded after the curing. Since it is an out-of-autoclave procedure, we apply vacuum pressure to attain the required compaction of the plies. For this purpose, vacuum bag, sealant tape, release film, breather cloth, and a caul plate (which can be re-used after each cure) were employed. Sealant tape is used to seal the bagging system, and other consumables are used to apply perfect vacuum. Release film prevents the caul plate and breather from sticking to the prepreg. The caul plate is a thin aluminium plate used to help provide a smooth surface finish on the top face of the laminate and to help apply uniform pressure. Other equipment would include a vacuum pump, valves and oven.

## 4.2 Curing Cycle

The data sheet of the prepreg [39] provides multiple possible curing procedures for curing the prepreg depending on the glass transition temperature ($T_g$) we would like to achieve. For attaining the required effective modulus, it is recommended to cure such that we reach the maximum $T_g$. Thus, to obtain a $T_g$ of $135^oC$ *to* $145^oC$, it was recommended to cure the laminate for *1 hour* at $140^oC$ with a ramp up and ramp down of $2^oC/min$ from room temperature (*25°C*). An initial practice run was performed on the tool to find the temperature profile. Figure 8 shows the temperature profile for the specified cure cycle.

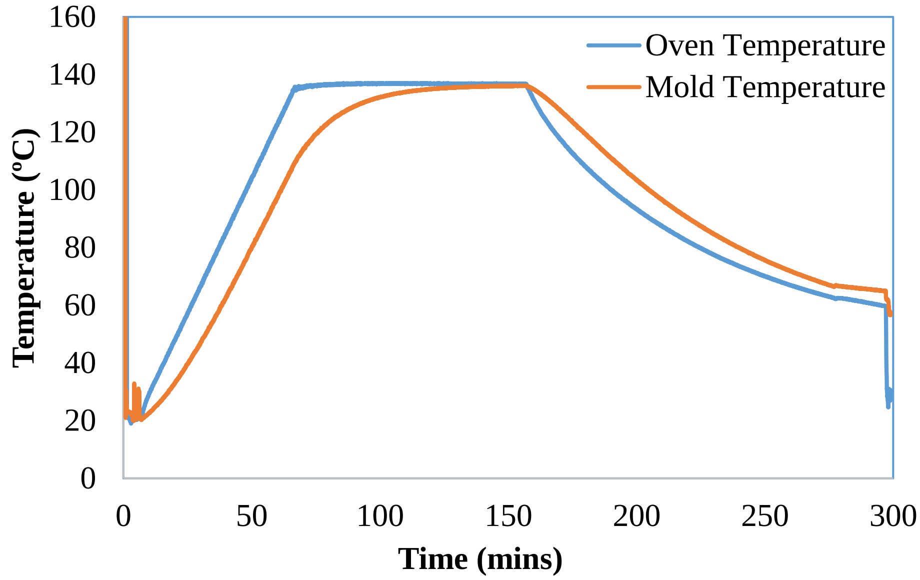



**FIGURE 8: TEMPERATURE PROFILE OF THE MOULD AND OVEN WITH THE SPECIFIED CURING CYCLE.**

It was found that there is a lag between the tool temperature and the preset cycle, so the hold temperature time was extended by *45 minutes* to compensate for this delay. Hence the curing period was changed to *1 hour 45 minutes* of curing at *140°C* with a ramp up and ramp down of *2°C/min*.

## 4.3 Layup and Debulk

The ply preparation and the layup were done over the course of two days. On the first day, the required plies were cut to planned size and ply angle and preserved in a frozen state until layup. On the second day, we thaw the plies, lay them up and cure the laminate in the oven. The prepregs are allowed to thaw for about *10 hours* before they are removed from the plastic bag for cutting; this prevents them from absorbing moisture. The required dimensions of the final laminate were *53.8cm x 6.45cm*. To avoid any damage to the final part due to cutting and to remove any edge defects from the laminate, the plies were cut with an additional *3.8cm* to the final dimension. For the ease of cutting process, a flat pattern cut out of cardboard was used to do the markings on the prepreg. Usually, to reduce the wastage of raw materials, some of the angled plies are cut in different smaller shapes that are combined to obtain the actual form when laid down. However, doing so could result in ply overlaps or if not laid down well, lead to fibre discontinuities. For avoiding any unknown effects on the acoustic behaviour due to such problems, plies of very precise dimensions were cut. Care was also taken to reduce the waste, keeping this constraint in mind.

On the second day, since the laminate is not as large a mass as the prepreg rolls, it requires much less time to thaw. We get all the consumables ready while the prepreg heats up to room temperature. The release film was cut to the dimensions of the laminate and breather was cut to *80%* of the mould size. We use the sealant tape and vacuum bag to vacuum seal the layup, and a valve is attached to the bag to evacuate air inside the bag using a vacuum pump. Edge breathers used to assist the release of entrapped air, and volatiles from the laminate are placed in contact with all four sides of the laminate. They were made from sealant tape and woven glass fabric. Glass fabric and sealant tape were cut to the edge dimensions of the laminate; the glass fabric is rolled around the sealant tape leaving a portion of the sealant free to stick to the mould surface. A portion of the glass material is also left to hang freely. Care must be taken to make sure the glass fibres are in contact with the breather so that air can flow and thus be evacuated.

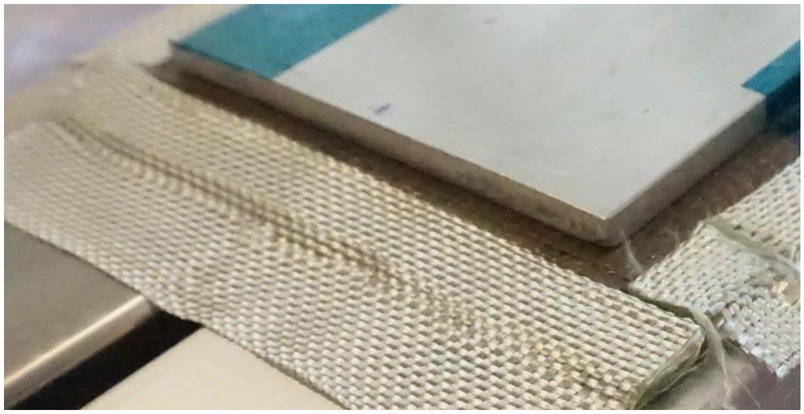


**FIGURE 9: GLASS FIBRE EDGE BREATHER FOR EVACUATION OF AIR AND VOLATILES DURING CURING.**

The layup is always a step-wise process, where we layup few plies first, then we debulk them to compact the plies and reduce the amount of entrapped air. Then we add more plies and continue the debulking process until all plies are laid. In our manufacturing, since the material used was very tacky, there was no issue regarding the first ply sticking to the mould or each subsequent ply holding well to each other. Thus, to reduce the processing time, we laid down the laminate in two halves and debulked them for *1 hour* before combining the two halves together. For the debulking process, the release film is put on top of the plies followed by the breather. The breather needs to be in contact with the vacuum valve so that air can be removed efficiently. Once sealed, a vacuum is applied and checked for any leaks from the bag. To check the quality of bagging, we connected a vacuum gauge, and if the pressure does not drop by more than *5 psi* in less *5 minutes,* then the bagging is good.

After *1 hour* of initial debulk, the vacuum pump is disengaged, and the vacuum bag is removed. Now one-half is laid over the other, making sure we do not make a mistake in the ply sequence. The edge breathers are placed in close contact with the edges of the plies (the edge breathers are of almost the same thickness as that of the plies). The caul plate is placed on top of the laminate, which acts as a top mould. The release film is laid over the caul plate, of same dimensions so that the breather (which will cover the entire mould) does not stick to the caul plate during the cure.  It is essential that the breather is in contact with edge breathers and there be a path to the vacuum valve for the air flow. More layers of breather are used near the valve to prevent any resin from entering the valve. Once everything is in place, the bag is sealed, and the vacuum is applied. Again, a similar bag quality check is performed to check for leaks. The final debulk is carried out for *8 hours*, before turning on the oven to cure the laminate.

## 4.4 Final Part

After *8 hours* of debulking and about *4.5 hours* of cure cycle, the laminate is finally ready to be demoulded. Cautiously this step must be performed so that we do not damage the final part. All the consumables get discarded after demoulding. Sometimes the edge breather might get stuck to the laminate, but this can be machined out. The laminates were marked on all four edges to the required dimension, and the laminate was cut square using a wood cutting machine saw from the architecture wood workshop. The cut laminates did not have any visible signs of damage, and the edges of the cuts were very smooth.

# EXPERIMENTS 5

Two different sets of experimental studies were conducted as part of the thesis work. One was to understand the influence of *5* different parameters, namely the moduli ($E_1$, $E_2$ and $E_f$), thickness and density on the acoustic parameters such as natural frequency and damping ratio. This study would help to better design the layup for successfully mimicking the behaviour of Rosewood. The second study involved understanding the effect of humidity and temperature on the natural frequency and damping ratio. This second study will help us in exploring if the suggested alternatives are more resistant to these conditions. We shall look into the instruments that were employed for these studies, and detail the setup and precautions taken while conducting these experiments. Followed by an explanation of how the two studies were designed and conducted. Also, the samples that were tested are described in detail, using a system of naming abbreviations, to ease the result discussion in the next chapter.

## 5.1 Instrumentation

The whole thesis work is based on the modal experiments that were conducted on the samples. All the modal tests have been carried out as per ASTM standard, E1876-09 [41]. Free-free boundary conditions were used for testing the samples. A mini-hammer and accelerometer were used to excite and record the response of the samples. All the test equipment was borrowed from the Computational Acoustic Modeling Laboratory (CAML) in the Music Technology Department at McGill University.

***Mini- Hammer:*** The hammer is a device that is used to excite the sample and make it vibrate. The size of the hammer is chosen depending on the size and type of sample that we are testing and it also depends on the kind of boundary conditions it is tested. It is also important to note how hard the hammer impact tip should be. If the material to be tested is very soft, then it is recommended to use a hammer with rubber tips, even though it might affect the frequency range that can be measured. Since the samples that we tested are mostly made of flax fibres, a steel tip mini hammer could be used. A PCB Piezotronics Model 086E80 mini hammer [42] was used for all studies in the thesis. The hammer has a sensor which gives the electronic signal in terms of voltage depending on the force of impact applied to the sample. The specifications of the hammer are shown in Tables 4 and 5.

**FIGURE 10: PCB PIEZOTRONICS MODEL 086E80 MINI HAMMER.**

**TABLE 4: OPERATING SPECIFICATION OF THE PCB PIEZOTRONICS MODEL 086E80 MINI HAMMER. [42]**

| **Parameters** | **Unit** |
|---|---|
| Sensitivity (±20%) | 22.5 mV/N |

| | |
|---|---|
| Measurement Range | 222 Npk |
| Resonant Frequency | ≥100 kHz |
| Non-Linearity | ≤ 1% |
| Excitation Voltage | 20 to 30 VDC |
| Constant Current Excitation | 2 to 20 mA |
| Output Impedance | <100 Ohm |
| Output Bias Voltage | 8 to 14 VDC |
| Discharge Time Constant | ≥ 100 sec |

**TABLE 5: PHYSICAL SPECIFICATION OF THE PCB PIEZOTRONICS MODEL 086E80 MINI HAMMER. [42]**

| **Physical Parameter** | **Units** |
|---|---|
| Sensing Element | Quartz |
| Sealing | Epoxy |
| Hammer Mass | 4.8 g |
| Head Diameter | 6.3 mm |
| Tip Diameter | 2.5 mm |
| Hammer Length | 107 mm |
| Extender Mass Weight | 1.25 g |

***Accelerometer:*** Accelerometers are piezoelectric-based sensors, which are used to measure the acceleration of a system. For these experiments, the sensors are used to gauge the acceleration of the samples due to hammer excitation. There is again a wide range of these sensors that are available in the lab. Since it is a contact-based sensor, the primary parameter that we need to look for is the weight of the sensor and the wire that extends from the sensor. It is critical that the sensors are not too heavy for the sample. A PCB Piezotronics Model 352A73 accelerometer sensor [43] were used in this study, with specifications shown in Tables 6 and 7. Wax was used to stick the sensor to the sample. Like the hammer, the accelerometer also sends the response of the samples in the form of electrical signals, which are processed to get the required outputs.

**FIGURE 11: PCB PIEZOTRONICS MODEL 352A73 ACCELEROMETER SENSOR.**

**TABLE 6: OPERATING SPECIFICATION OF PCB PIEZOTRONICS MODEL 352A73 ACCELEROMETER SENSOR [43]**

| **Parameter** | **Units** |
|---|---|
| Sensitivity (±20%) | 0.51 mV/(m/$s^2$) |
| Measurement Range | ±9810 m/$s^2$pk |
| Frequency Range (±5%) | 2.0 to 10000 Hz |
| Frequency Range (±10%) | 1.5 to 25000 Hz |
| Frequency Range (±3 dB) | 0.7 to 40000 Hz |
| Resonant Frequency | ≥70 kHz |
| Broadband Resolution (1 to 10000 Hz) | 0.02 m/$s^2$ rms |
| Non-Linearity | ≤ 1% |
| Transverse Sensitivity | ≤ 5% |
| Overload Limit | ±98.0 m/$s^2$pk |
| Temperature Range | -54 to +121ºC |
| Excitation Voltage | 18 to 30 VDC |
| Constant Current Excitation | 2 to 20 mA |
| Output Impedance | ≤ 200 Ohm |

| | |
|---|---|
| Output Bias Voltage | 7 to 12 VDC |
| Discharge Time Constant | 0.2 to 1.0 sec |
| Settling Time (within 10% of bias) | < 3 sec |
| Spectral Noise (1 Hz) | 8580(μm/$s^2$)/$Hz^{1/2}$ |
| Spectral Noise (10 Hz) | 1470(μm/$s^2$)/$Hz^{1/2}$ |
| Spectral Noise (100 Hz) | 440(μm/$s^2$)/$Hz^{1/2}$ |
| Spectral Noise (1 kHz) | 196(μm/$s^2$)/$Hz^{1/2}$ |
| Spectral Noise (10 kHz) | 98(μm/$s^2$)/$Hz^{1/2}$ |

**TABLE 7: PHYSICAL SPECIFICATION OF PCB PIEZOTRONICS MODEL 352A73 ACCELEROMETER SENSOR [43]**

| **Physical Parameter** | **Units** |
|---|---|
| Size (Height x Length x Width) | 2.8 x 8.6 x 4.1 mm |
| Weight (without cable) | 0.3 g |
| Sensing Element | Ceramic |
| Sensing Geometry | Shear |
| Housing Material | Titanium |
| Sealing | Hermetic |
| Cable Length | 3.05 m |
| Mounting | Adhesive |

***Other devices***: For improving the signal that is received from the sensors, a signal amplifier was used. Both the accelerometer and the hammer were connected to the amplifier, and the amplifier was connected to a data acquisition (DAQ) unit which was in turn attached to the laptop. A PCB Piezotronics Model 482C [44] series signal conditioner and a National Instrument Model USB 4431 DAQ unit [45] were employed for this purpose.

**TABLE 8: OPERATING SPECIFICATION OF PCB PIEZOTRONICS MODEL 482C SERIES SIGNAL CONDITIONER [44]**

| **Parameters** | **Units** |
|---|---|
| Channels | 4 |
| Sensor Input Types | ICP® |
| Output Range (Max) | ±10 V |
| Low Frequency Response (-5%) | < 0.1 Hz |
| High Frequency Response (-5%) | >1000 kHz |
| Phase Response (at 1 kHz) | ±1º |
| Cross Talk (max) | -72 dB |
| Temperature Range | 0 to +50ºC |
| AC Power (47 to 63 Hz) | 100 to 240 VAC |
| Excitation Voltage (±VDC) | +26 VDC |
| Constant Current Excitation | 2 to 20 mA |
| Overload Threshold (±1.0 Vpk) | ±10 Vpk |
| Discharge Time Constant (0 to 50%) | >5 sec |
| Broadband Electrical Noise (1 to 10000 Hz) | 3.5 μVrms |
| Spectral Noise (1 Hz) | 1.30 $\mu V/Hz^{1/2}$ |
| Spectral Noise (10 Hz) | 0.10 $\mu V/Hz^{1/2}$ |
| Spectral Noise (100 Hz) | 0.08 $\mu V/Hz^{1/2}$ |
| Spectral Noise (1 kHz) | 0.07 $\mu V/Hz^{1/2}$ |

| | |
|---|---|
| Spectral Noise (10 kHz) | 0.07 $\mu V/Hz^{1/2}$ |
| Size (Height x Width x Depth) | 8.1 x 20 x15 cm |
| Weight | 567 g |

**TABLE 9: SPECIFICATIONS OF NATIONAL INSTRUMENT MODEL USB 4431 DAQ UNIT [45]**

| **Parameters** | **Units** |
|---|---|
| Input Range | ±10 Vpk |
| FIFO buffer size | 1023 samples (shared between all channels) |
| Absolute Maximum Input Voltage (Positive Terminal) | ±60 Vpk |
| Absolute Maximum Input Voltage (Negative Terminal) | ±10 Vpk |
| AI Gain Accuracy (10 to 40ºC) | ±0.035 dB max |
| AI Offset (10 to 40ºC) | ±2.25 mV max |
| AI Frequency Flatness (20 Hz to 46.4 kHz) | ±0.02 dB max |
| AI Distortion Plus Noise | -80 dB max |
| AI Noise (46.4 kHz) | 100 $\mu V_{rms}$ max |
| AI Crosstalk (46.4 kHz) | -90 dB |
| Operating Temperature | -30 to 70ºC |
| Relative Humidity Range | 0 to 95% RH |
| Dimensions | 142 x 180 x 38 mm |
| Weight | 675 g |

***Experimental Setup:*** As mentioned earlier, the tests were conducted according to the ASTM standards. Figure 12 shows the test setup that was used to carry out the tests.

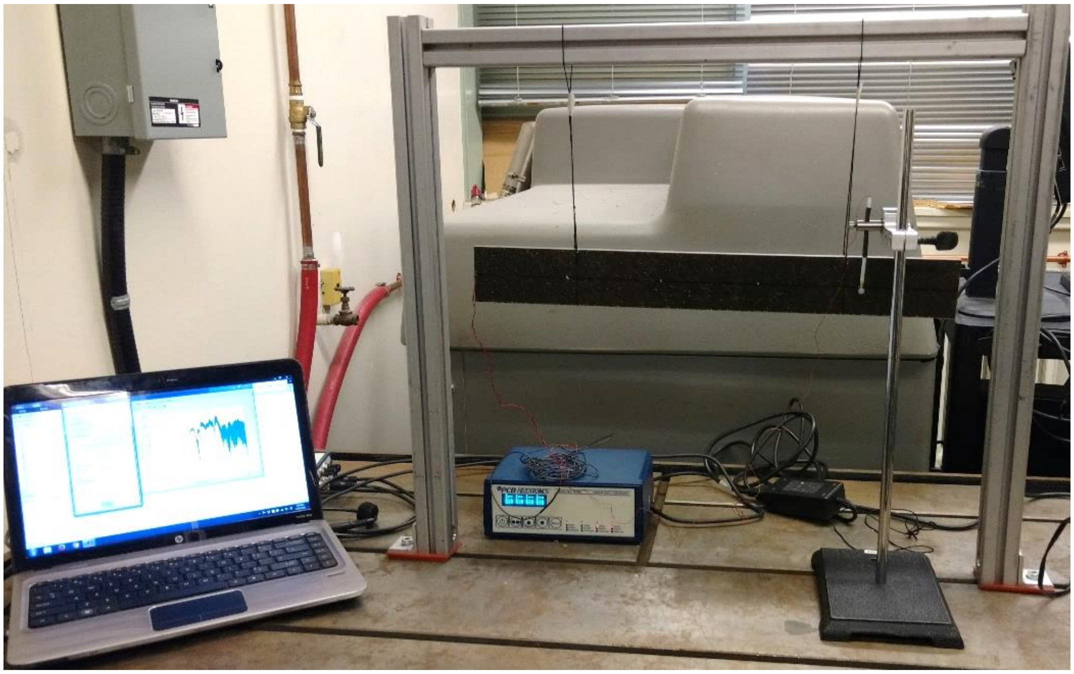


**FIGURE 12: TEST SETUP FOR THE MODAL TESTING.**

A lathe bed was used as the table to conduct all modal tests. Since the lathe bed is a solid block of metal, the amount of vibration that could be transmitted from the ground would be reduced to minimum, which helps in isolating the test setup. Aluminium rods were used to make the frame for hanging the test samples. The rods were attached to the bed with the use of T-head bolts. Between the rod and the bed, silicon padding of *0.5cm* was used to damp any small vibrations that could be transferred from the devices that were placed on the lathe bed. This way the frame is entirely isolated from the surrounding vibration. Another aspect to consider is the air circulation. It was important to conduct the tests where the air movement was at a minimum otherwise the sample could oscillate since it is in the free-free state. The tests were performed in the testing room which is a small enclosed place, hence minimising any significant air movement.

A chemistry stand was used for holding the hammer. As the stand is light, it was easy to move around to change the height and position the hammer. In this testing, the hammer must hit the sample only one time hence the hammer oscillation should be locked after the first hit. For this purpose, a custom-made hammer holder was made in the lab, which locks the hammer movement in the vertical position after the first impact.

**FIGURE 13: MINI HAMMER HOLDER.**

According to the ASTM standard, the sample must be hung at a distance of *0.224l* (*l* being the total length of the sample) from each end of the sample as shown in Figure 14. The nodes of the sample are at this distance from the ends. Nodes are the points where the displacement is zero when the sample is excited. Thus, by supporting the sample at this location, it would minimise any distortion to the natural modes and prevent additional damping to the system. Samples were hang using nylon thread. The distance from the frame to the samples was kept long enough so that the samples could vibrate freely. A mid-point line was drawn on all the samples and the accelerometer adhered to the sample with the help of wax at one end. Six equidistant points were marked on the sample along the mid-point line. The sample was excited at these points with the hammer, and the position of the accelerometer was kept constant.

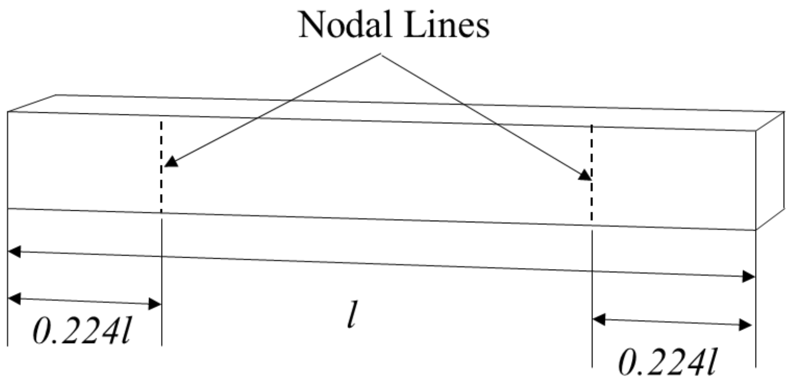



**FIGURE 14: SCHEMATIC OF A SAMPLE INDICATING THE NODAL LINES.**

Both the accelerometer and the hammer were connected to the signal conditioner with a gain of *10*. The outputs of these two signals were then attached to the DAQ unit which was then linked to the laptop. MATLAB code written by Professor Gary Scavone from Music Technology Department was used to process these signals and produce the required frequency plots. The code is simply used to process the responses read from the sensors and performs the FFT accounting the calibration and sensitivity of the sensor. The material data of the sample tested does not have influence over the program. All the interactions with the electronics and the result processing were done using this program. The program has trigger options where once the hammer excites the sample, it triggers and records the signal from the accelerometer. There is also an option to delay the recording. For the experiments conducted both trigger and delay options were used to ease the recording process. There was a delay of *2 secs* before recording, and once we hit the record button, the trigger turns on and waits for the signal from a hammer. When it receives the signal from hammer then, after the specified time delay, the response is recorded for *2 sec*. A sample rate of *44100 /sec* was used, and frequency bandwidth of *20 Hz to 22.05 kHz* was recorded. Tasks such as damping ratio calculations, mode and mode shape recognition cannot be done using this code and would require a separate post-processing.

## 5.2 Study 1: Effect of 5 Parameters ($E_1$, $E_2$, $E_f$, thickness and density) on the Natural Frequency.

The natural frequency is one of the most important parameters when it comes to acoustic properties, especially in the music industry, as the sound produced depends on the modes by which the material is vibrating. Hence it is vital to understand what are the main parameters that need to be accounted for designing a composite to mimic the properties of wood. Five parameters at two levels were chosen for the testing. For conducting this study, Taguchi's DOE technique was employed which reduced the number of tests from *32* to *8*. We need to note, for the case of these experiments, *32* trials would have required designing and manufacturing *32* different laminates and testing for their natural frequency and damping. Thus, the reduction in the number of experiments to *8* is a huge saving regarding material and time.

In this study, initially, seven different parameters were considered. When seven different parameters were taken, it was tough to design a layup for each trial due to the manufacturing restrictions that were considered. Even with five parameters, the process of designing eight different laminates with a certain value of properties was complicated. Hence, an *8%* allowance in the variation of the parameters was permitted to design the laminates reasonably. Tables 10 and 11 lists the values of the parameters that were considered and the combinations of these parameters.

**TABLE 10: FIVE PARAMETERS AND THEIR RESPECTIVE VALUES AT EACH LEVEL.**

| Parameters | Level Name | Value | Level Name | Value |
|---|---|---|---|---|
| $E_1$ (GPa) | A1 | 18.1 | A2 | 20 |
| $E_2$ (GPa) | B1 | 2.5 | B2 | 4 |
| $E_f$ (GPa) | C1 | 18.1 | C2 | 22 |
| Density (g/cc) | D1 | 0.76 | D2 | 0.83 |
| Thickness (cm) | E1 | 0.58 | E2 | 0.8 |

**TABLE 11: COMBINATION OF PARAMETERS AT DIFFERENT LEVELS FOR EACH TRIAL.**

| Trail | Combinations | | | | |
|---|---|---|---|---|---|
| T1 | A1 | B1 | C1 | D2 | E2 |
| T2 | A2 | B1 | C1 | D1 | E1 |
| T3 | A1 | B2 | C1 | D1 | E2 |
| T4 | A2 | B2 | C1 | D2 | E1 |
| T5 | A1 | B1 | C2 | D2 | E1 |
| T6 | A2 | B1 | C2 | D1 | E2 |
| T7 | A1 | B2 | C2 | D1 | E1 |
| T8 | A2 | B2 | C2 | D2 | E2 |

All the laminates were designed using a MATLAB code, which was developed as part of the project to make the selection process easier. The details of the way the program works are illustrated in Appendix B at the end of the thesis. Once these laminates were manufactured, they were cut to the exact dimensions and dried before testing.

## 5.3 Study 2: Effect of Humidity and Temperature on the Acoustic Behaviour (Natural Frequency and Damping ratio)

The next part of the thesis work was to understand the effect of humidity and temperature on the suggested alternatives and compare them with the behaviour of Rosewood. As both Rosewood and flax fibres are susceptible to these effects, it is vital to understand the implications for the acoustic response namely, natural frequency and damping ratio.

Damping ratio is usually considered to increase with the absorption of water. As damping ratio has a significant effect on the sound quality of the instrument, it is important to understand this behaviour.

In general, depending on the location, musical instruments could be subjected to different temperatures and humidity levels, where the temperature could reach as high as *50ºC* and humidity could attain a maximum of *100% RH*. In the study, three temperature and three humidity levels were considered and, in total, *9* trials were conducted. A conditioning chamber that was built in-house was used for these experiments. Table 12 below summarises the trials conducted. The conditioning chamber is a square aluminium box that has been covered with insulation material. The space in it is divided by trays placed at different heights, to place the samples. At the roof of the chamber, an electric fan is fixed, and to the inner end, a heating rod is attached to heat the unit. A salt water bath is used to get the required humidity. Depending on the required humidity levels, different salt solutions are used. Obtaining a moisture level of *50% RH* or higher was tough. Hence, the conditioning chamber in the Music Department owned by Prof. Gary Scavone was used (Appendix C). Before running the tests, practice runs were done for each test case and; Omega OM-92 temperature, and humidity data logger (Appendix D) was used to record the real-time data.

**TABLE 12: TEST MATRIX FOR HUMIDITY AND TEMPERATURE EXPERIMENTS.**

| Temperature (ºC) | Relative Humidity (% RH) | | |
|---|---|---|---|
| | 50 | 75 | >85 |
| **25** | X | X | X |
| **35** | X | X | X |
| **45** | X | X | X |

For > *85% RH*, tap water was directly used without any salt. It was not possible to go beyond *90% RH* when the temperature was increased to *35ºC* and *45ºC*. For achieving *75% RH*, sodium chloride (salt) was used. It is required to use a saturated salt solution hence, once the prepared salt solution is poured into the trays extra salt is added on the trays to make sure the solution remains saturated. Because of the conditions of the room where the conditioning chamber was located, it was difficult to get the required *50% RH*, and the lowest possible relative humidity was about *67% RH*. Thus, all the *50% RH* tests was done with different humidity chamber as mentioned above.

Before every conditioning run, the samples were dried for *6 hours* in the oven at *100ºC*. The sample weights were measured before and after drying. During the drying period, the conditioning chamber is set to the required temperature and humidity with the help of the salt water bath and heating rod. When the samples are dried, the weights are measured, and they are placed inside the conditioning chamber and the time is noted. Exactly after *24 hours* of conditioning, modal testing was performed on the samples. The tests ran for about *60 minutes* for each trail. The accelerometer position was fixed, and the response was measured at three different points of excitation using the instrumented hammer. At each location, three repetitions were performed. The drying time was fixed after performing a separate drying test where the weight of the samples was measured every hour for *8 hours* of drying at *100ºC*. It was found that the weight did not reduce with any significant value after *6 hours* (*~0.01 g*) so it was concluded that *6 hours* of drying should be ideal after each trial.

## 5.4 Samples

As part of the thesis, in total *9* samples were manufactured using FLAXPREG UD *180* prepreg and balsa as the core material. Table 13 below lists the ply sequence and properties of these laminates. The nomenclature employed in the table will be utilized in rest of the thesis to refer to these samples.

**TABLE 13: LIST OF LAMINATES THAT WERE MANUFACTURED AND THEIR PROPERTIES.**

| Laminates | $E_1$ (Gpa) | $E_2$ (Gpa) | $E_f$ (Gpa) | Density (g/cc) | Thickness (cm) | Layup |
|---|---|---|---|---|---|---|
| F_1 | 18.6 | 5.6 | 18.1 | 0.88 | 0.79 | [±45_2/0_7/B]s |
| F_2 | 20.4 | 2.6 | 18.5 | 0.76 | 0.58 | [0_2/B/±15/0_3]s |
| F_3 | 17.8 | 3.76 | 18.05 | 0.74 | 0.79 | [0_2/B/40/-45/5/-10/0/0.5B]s |
| F_4 | 20.9 | 4.7 | 18.4 | 0.87 | 0.57 | [±30_2/0.5B/0_4]s |
| F_5 | 20.1 | 2.3 | 22.5 | 0.74 | 0.79 | [0_4/B/0_5/0.5B]s |
| F_6 | 18.2 | 3.9 | 22.1 | 0.76 | 0.58 | [5/15/10/-15/B/15/-45/10]s |
| F_7 | 20.3 | 4.2 | 21.8 | 0.82 | 0.76 | [±45/0_8/B]s |
| F_8 | 22.7 | 2.83 | 18.4 | 0.88 | 0.85 | [±15/0/B/0_8]s |
| F_9 | 21.4 | 3.3 | 25.6 | 0.87 | 0.62 | [±15_3/0_2/B]s |

**FIGURE 15: FLAX FRETBOARD SAMPLES MANUFACTURED.**

The laminates length and width were kept constant at *53.8cm x 6.45cm*. 'B' in the table indicates, balsa core of *0.8 mm* thickness.

Apart from these samples, 2 more samples were manufactured from flax fibre composite and balsa core but using an autoclave manufacturing process. These samples were given to us from KU Leuven University, Belgium. Another sample made of a combination of woven and unidirectional (UD) flax prepreg with balsa core using an out-of-autoclave technique was prepared at our lab. The samples were again of the same dimensions as that of the samples manufactured as part of the thesis. Table 14 lists their properties which are of concern in this thesis. Here W_1 is the woven and UD combination and K_1 and K_2 are the samples from KU Leuven.

**TABLE 14: LIST OF OTHER FLAX FIBRE SAMPLES THAT WERE TESTED, AND THEIR PROPERTIES.**

| Laminates | $E_1$ (GPa) | $E_2$ (GPa) | $E_f$ (GPa) | Density (g/cc) | Thickness (cm) | Layup |
|---|---|---|---|---|---|---|
| W_1 | 18.79 | 3.50 | 21.10 | 0.83 | 0.55 | [0w/0_6/B]s |
| K_1 | 17.40 | 2.17 | 25.80 | 0.82 | 0.56 | [±15_3/0_2/B]s |
| K_2 | 17.60 | 2.27 | 19.50 | 1.07 | 0.46 | [0_3/B/±20_3]s |

**FIGURE 16: RICHLITE, BAMBOO AND W_1 SAMPLES RESPECTIVELY.**

Finally, we had a sample of Rosewood as a baseline measure. A few candidate alternatives, which are available in the market were also considered: a sample of bamboo fibre composite and a paper and phenolic resin based composite from Richlite was used in the studies. The sample from Richlite was not of the same dimensions as that of rest of the samples. However, since they were only used in the second study to understand the effect of humidity and temperature, it was not a necessity. The sample of Rosewood will be referred as Rosewood, Bamboo composite as Bamboo and the sample of paper based composite as Richlite in rest of the thesis.

**FIGURE 17: ROSEWOOD SAMPLE.**

For the first study, all samples from F_1 to F_7 and K_2 were used as the eight different samples. For the second study, F_1, F_8, F_9, W_1, K_1, K_2, Rosewood, Bamboo and Richlite were used to conduct the studies.

# RESULTS AND DISCUSSIONS 6

For a better understanding and to make optimal designs of flax laminates that can close match the properties of the Rosewood, as a replacement for the fretboard in guitars, two different studies were conducted. One was done to identify the relevant parameters to design a layup and other to understand the material behaviour at various temperature and humidity conditions. The procedure and concepts behind these tests were explained in detail in the previous chapter, and now we shall discuss the results of these studies.

## 6.1 Experimental Modal Testing

All the samples that were examined as part of the two studies used the setup explained in the previous chapter. A common frequency output is shown in Figure 18, taking the example of a flax composite tested at *50% RH* and *45°C*.

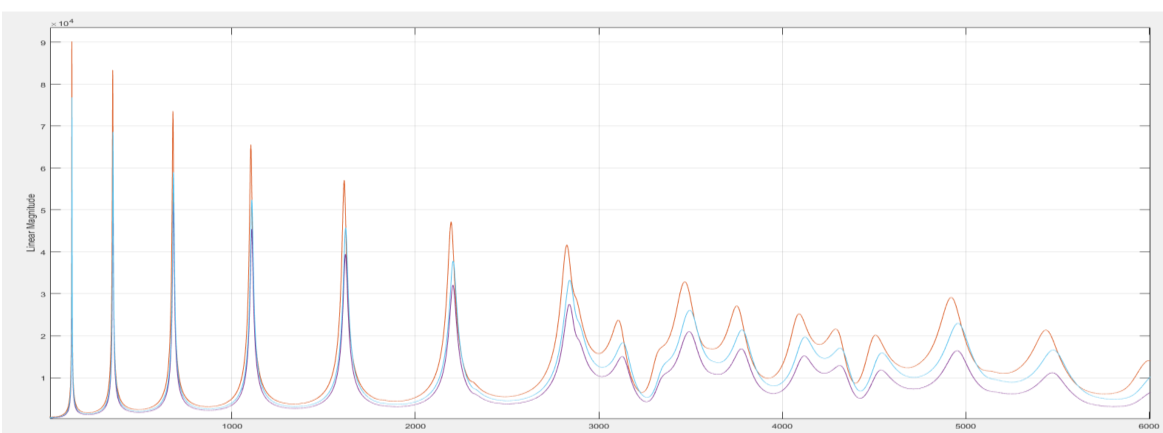



**FIGURE 18: FREQUENCY RESPONSE GRAPH IS TAKEN FOR A FLAX COMPOSITE IN TERMS OF DISPLACEMENT MAGNITUDE VS FREQUENCY.**

Figure 18 shows the linear magnitude vs. frequency graph that is obtained using the program that was mentioned in section 5.3 from the previous chapter. Each peak in the chart indicates one natural mode of vibration for the sample. The first three peaks are the first three modes of the laminate. A key point to notice is that first six modes are well spaced apart. This behaviour allows us to use the half-power bandwidth method to calculate the damping ratios.

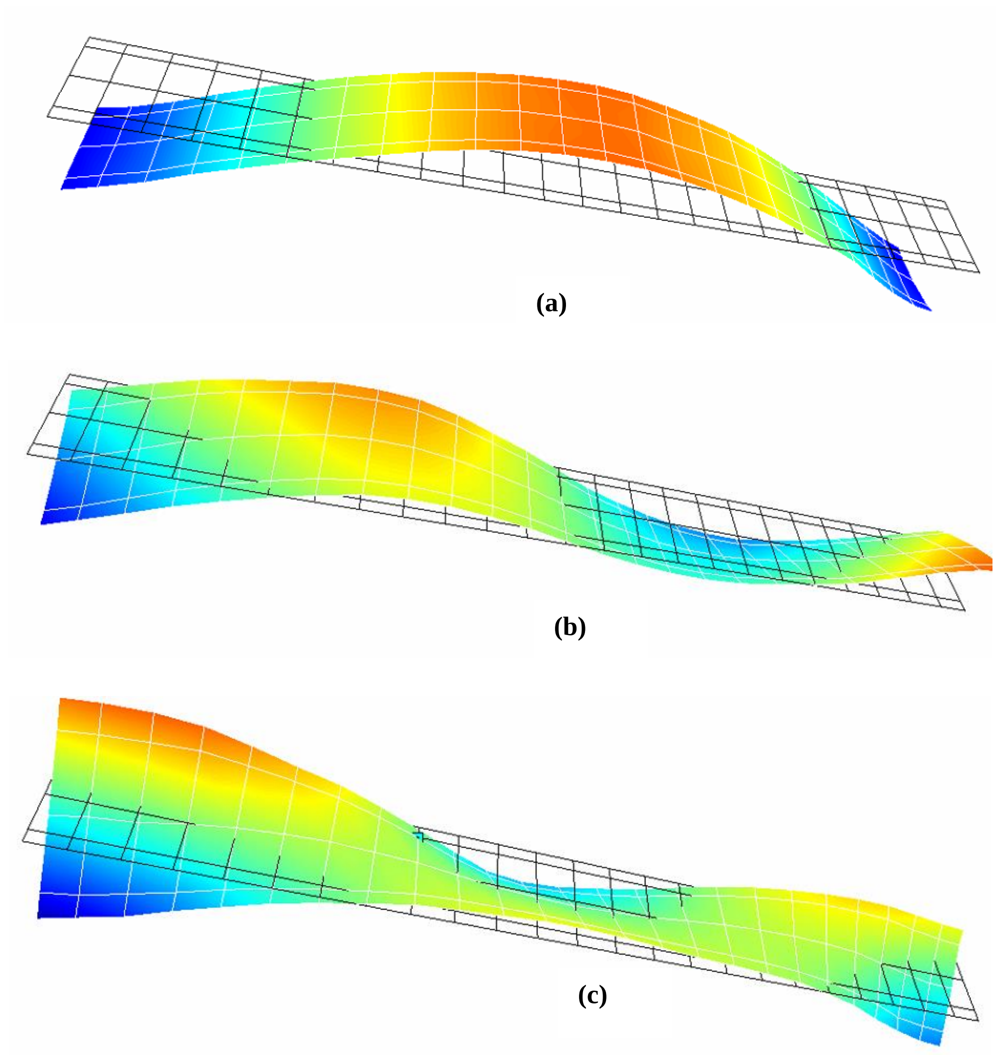



**FIGURE 19: (A) MODE 1, (B) MODE 2, (C) MODE 3. THE FIRST THREE MODES OF VIBRATION FOR THE FLAX SAMPLE.**

Figure 19 shows the first three mode shapes of vibration experienced by the laminate. First and second modes are bending modes, although the second mode also has a small amount of twisting at the ends. The third mode has a lot more twisting of the laminate.

## 6.2 Study 1: Effect of 5 parameters ($E_1$, $E_2$, $E_f$, thickness and density) on the Natural Frequency

Applying Taguchi's design of experiment technique, eight different laminates were manufactured and tested to obtain their natural modes and damping ratios. Damping ratios were obtained using the half-power bandwidth method. After these data, had been obtained, ANOVA procedure was employed to identify the influence of the five parameters under consideration. The natural modes and corresponding damping ratios are listed in Table 15 for the eight samples. For an illustration of the calculation, natural Mode 1 is taken as an example, and details are provided. The results of Mode 2 and Mode 3 are also presented and discussed in the thesis.

**TABLE 15: FIRST THREE NATURAL MODES AND RESPECTIVE DAMPING RATIOS OF THE SAMPLES TESTED IN STUDY 1.**

| Fretboard Samples | Mode 1 (Hz) | Damping Ratio (%) | Mode 2 (Hz) | Damping Ratio (%) | Mode 3 (Hz) | Damping Ratio (%) |
|---|---|---|---|---|---|---|
| F_1 | 108 | 0.73 | 294.4 | 0.80 | 454.6 | 0.72 |
| F_2 | 98.6 | 0.54 | 206.2 | 0.89 | 268.8 | 0.56 |
| F_3 | 112.4 | 0.67 | 303.1 | 0.57 | 579.7 | 0.68 |
| F_4 | 73.7 | 0.54 | 205.6 | 0.61 | 341.5 | 0.75 |
| K_2 | 117.4 | 0.68 | 298.1 | 0.77 | 319 | 0.66 |
| F_5 | 149.7 | 0.53 | 278.9 | 0.90 | 400.4 | 0.55 |
| F_6 | 108 | 0.65 | 267.5 | 0.84 | 296.1 | 0.88 |
| F_7 | 115.4 | 0.55 | 313.6 | 0.60 | 603.6 | 0.63 |

***ANOVA:*** Keeping in mind the combination of the two levels of the five parameters from Table 11, the results in Table 15 are arranged according to their respective trial number. Thus, we can see K_2 in the fifth row of the table. The ANOVA calculation for natural Mode 1 is performed as follows;

No. of Experiments, $n = 8$

Total degrees-of-freedom, $f_T = 7$

Number of levels, $l = 2$

Degrees-of-freedom of each parameter, $f = 1$

Degrees-of-freedom of error, $f_e = f_T - 5*f = 2$

Summation of the result from all experiments, $T = 883.16$

Correction factor, $C.F. = T^2/N = 97496.448$

Total sum of squares, $S_T = (Y1^2 + \ldots + Y2^2) - C.F. = 3122.081$

From Table 11, remember the nomenclature used to represent each level of all the parameters. The next step is to calculate the sum of the output for the respective levels of each parameter. From now the total of each parameter will be referred to by the level name.

**TABLE 16: SUM AND MEAN OF THE OUTPUT FOR EACH LEVEL OF THE PARAMETERS.**

| Level | Sum | | Mean = Sum/4 |
|---|---|---|---|
| A1 | Y1+Y3+Y5+Y7 | 445.8 | 111.45 |
| A2 | Y2+Y4+Y6+Y8 | 437.36 | 109.34 |
| B1 | Y1+Y3+Y5+Y7 | 473.68 | 118.42 |

| | | | |
|---|---|---|---|
| B2 | Y3+Y4+Y7+Y8 | 490.50 | 102.37 |
| C1 | Y1+Y2+Y3+Y4 | 392.66 | 98.17 |
| C2 | Y5+Y6+Y7+Y8 | 490.50 | 122.63 |
| D1 | Y2+Y3+Y6+Y7 | 468.68 | 117.17 |
| D2 | Y1+Y4+Y5+Y8 | 414.48 | 103.62 |
| E1 | Y2+Y4+Y5+Y7 | 397.66 | 99.42 |
| E2 | Y1+Y3+Y6+Y8 | 485.50 | 121.38 |

Sum of square for parameter A, $S_A = (A1^2/N_{A1}) + (A2^2/N_{A2}) – C.F. = 8.9042$

Variance of parameter A, $V_A = S_A/f = 8.9042$

Similarly, the sum of squares and variance are calculated for other four parameters.

Then, the sum of squares of error, $S_e = S_T – (S_A + .... + S_E) = 69.7$

And variance of error, $V_e = S_e/f_e = 34.85$

Variance ratio of parameter A, $F_A = V_A/V_e = 0.2556$

Pure sum of squares for parameter A, $S_A^{'} = S_A – (V_e * f_A) = -25.9458$

Finally, the percentage influence of parameter A, $P_A = (S_A^{'}/S_T)*100 = -0.83\%$

**TABLE 17: ANOVA RESULTS FOR NATURAL MODE 1.**

| **Parameters** | **Sum of Squares** | **Variance** | **Variance Ratio** | **Pure Sum of Squares** | **Percentage Influence (%)** |
|---|---|---|---|---|---|
| $E_1$ | 8.9042 | 8.9042 | 0.2555 | -25.9458 | -0.8310 |
| $E_2$ | 515.2005 | 515.2050 | 14.7835 | 480.3550 | 15.3857 |
| $E_f$ | 1196.5832 | 1196.5830 | 34.3352 | 1161.7330 | 37.2102 |
| Density | 367.2050 | 367.2050 | 10.5367 | 332.3550 | 10.6453 |
| Thickness | 964.4832 | 964.4832 | 27.6753 | 929.6332 | 29.7761 |

Each parameter was referred to using the designated level names for calculation purposes till now. Table 17 shows the ANOVA results that were computed for natural Mode 1 and gave the percentage influence of each parameter. The error was calculated to be *7.82%*. The error usually accounts for errors in experiments performed or indicates that there might be other parameters that might not have been accounted. It is seen that the flexural modulus ($E_f$) has the maximum influence on Mode 1 and thickness has the next biggest role. As the first mode is a bending mode, it is reasonable that the flexural modulus is the most important parameter among the rest. These two are followed by the modulus ($E_2$) in 2-direction of the laminate and finally the density. Surprisingly we find that for the first mode, modulus ($E_1$) in 1-direction has a negative influence. Regarding ANOVA, when a parameter has very low or a negative impact it indicates that the parameter does not have much influence and it can be pooled, and the percentage can be redistributed. The steps are shown for this example where $E_1$ is pooled to obtain the new percentage influences.

For pooling the $E_1$ term, the sum of the square of $E_1$ is added to the sum of the square of the error term and the degree-of-freedom of $E_1$ is added to the error.

Hence the new Error variance, $V_e = 26.2014$

And $f_e = 3$

**TABLE 18: ANOVA RESULTS FOR NATURAL MODE 1 AFTER E1 WAS POOLED.**

| Parameters | Sum of Squares | Variance | Variance Ratio | Pure Sum of Squares | Percentage Influence |
|---|---|---|---|---|---|
| $E_2$ | 515.2005 | 515.2050 | 19.6632 | 489.0036 | 15.66285 |
| $E_f$ | 1196.5832 | 1196.5830 | 45.6687 | 1170.382 | 37.4875 |
| Density | 367.2050 | 367.2050 | 14.0147 | 341.0036 | 10.9223 |
| Thickness | 964.4832 | 964.4832 | 36.8104 | 938.2818 | 30.0531 |

Table 18 shows the results after pooling the $E_1$ term. The error reduces from *7.82%* to *5.88%*. The percentage influence of the other parameters is increased by a small amount. The best way to check if the obtained ANOVA result is reliable is to look at the variance ratio. From the standard variance ratio chart, for the given DOF of the parameter and DOF of the error, the corresponding variance ratio is taken. If the variance ratio from the calculation is above or equal to this value, then the percentage calculated has the corresponding confidence level of the chart. For a confidence level of *95%*, the variance ratio is found to be *10.128* at $f_e = 3$ and $f = 1$ (see Appendix E). We can see from the Table 18 that all the variance ratios are above this value hence showing that the calculated influence measures are correct.

**TABLE 19: ANOVA RESULTS FOR NATURAL MODE 2 AFTER POOLING THE INSIGNIFICANT TERMS.**

| Parameters | Sum of Squares | Variance | Variance Ratio | Pure Sum of Squares | Percentage Influence |
|---|---|---|---|---|---|
| $E_1$ | 3160.125 | 3160.125 | 11.33464 | 2881.322 | 22.73269 |
| $E_f$ | 2760.245 | 2760.245 | 9.90036 | 2481.443 | 19.57776 |
| Thickness | 5639.220 | 5639.220 | 20.22658 | 5360.418 | 42.29193 |

**TABLE 20: ANOVA RESULTS FOR NATURAL MODE 3 AFTER POOLING THE INSIGNIFICANT TERMS.**

| Parameters | Sum of Squares | Variance | Variance Ratio | Pure Sum of Squares | Percentage Influence |
|---|---|---|---|---|---|
| $E_1$ | 8404.561 | 8404.561 | 3.060657 | 5658.563 | 8.012566 |
| $E_f$ | 7793.761 | 7793.761 | 2.838225 | 5047.763 | 7.147669 |
| Thickness | 43438.78 | 43438.78 | 15.81894 | 40692.78 | 57.62128 |

Tables 19 and 20 show the ANOVA results for natural Mode 2 and Mode 3. The results are presented after the pooling of insignificant terms are performed. The error for Mode 2 is calculated as *15.39%* and *27.22%* for Mode 3. Looking at the variance ratio, it is clear that they do not have *95%* confidence level, but they meet the requirement for a *90%* confidence level. The variance ratio from the charts for *90%* confidence level is *5.5383*, and all the variance for these modes are above this value. Another point to note is that we see an increasing trend in the error parameter, which could be because we have excluded parameters such as shear modulus. Other D matrix terms might be of possible importance, given that the Mode 2 had a bit of twist in its mode shape and Mode 3 was a twisting mode. When we compare the results of all three modes, it is seen that importance of thickness continuously increases. Thus, it is crucial to have the thickness constant while designing a laminate. Also, the influence of $E_1$ is seen more in the case of Mode 2 and Mode 3.

The same procedure was applied to damping ratios of the Mode 1 alone, and the results are presented in Table 21. The reason for analysing only the first mode is that for a free-free condition, upon excitation of the samples, the first mode will always dominate in comparison to other modes.

**TABLE 21: ANOVA RESULTS FOR A DAMPING RATIO OF NATURAL MODE 1.**

| **Parameters** | **Sum of Squares** | **Variance** | **Variance Ratio** | **Pure Sum of Squares** | **Percentage Influence** |
|---|---|---|---|---|---|
| $E_1$ | 0.040612 | 0.040612 | 249.9231 | 0.04045 | 91.33503 |
| $E_2$ | 0.000612 | 0.000612 | 3.769231 | 0.00045 | 1.016088 |
| $E_f$ | 0.000612 | 0.000612 | 3.769231 | 0.00045 | 1.016088 |
| Density | 0.001512 | 0.001512 | 9.307692 | 0.00135 | 3.048264 |
| Thickness | 0.000612 | 0.000612 | 3.769231 | 0.00045 | 1.016088 |

Table 21 presents the results without the pooling operation. The error was calculated to be *2.57%*. At a confidence level of *99.5%*, the variance ratio is found to be *198.5* for $f_e = 2$ and $f = 1$, from the chart. It is seen that the variance ratio of the $E_1$ term is at *249.92* which is way more than the minimum value. We know that if the rest of the parameters were pooled, this value would go even higher and so will the influence percentage. The main reason for this could be that the damping ratio can be related to strain energy loss and strain energy is related to the modulus term ($E_1$). This concludes that $E_1$ is relevant about damping ratio.

## 6.3 Study 2: Effect of Humidity and Temperature on the Acoustic Behaviour (Natural Frequency and Damping Ratio)

Flax fibres are susceptible to moisture and temperature effects, so it is important to see how bad or good they perform in comparison to the material it would be replacing, Rosewood. As mentioned in the experimental section, in total nine different samples were tested at three different temperature and humidity levels, for a total of *9* different trials. Also, the samples were tested in their dry state as well. The findings from this study are as follows;

**TABLE 22: PERCENTAGE CHANGE IN SAMPLE WEIGHT, FOR EACH TRIAL.**

| **Sample** | **25/85** | **25/75** | **25/50** | **35/85** | **35/75** | **35/50** | **45/85** | **45/75** | **45/50** |
|---|---|---|---|---|---|---|---|---|---|
| F_1 | 1.54 | 0.61 | 0.58 | 1.66 | 0.96 | 0.58 | 1.66 | 1.28 | 0.73 |
| F_8 | 1.22 | 0.51 | 0.51 | 1.26 | 0.79 | 0.47 | 1.38 | 1.15 | 0.63 |
| F_9 | 1.67 | 0.70 | 0.49 | 1.79 | 1.03 | 0.60 | 1.79 | 1.30 | 0.76 |
| Bamboo | 8.72 | 1.99 | 1.28 | 6.75 | 2.44 | 1.22 | 5.45 | 3.12 | 1.53 |
| Rosewood | 7.91 | 4.02 | 2.88 | 7.57 | 4.09 | 2.75 | 6.95 | 4.90 | 3.27 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| K_1 | 2.65 | 1.35 | 0.82 | 2.59 | 1.53 | 0.77 | 2.60 | 1.95 | 1.18 |
| K_2 | 3.09 | 1.61 | 1.16 | 3.09 | 1.81 | 1.10 | 3.16 | 2.46 | 1.55 |
| W_1 | 3.22 | 1.73 | 1.17 | 2.97 | 1.67 | 1.05 | 2.97 | 2.04 | 1.36 |
| Richlite | 0.92 | 0.50 | 0.35 | 0.96 | 0.46 | 0.31 | 0.77 | 0.54 | 0.39 |

Table 22 shows the percentage change in the sample weight for all the *nine* trials that were conducted. In the title row, the numbers, in the format $N_1/N_2$, indicate temperature (*°C*) / relative humidity (*% RH*). Note from the table; Rosewood always absorbed more moisture than all the other samples except for one trial, where Bamboo has higher weight gain. Richlite had the least increase in all the samples. The samples F_1, F_8 and F_9, performed quite well in comparison to other samples with an overall gain of no more than *1.67%* in weight, whereas other samples are seen to have more than *3%* increase in weight. Similar results are given below in Table 23 for Natural Mode 1 and the corresponding damping ratios. Since similar trends are noticed in other modes, those results are included in Appendix F, and only Mode 1 results are discussed here.

**TABLE 23: NATURAL MODE 1 FREQUENCY VALUES FOR SAMPLES, FOR EACH TRAIL.**

| **Sample** | **Dry** | **25/85** | **25/75** | **25/50** | **35/85** | **35/75** | **35/50** | **45/85** | **45/75** | **45/50** |
|---|---|---|---|---|---|---|---|---|---|---|
| F_1 | 130.5 | 123.5 | 127.9 | 129.5 | 122.8 | 127.2 | 129.5 | 122.5 | 125.2 | 128.9 |
| F_8 | 107.3 | 105.0 | 106.7 | 106.7 | 104.3 | 106 | 106.7 | 103.6 | 105 | 106 |
| F_9 | 108.7 | 104.3 | 107 | 108.3 | 103.6 | 106.3 | 108 | 103.3 | 105.3 | 107 |
| Bamboo | 73.35 | 63.93 | 69.31 | 72.67 | 64.6 | 69.65 | 72.34 | 66.28 | 68.97 | 72 |
| Rosewood | 87.14 | 82.43 | 85.46 | 87.14 | 83.1 | 85.46 | 87.14 | 83.78 | 85.46 | 86.81 |
| K_1 | 85.46 | 77.05 | 82.77 | 85.46 | 77.38 | 82.1 | 85 | 78.73 | 81.42 | 84.45 |
| K_2 | 117.4 | 108 | 113 | 115.7 | 107.7 | 112.4 | 115.7 | 107.7 | 110.4 | 114.1 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| W_1 | 96.56 | 88.49 | 92.53 | 94.21 | 88.15 | 92.19 | 94.54 | 88.82 | 90.84 | 93.53 |
| Richlite | 91.18 | 87.48 | 90.17 | 90.84 | 87.48 | 89.5 | 90.52 | 87.14 | 88.49 | 89.83 |

The variation in natural Mode 1 for each trial is shown in the above Table 23. Though there was a change in weight in all the samples for each trail, some of the samples did not show any change in Mode 1 in certain cases. For example, Rosewood did not have a change in its mode value at *25/50* and *35/50* even though it had gained weight at both these trials. It can also be noted that the weight gain has resulted in a decrease in the natural frequencies for all the samples. This change was an expected trend as mass is inversely proportional to the frequency of the system. When we look at the percentage change in natural frequency, even though Rosewood always showed a tendency for maximum absorption of moisture, the highest variation in the frequency is found to be *5.41%*. Similar to Rosewood, F_1, F_8, F_9 and Richlite have maximum variation ranging from *4.43% to 6.13%*. This small change is an expected trend as these samples absorbed less moisture compared to the rest. Bamboo, K_1, K_2 and W_1 had higher levels of variation in their frequency with their maximum difference ranging from *8.26% to 11.93%*.

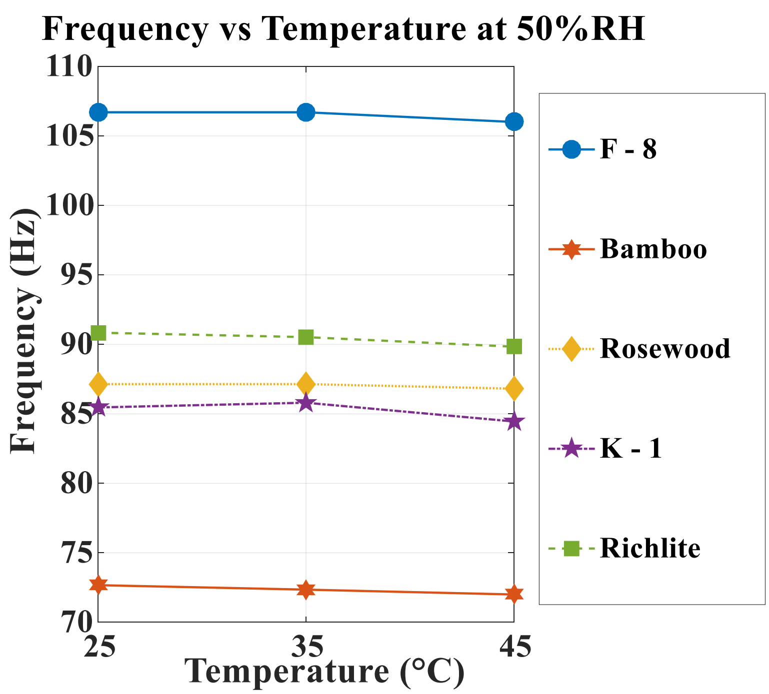
**TABLE 24: DAMPING RATIO AT NATURAL MODE 1 OF SAMPLES, FOR EACH TRAIL.**

| **Sample** | **Dry** | **25/85** | **25/75** | **25/50** | **35/85** | **35/75** | **35/50** | **45/85** | **45/75** | **45/50** |
|---|---|---|---|---|---|---|---|---|---|---|
| F_1 | 0.54 | 0.95 | 0.69 | 0.55 | 0.81 | 0.58 | 0.8 | 0.8 | 0.71 | 0.61 |
| F_8 | 0.68 | 1.25 | 0.69 | 0.66 | 0.81 | 0.68 | 0.62 | 0.77 | 0.63 | 0.61 |
| F_9 | 0.61 | 1.01 | 0.73 | 0.62 | 0.89 | 0.66 | 0.66 | 0.81 | 0.66 | 0.55 |
| Bamboo | 0.59 | 0.98 | 0.96 | 0.58 | 0.95 | 0.89 | 0.69 | 0.96 | 1.0 | 0.73 |
| Rosewood | 0.47 | 0.55 | 0.53 | 0.34 | 0.55 | 0.64 | 0.42 | 0.56 | 0.52 | 0.39 |

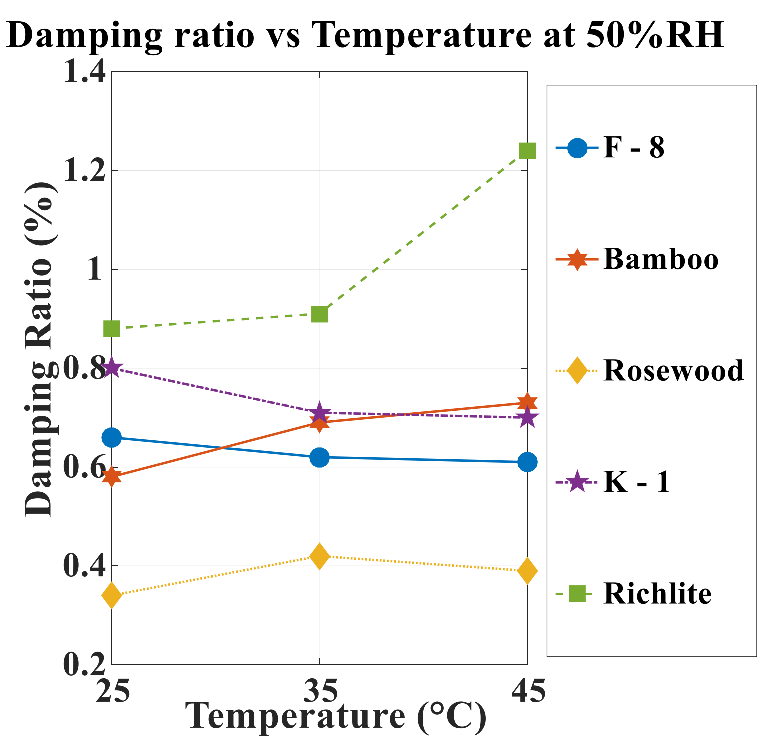
| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| K_1 | 0.6 | 0.86 | 0.89 | 0.8 | 1.27 | 0.91 | 0.71 | 1.25 | 0.99 | 0.7 |
| K_2 | 0.5 | 0.77 | 0.88 | 0.75 | 1.04 | 0.73 | 0.68 | 1.04 | 0.91 | 0.75 |
| W_1 | 0.54 | 0.81 | 0.86 | 0.49 | 1.07 | 0.78 | 0.75 | 1.07 | 0.85 | 0.7 |
| Richlite | 0.93 | 1.08 | 0.94 | 0.88 | 1.12 | 0.84 | 0.91 | 1.04 | 0.94 | 1.24 |

The damping ratio at Mode 1 for all the samples at each trail is shown in Table 24. It is seen that none of the samples could match the damping properties of that of the Rosewood. K_1 was very close to the value of Rosewood regarding natural frequency, but a similar result is not seen regarding damping. Looking at Table 24 we can also say that we do not see any trend in the variation. It should also be noted that damping measurements are a tough task as the damping is influenced by so many factors and this might have also influenced such behaviour. Regarding percentage change in damping ratios, K_1 and K_2 had a change of more than *100%*. Surprisingly, Rosewood did not show much of an increase in damping ratio compared to the amount of moisture it had absorbed. For samples F_1, F_8, F_9 and Bamboo, there was a maximum change of variation from *65.57% to 83.82%*. Richlite had the minimum in comparison to all the other samples, *33.33%* but again it can be seen that Richlite starts off with a high value of damping ratio.

For a closer look at the effect of temperature and humidity on the natural frequency and damping ratio, these two parameters are plotted against temperature keeping humidity constant and against humidity keeping the temperature constant. For this purpose, results of F_8, Bamboo, Rosewood K_1 and Richlite are used.



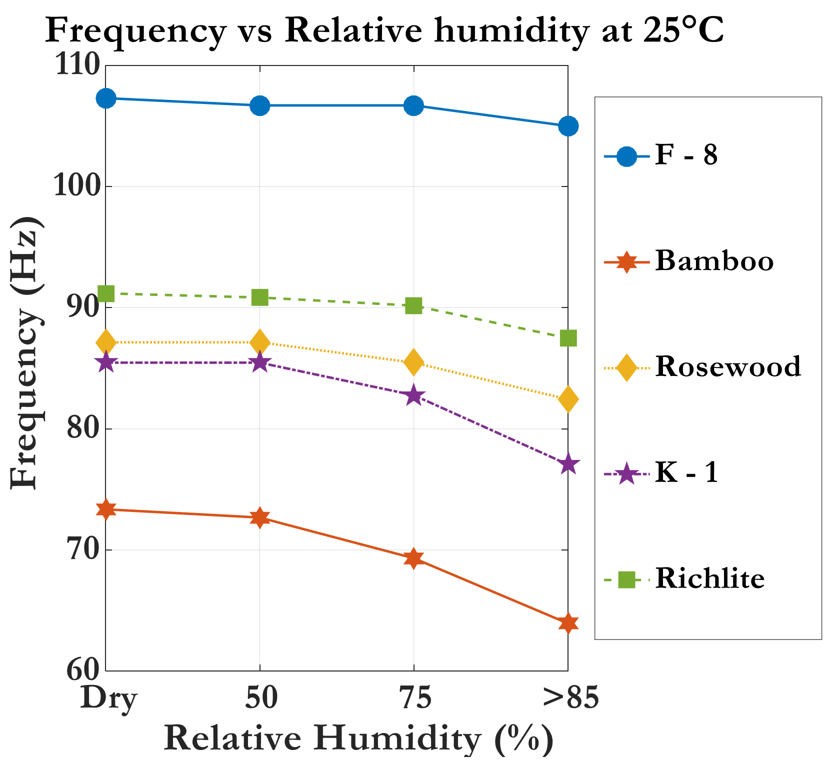

(a)



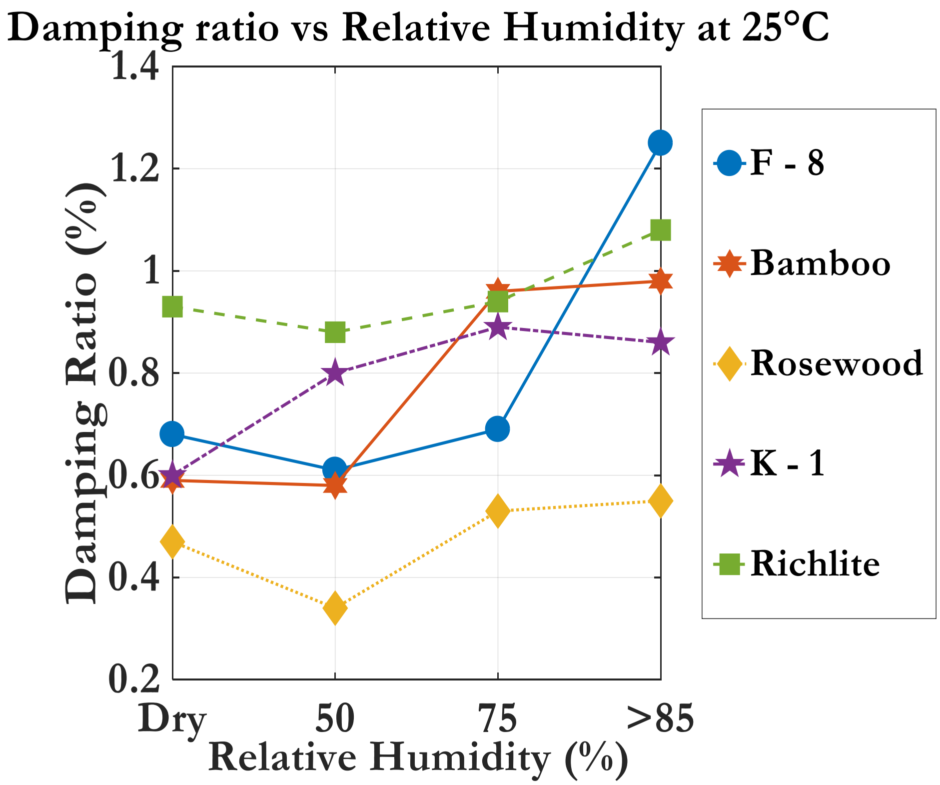

(b)

**Figure 20: (a) Variation in natural mode 1 vs. temperature, (b) Variation in damping ratio at mode 1 vs. temperature. For both cases, data at 50% RH was used.**

At a constant level of humidity, when the temperature is varied, we can see from the graph in Figure 20(a) that the natural frequencies are not significantly affected. In all the five samples that are shown, the variation is less than *1%*. However, the similar trend is not seen in the case of damping ratio. Damping ratio seems to increase for the case of Rosewood, Bamboo and Richlite while it decreased for the case of the flax composites. Among all the samples, Richlite showed the largest increase in damping ratio.




(a)




(b)

**FIGURE 21: (A) VARIATION IN NATURAL MODE 1 VS. RELATIVE HUMIDITY, (B) VARIATION IN DAMPING RATIO AT MODE 1 VS. HUMIDITY. FOR BOTH CASES, DATA AT 25°C WAS USED.**

Next, we look at the variation of natural frequency and damping ratio at varying humidity levels (Figures 21(a) and (b)). We can see that there is a significant change in natural frequency with an increase in humidity. This change can be accounted for the increase in the weight gain with an increase in moisture. Bamboo has the maximum change of *12.84%* followed by K_1 at *9.84%* change in natural frequency. F_8 has the minimum change of *2.14%*. Regarding damping ratio, we do not see a very clear trend, but overall the damping ratio has increased compared to what it was in the dry state. The F_8 damping ratio seems comparatively stable up to *75% RH*, but it jumped when the humidity went beyond *85% RH*. K_1 and Bamboo damping ratios increased and looked like they eventually stabilised.

Rosewood did not have much change in its damping ratio compared to rest of the samples despite the amount of moisture it had absorbed.

From the study, we can say that all the samples are more sensitive to humidity than to temperature. Rosewood, though it absorbed the larger amount of moisture, the damping ratio was not affected much. This behaviour is a point that needs to be addressed when designing alternatives using composite materials.

# CONCLUSIONS 7

Two different studies were conducted as part of the project. One was to understand the importance of the parameters that could affect the design of a wood replacement material. The second was to understand the effect of humidity and temperature on these replacement materials. *9* different samples were manufactured for these studies, and *15* samples were tested in total using a hammer and accelerometer setup to obtain their natural frequency and the frequency domain plots (used to calculate the damping ratios).

- Factors such as moduli, thickness and density were considered for the study, and some other factors were ignored due to the difficulty in designing laminates that satisfy all these predefined parameters. After the ANOVA calculations for Mode 1, it was found that flexural modulus, thickness, density and modulus $E_2$ are the critical parameters ranked as listed in descending order. Extending the ANOVA calculations to Mode 2 and Mode 3, it was found the percentage importance of thickness keeps increasing, and flexural modulus does not play much of a role at higher modes.
- In the ANOVA calculations, we also noticed that the error percentage increases as we move to higher modes. This increase indicates that other parameters that were not considered such as shear modulus and Poisson's ratio might have their influence on the natural modes.

- The ANOVA performed for the damping ratio found that modulus $E_1$ is the most important parameter that controls the damping. This result could be explained as damping is related to energy dissipation during vibration, stored in the system due to excitation load as strain energy. Since the strain energy is directly related to the modulus $E_1$ of the system, we can see a direct relation to the both these properties. We can also see similar work in the literature where damping calculations are made based on the modulus of the constituents of a laminate [34, 35].
- In the second study, it was found that the composite material from Richlite absorbed the least percentage of moisture in comparison to all the samples. Flax composite samples did not have a gain of more than *3%* by weight. Rosewood, though the material absorbed the maximum amount of moisture in comparison to all the samples tested, did not have an adverse effect at its natural frequency or damping ratio. The highest drop in its natural frequency was *10%* and damping ratio increased by *50%*. However, for other materials, such as Bamboo and Richlite, the change was much higher. Flax was found to be quite stable in comparison to Bamboo and Richlite, which shows that flax composites could be a better alternative.
- Regarding natural frequency, all the samples were found to be more sensitive to humidity than temperature, as the change was less than *1%* for all the samples with increasing temperature. Regarding damping ratio, it was found that samples behave differently than what was expected. The initial hypothesis was to see a continuous increase in the damping ratio, but it was concluded that they tend to have a zig-zag pattern, where they sometimes increase or decrease. Samples had more than *100%*

increase in their damping ratio under certain conditions. Also, the damping was found to be higher for all sample in comparison to Rosewood. Thus, the laminates are required to be better designed for damping.

From the variety of fretboard alternatives that were manufactured to understand the importance of various properties, we can derive some guidelines on how to choose materials and design laminates.

- It is important to make sure we achieve the same thickness as in case of traditional wooden fretboards as it is found that thickness plays a major role in determining the natural modes of the component.
- It would be fruitful to choose a fiber resin system where the resin elastic modulus is as low as possible to achieve the desired moduli ratio.
- In terms of fiber orientation, from the samples tested it is seen that variation of fiber orientation within ±20º results in lower damping ratios.
- Since flax also absorbs moisture, it seems to be more relevant to use unidirectional fiber plies than woven as the woven fabric end up absorbing more moisture.
- For the core, it is found that having the core away from the neutral axis of the laminate results in better damping ratios, meaning we can achieve much closer damping properties but it must also be noted that having the core too close to the surface might be disadvantageous when it comes to machining of the fretboard.

# Future Work

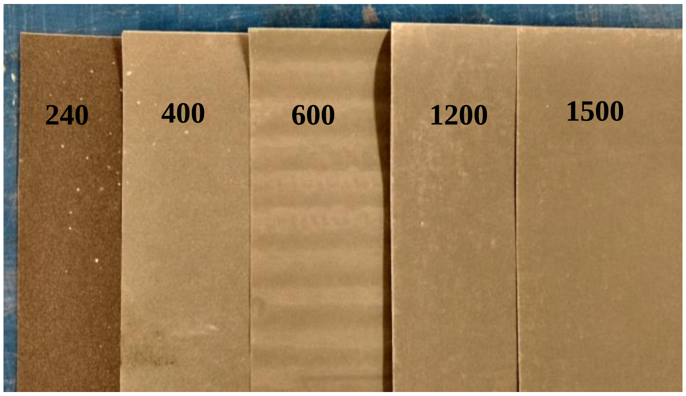
Given the nature of the project, we can openly say that it has a broad scope and lot more can be done to understand the possibilities of using natural fibres in the music industry and to improve the design.

- The focus of the project was only on natural fibre composites to keep the instrument completely natural. Since it is found that the damping is higher than that of the Rosewood sample, it would be interesting to see if this can be improved with a layer or layers of carbon fibre or glass fibre in the flax laminate.
- It was found in the literature that it is important to have a high $E_1/E_2$ ratio to have high anisotropy, but with the resin and fibre system, the maximum ratio we can design (accounting the values that are required to be achieved for other parameters) is about *10*. To improve this, we can look at different resin system, and if hybrid laminates become the choice, it is better to take dry fibres and use one resin system rather than to mix different prepreg materials.
- Given that the fretboard undergoes much machining and it is subjected to a lot of wear and tear, it would be good to perform wear resistance tests on the better designed laminates.

# APPENDICES

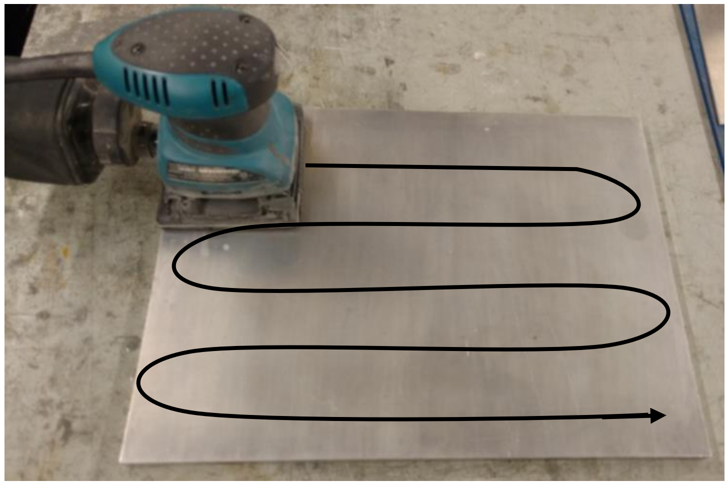
## Appendix A - Mould Polishing

Aluminium moulds were used as mould plates, and caul plates were used as top moulds. Both the moulds require a very smooth surface finish so that a similar surface can be achieved on the finished composite laminate. For achieving this, the moulds were polished with sandpaper at five different grit levels (240, 400, 600, 1200, 1500). At the 400-grit level, we should polish the mould until all the scratch marks are removed.



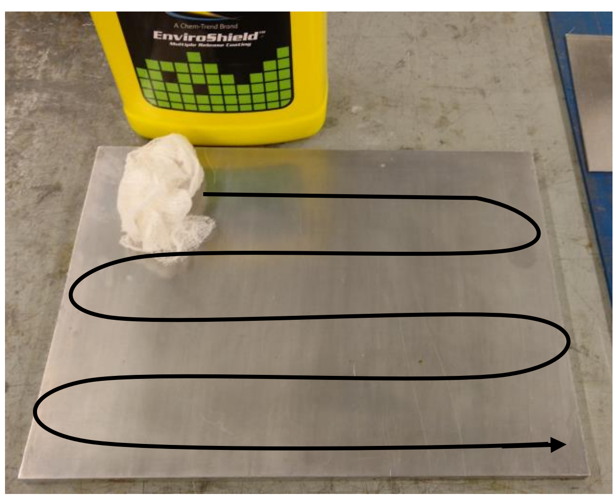

**DIFFERENT GRITS THAT WERE USED TO POLISH.**

The polishing should be carried out in one direction as shown in the figure below and care must be taken to prevent uneven material loss over the mould surface. Otherwise, this would result in trough regions that would affect the final part quality and might lead to the rough surface of the part and hinder the resin flow. Water is used as the lubricant during the polishing process. Once the mould and the caul plate are polished to the last grit level, they are cleaned completely with water and later with alcohol to get all the fine particles out of the mould.



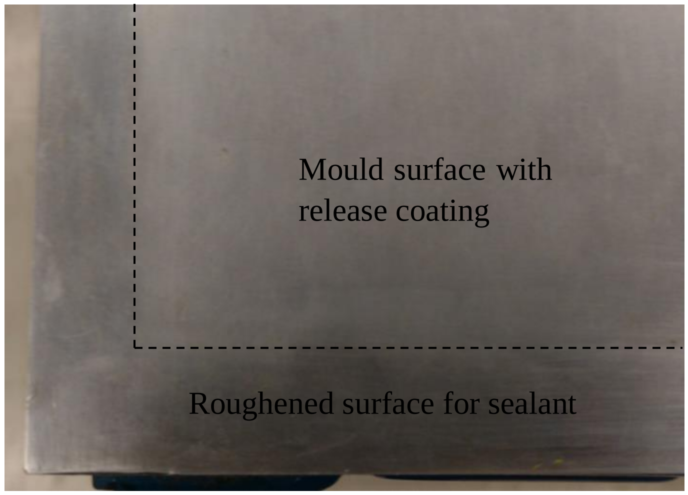
**MOULD AND THE POLISHER, THE ARROW INDICATES HOW THE POLISHER SHOULD BE MOVED OVER THE MOULD.**

As a final step, the mould is treated with Environment Shield release coating to prevent the resin from sticking. Five coats are done at an interval of *25 minutes* during which the coat dries. Again, the coating is done in a similar manner to polishing, were a cotton cloth is soaked with the agent and wiped on the surface as shown in the figure followed by using a dry cloth to remove the excess from the mould surface.




**DIFFERENT GRITS THAT WERE USED TO POLISH.**

A half inch of the release surface must be roughened out along the edges of the mould for the sealant tape to stick effectively without leaks as shown in the figure below. We can also use a tape to cover the region before applying the release agent and later un-tape the area.

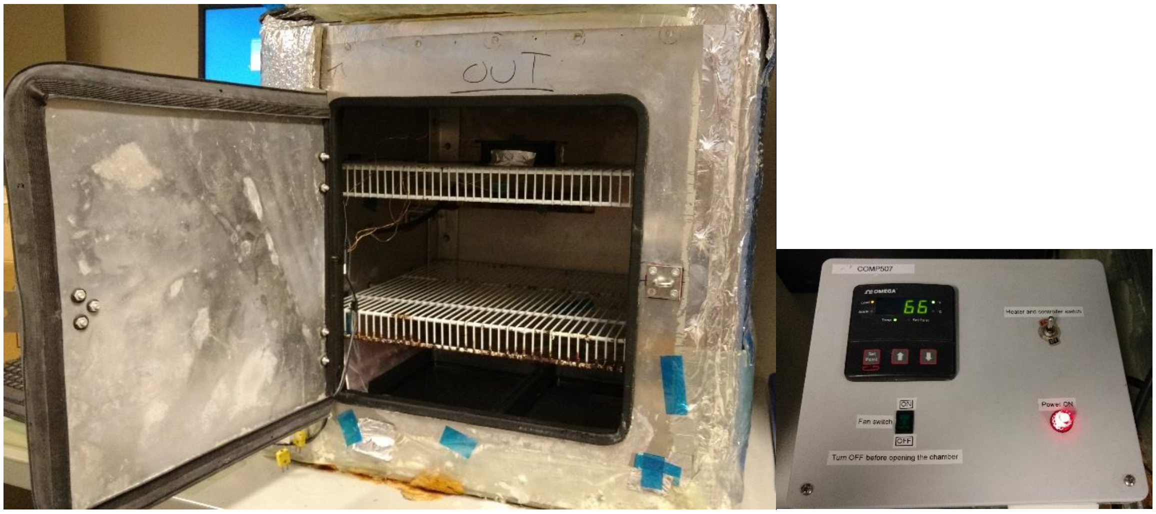



**DIFFERENT GRITS THAT WERE USED TO POLISH.**

# Appendix B - Layup design for samples manufactured

Before the manufacturing of the fretboards, the layups were designed using a MATLAB code that was developed as part of the work. The program accounts the properties of both the prepreg and the core. The program also varies the position of the core along the laminate thickness. Though it does not use any optimisation technique, it stores all the possible layup sequence with the effective laminate properties that are within specified limits in an excel spreadsheet. Depending on the number of ply angles considered, the run time varies due to the large possible combinations. As larger $E_1$ to $E_2$ ratio was required, the ply angles were varied only between $-45^o$ and $45^o$ and the ply angles were in multiples of $5^o$. So, this gave a huge list of ply angles to choose from. The results of the selected laminate were verified with the MLAM software that was developed by Prof. Larry Lessard before the laminates were manufactured.

# Appendix C – Humidifiers




**HUMIDIFYING CHAMBER AND CONTROLLER BUILD IN THE LAB.**

**HUMIDIFYING CHAMBER FROM CAML, MUSIC DEPARTMENT.**

# Appendix D – Data Logger Specifications [46]

| **Parameter** | **Units** |
|---|---|
| Range – Temperature | -30ºC to 80ºC |
| Resolution – Temperature | 0.01ºC |
| Accuracy - Temperature | ±0.3ºC |
| Range – Humidity | 0 to 100% RH |
| Resolution – Humidity | 0.01% RH |
| Accuracy – Humidity | ±3% RH over 2- to 80% RH range; ±5% RH below 20% RH or 80% RH. |
| Dimensions | 53mm x 33mm x 15mm |
| Weight | 25g |

# Appendix E – F tables

$f_1$ = Number of degrees of freedom of numerator
$f_2$ = Number of degrees of freedom of denominator

| $f_2$ \ $f_1$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 24 | 30 | 40 | 60 | 120 | ∞ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 39.864 | 49.500 | 53.593 | 55.833 | 57.241 | 58.204 | 58.906 | 59.439 | 59.858 | 60.195 | 60.705 | 61.220 | 61.740 | 62.002 | 62.265 | 62.529 | 62.794 | 63.061 | 63.328 |
| 2 | 8.5263 | 9.0000 | 9.1618 | 9.2434 | 9.2926 | 9.3255 | 9.3491 | 9.3668 | 9.3805 | 9.3916 | 9.4081 | 9.4247 | 9.4413 | 9.4496 | 9.4579 | 9.4663 | 9.4746 | 9.4829 | 9.4913 |
| 3 | 5.5383 | 5.4624 | 5.3908 | 5.3427 | 5.3092 | 5.2847 | 5.2662 | 5.2517 | 5.2400 | 5.2304 | 5.2156 | 5.2003 | 5.1845 | 5.1764 | 5.1681 | 5.1597 | 5.1512 | 5.1425 | 5.1337 |
| 4 | 4.5448 | 4.3246 | 4.1908 | 4.1073 | 4.0506 | 4.0098 | 3.9790 | 3.9549 | 3.9357 | 3.9199 | 3.8955 | 3.8689 | 3.8443 | 3.8310 | 3.8174 | 3.8036 | 3.7986 | 3.7753 | 3.7607 |
| 5 | 4.0604 | 3.7797 | 3.6195 | 3.5202 | 3.4530 | 3.4045 | 3.3679 | 3.3393 | 3.3163 | 3.2974 | 3.2682 | 3.2380 | 3.2067 | 3.1905 | 3.1741 | 3.1573 | 3.1402 | 3.1228 | 3.1050 |
| 6 | 3.7760 | 3.4633 | 3.2888 | 3.1808 | 3.1075 | 3.0546 | 3.0145 | 2.9830 | 2.9577 | 2.9369 | 2.9047 | 2.8712 | 2.8363 | 2.8183 | 2.8000 | 2.7812 | 2.7620 | 2.7423 | 2.7222 |
| 7 | 3.5894 | 3.2574 | 3.0741 | 2.9605 | 2.8833 | 2.8274 | 2:7849 | 2.7516 | 2.7247 | 2.7025 | 2.6681 | 2.6322 | 2.5947 | 2.5723 | 2.5555 | 2.5351 | 2.5142 | 2.4928 | 2.4708 |
| 8 | 3.4579 | 3.1131 | 2.9238 | 2.8064 | 2.7265 | 2.6683 | 2.6241 | 2.5893 | 2.5612 | 2.5380 | 2.5020 | 2.4642 | 2.4246 | 2.4041 | 2.3830 | 2.3614 | 2.3391 | 2.3162 | 2.2926 |
| 9 | 3.3603 | 3.0065 | 2.8129 | 2.6927 | 2.6106 | 2.5509 | 2.5053 | 2.4594 | 2.4403 | 2.4163 | 2.3789 | 2.3396 | 2.2983 | 2.2768 | 2.2547 | 2.2320 | 2.2085 | 2.1843 | 2.1592 |
| 10 | 3.2850 | 2.9245 | 2.7277 | 2.6053 | 2.5216 | 2.4606 | 2.4140 | 2.3772 | 2.3473 | 2.3226 | 2.2841 | 2.2435 | 2.2007 | 2.1784 | 2.1554 | 2.1317 | 2.1072 | 2.0818 | 2.0554 |
| 11 | 3.2252 | 2.8595 | 2.6602 | 2.5362 | 2.4512 | 2.3981 | 2.3416 | 2.3040 | 2.2735 | 2.2482 | 2.2087 | 2.1671 | 2.1230 | 2.1000 | 2.0762 | 2.0516 | 2.0261 | 1.9997 | 1.9721 |
| 12 | 3.1765 | 2.8068 | 2.6055 | 2.4801 | 2.3940 | 2.3310 | 2.2828 | 2.2446 | 2.2135 | 2.1878 | 2.1474 | 2.1049 | 2.0597 | 2.0360 | 2.0115 | 1.9861 | 1.9597 | 1.9323 | 1.9036 |
| 13 | 3.1362 | 2.7632 | 2.5603 | 2.4337 | 2.3467 | 2.2830 | 2.2341 | 2.1953 | 2.1638 | 2.1376 | 2.0966 | 2.0532 | 2.0070 | 1.9827 | 1.9576 | 1.9315 | 1.9043 | 1.8759 | 1.8462 |

**F TABLE FOR 90% CONFIDENCE [38].**

$f_1$ = Number of degrees of freedom of numerator
$f_2$ = Number of degrees of freedom of denominator

| $f_2$ \ $f_1$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 24 | 30 | 40 | 60 | 120 | ∞ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 161.45 | 199.50 | 215.71 | 224.58 | 230.16 | 233.99 | 236.77 | 238.88 | 240.54 | 241.88 | 243.91 | 245.95 | 248.01 | 249.05 | 250.09 | 251.14 | 252.20 | 253.25 | 254.32 |
| 2 | 18.513 | 19.000 | 19.614 | 19.247 | 19.296 | 19.330 | 19.353 | 19.371 | 19.385 | 19.396 | 19.413 | 19.429 | 19.446 | 19.454 | 19.462 | 19.471 | 19.479 | 19.487 | 19.496 |
| 3 | 10.128 | 9.5521 | 9.2766 | 9.1172 | 9.0135 | 8.9406 | 8.8868 | 8.8452 | 8.8123 | 8.7855 | 8.7446 | 8.7029 | 8.6602 | 8.6385 | 8.6166 | 8.5944 | 8.5720 | 8.5494 | 8.5265 |
| 4 | 7.7086 | 6.9443 | 6.5914 | 6.3883 | 6.2560 | 6.1631 | 6.0942 | 6.0410 | 5.9988 | 5.9644 | 5.9117 | 5.8578 | 5.8025 | 5.7744 | 5.7459 | 5.7170 | 5.6878 | 5.6581 | 5.6281 |
| 5 | 6.6079 | 5.7861 | 5.4095 | 5.1922 | 5.0503 | 4.9503 | 4.8759 | 4.8183 | 4.7725 | 4.7351 | 4.6777 | 4.6188 | 4.5581 | 4.5272 | 4.4957 | 4.4638 | 4.4314 | 4.3984 | 4.3650 |
| 6 | 5.9874 | 5.1433 | 4.7571 | 4.5337 | 4.3874 | 4.2830 | 4.2066 | 4.1468 | 4.0990 | 4.0600 | 3.9999 | 3.9381 | 3.8742 | 3.8415 | 3.8082 | 3.7743 | 3.7398 | 3.7047 | 3.6688 |
| 7 | 5.5914 | 4.7374 | 4.3468 | 4.1203 | 3.9715 | 3.8660 | 3.7870 | 3.7257 | 3.6767 | 3.6365 | 3.5747 | 3.5108 | 3.4445 | 3.4105 | 3.3758 | 3.3404 | 3.3043 | 3.2674 | 3.2298 |
| 8 | 5.3177 | 4.4590 | 4.0662 | 3.8378 | 3.6875 | 3.5806 | 3.5005 | 3.4381 | 3.3881 | 3.3472 | 3.2840 | 3.2184 | 3.1503 | 3.1152 | 3.0794 | 3.0428 | 3.0053 | 2.9669 | 2.9276 |
| 9 | 5.1174 | 4.2565 | 3.8626 | 3.6331 | 3.4817 | 3.3738 | 3.2927 | 3.2296 | 3.1789 | 3.1373 | 3.0729 | 3.0061 | 2.9365 | 2.9005 | 2.8637 | 2.8259 | 2.7872 | 2.7475 | 2.7067 |
| 10 | 4.9646 | 4.1028 | 3.7083 | 3.4780 | 3.3258 | 3.2172 | 3.1355 | 3.0717 | 3.0204 | 2.9782 | 2.9130 | 2.8450 | 2.7740 | 2.7372 | 2.6996 | 2.6609 | 2.6211 | 2.5801 | 2.5379 |
| 11 | 4.8443 | 3.9823 | 3.5874 | 3.3567 | 3.2039 | 3.0946 | 3.0123 | 2.9480 | 2.8962 | 2.8536 | 2.7876 | 2.7186 | 2.6464 | 2.6090 | 2.5705 | 2.5309 | 2.4901 | 2.4480 | 2.4045 |
| 12 | 4.7472 | 3.8853 | 3.4903 | 3.2592 | 3.1059 | 2.9961 | 2.9134 | 2.8486 | 2.7964 | 2.7534 | 2.6866 | 2.6169 | 2.5436 | 2.5055 | 2.4663 | 2.4259 | 2.3842 | 2.3410 | 2.2962 |
| 13 | 4.6672 | 3.8056 | 3.4105 | 3.1791 | 3.0254 | 2.9153 | 2.8321 | 2.7669 | 2.7144 | 2.6710 | 2.6037 | 2.5331 | 2.4589 | 2.4202 | 2.3803 | 2.3392 | 2.2966 | 2.2524 | 2.2064 |

**F TABLE FOR 95% CONFIDENCE [38].**

$f_1$ = Number of degrees of freedom of numerator
$f_2$ = Number of degrees of freedom of denominator

| $f_2$ \ $f_1$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 24 | 30 | 40 | 80 | 120 | ∞ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 16211 | 20000 | 21615 | 22500 | 23056 | 23437 | 23715 | 23925 | 24091 | 24224 | 24426 | 24630 | 24836 | 24940 | 25044 | 25148 | 25253 | 25359 | 25465 |
| 2 | 198.50 | 199.00 | 199.17 | 199.25 | 199.30 | 199.33 | 199.36 | 199.37 | 199.39 | 199.40 | 199.42 | 199.43 | 199.45 | 199.46 | 199.47 | 199.47 | 199.48 | 199.49 | 199.51 |
| 3 | 55.552 | 49.799 | 47.467 | 46.195 | 45.392 | 44.838 | 44.434 | 44.126 | 43.882 | 43.686 | 43.387 | 43.085 | 42.778 | 42.622 | 42.466 | 42.308 | 42.149 | 41.989 | 41.829 |
| 4 | 31.333 | 26.284 | 24.259 | 23.155 | 22.456 | 21.975 | 21.622 | 21.352 | 21.139 | 20.967 | 20.705 | 20.438 | 20.167 | 20.030 | 19.892 | 19.752 | 19.611 | 19.468 | 19.325 |
| 5 | 22.785 | 18.314 | 16.530 | 15.556 | 14.940 | 14.513 | 14.200 | 13.961 | 13.772 | 13.618 | 13.384 | 13.146 | 12.903 | 12.780 | 12.656 | 12.530 | 12.402 | 12.274 | 12.144 |
| 6 | 18.635 | 14.544 | 12.917 | 12.028 | 11.464 | 11.073 | 10.786 | 10.566 | 10.391 | 10.250 | 10.034 | 9.8140 | 9.5888 | 9.4741 | 9.3583 | 9.2408 | 9.1219 | 9.0015 | 8.8793 |
| 7 | 16.236 | 12.404 | 10.882 | 10.050 | 9.5221 | 9.1554 | 8.8854 | 8.6781 | 8.5138 | 8.3803 | 8.1764 | 7.9578 | 7.7540 | 7.6450 | 7.5345 | 7.4225 | 7.3088 | 7.1933 | 7.0760 |
| 8 | 14.688 | 11.042 | 9.5965 | 8.8061 | 8.3018 | 7.9520 | 7.6952 | 7.4960 | 7.3386 | 7.2107 | 7.0149 | 6.8143 | 6.6082 | 6.5029 | 6.3961 | 6.2875 | 6.1772 | 6.0649 | 5.9505 |
| 9 | 13.614 | 10.107 | 8.7171 | 7.9559 | 7.4711 | 7.1338 | 6.8849 | 6.6933 | 6.5411 | 6.4171 | 6.2274 | 6.0325 | 5.8318 | 5.7292 | 5.6248 | 5.5186 | 5.4104 | 5.3001 | 5.1875 |
| 10 | 12.826 | 9.4270 | 8.0807 | 7.3428 | 6.8723 | 6.5446 | 6.3025 | 6.1159 | 5.9676 | 5.8467 | 5.6613 | 5.4707 | 5.2740 | 5.1732 | 5.0705 | 5.9659 | 4.8592 | 4.7501 | 4.6385 |
| 11 | 12.226 | 8.9122 | 7.6004 | 6.8809 | 6.4217 | 6.1015 | 5.8648 | 5.6821 | 5.5368 | 5.4182 | 5.2363 | 5.0489 | 4.8552 | 4.7557 | 4.6543 | 4.5508 | 4.4450 | 4.3367 | 4.2256 |
| 12 | 11.754 | 8.5096 | 7.2258 | 6.5211 | 6.0711 | 5.7570 | 5.5245 | 5.3451 | 5.2021 | 5.0855 | 4.9063 | 4.7214 | 4.5299 | 4.4315 | 4.3309 | 4.2282 | 4.1229 | 4.0149 | 3.9039 |
| 13 | 11.374 | 8.1865 | 6.9257 | 6.2335 | 5.7910 | 5.4819 | 5.2529 | 5.0761 | 4.9351 | 4.8199 | 4.6429 | 4.4600 | 4.2703 | 4.1726 | 4.0727 | 3.9704 | 3.8655 | 3.7577 | 3.6465 |

**F TABLE FOR 99.5% CONFIDENCE [38].**

# Appendix F - Extended results of Study 2

**FREQUENCY AT NATURAL MODE 2 OF SAMPLES, FOR EACH TRAIL.**

| Sample | Dry | 25/85 | 25/75 | 25/50 | 35/85 | 35/75 | 35/50 | 45/85 | 45/75 | 45/50 |
|---|---|---|---|---|---|---|---|---|---|---|
| F_1 | 356.3 | 338.5 | 349.9 | 354.3 | 336.1 | 347.6 | 354 | 335.1 | 342.5 | 352.3 |
| F_8 | 292.4 | 285.7 | 290 | 290.4 | 283.6 | 288.3 | 290 | 281.3 | 285.3 | 288 |
| F_9 | 293.4 | 282 | 289 | 292.7 | 280.6 | 288 | 291.7 | 279.6 | 285 | 290 |
| Bamboo | 204.9 | 179 | 194.1 | 202.9 | 180.3 | 194.8 | 202.2 | 184.7 | 192.1 | 200.9 |
| Rosewood | 241.6 | 229.1 | 236.5 | 241.2 | 229.1 | 236.9 | 241.2 | 232.2 | 236.5 | 240.6 |
| K_1 | 234.8 | 212.6 | 227.1 | 234.2 | 213.6 | 225.4 | 234.8 | 217 | 223.4 | 231.5 |
| K_2 | 318 | 294.7 | 306.8 | 313.2 | 293.1 | 304.8 | 313.9 | 292.4 | 300.1 | 309.2 |
| W_1 | 266.5 | 245.6 | 256.4 | 261.4 | 245.3 | 255 | 262.1 | 245.9 | 252.3 | 259.1 |
| Richlite | 251.7 | 241.6 | 248.6 | 251 | 240.9 | 246.6 | 250 | 240.2 | 243.9 | 248 |

**DAMPING RATIO AT NATURAL MODE 2 OF SAMPLES, FOR EACH TRAIL.**

| Sample | Dry | 25/85 | 25/75 | 25/50 | 35/85 | 35/75 | 35/50 | 45/85 | 45/75 | 45/50 |
|---|---|---|---|---|---|---|---|---|---|---|
| F_1 | 0.64 | 0.88 | 0.75 | 0.60 | 0.87 | 0.66 | 0.64 | 0.85 | 0.71 | 0.61 |
| F_8 | 0.68 | 0.81 | 0.70 | 0.68 | 0.83 | 0.69 | 0.64 | 0.81 | 0.70 | 0.68 |
| F_9 | 0.64 | 0.86 | 1.26 | 0.72 | 1.57 | 0.66 | 0.73 | 0.95 | 0.84 | 0.61 |
| Bamboo | 0.46 | 0.82 | 0.78 | 0.62 | 1.08 | 0.84 | 0.72 | 1.25 | 0.86 | 0.64 |
| Rosewood | 0.37 | 0.56 | 0.39 | 0.39 | 0.77 | 0.27 | 0.37 | 0.48 | 0.41 | 0.35 |
| K_1 | 0.56 | 1.18 | 0.93 | 0.71 | 1.15 | 0.87 | 0.72 | 1.12 | 0.91 | 0.71 |
| K_2 | 0.76 | 1.25 | 0.80 | 0.71 | 1.09 | 0.80 | 0.67 | 1.12 | 0.86 | 0.70 |
| W_1 | 0.56 | 0.98 | 0.76 | 0.75 | 1.00 | 0.81 | 0.73 | 1.00 | 0.81 | 0.68 |
| Richlite | 0.85 | 1.06 | 0.95 | 0.90 | 1.04 | 0.89 | 0.85 | 1.03 | 0.90 | 0.87 |

**FREQUENCY AT NATURAL MODE 3 OF SAMPLES, FOR EACH TRAIL.**

| Sample | Dry | 25/85 | 25/75 | 25/50 | 35/85 | 35/75 | 35/50 | 45/85 | 45/75 | 45/50 |
|---|---|---|---|---|---|---|---|---|---|---|
| F_1 | 690.7 | 657.4 | 678.6 | 685.7 | 653.1 | 674.3 | 684.4 | 650.4 | 663.5 | 682.3 |
| F_8 | 560.5 | 546.7 | 557.2 | 557.2 | 544.4 | 554.5 | 556.5 | 539.7 | 547.8 | 553.8 |
| F_9 | 560.2 | 537.7 | 552.5 | 559.2 | 536 | 549.8 | 557.5 | 534.3 | 544 | 553.1 |
| Bamboo | 401.1 | 351.3 | 381.5 | 398.7 | 354.6 | 382.2 | 397 | 361.4 | 376.8 | 394.3 |
| Rosewood | 482.1 | 405.8 | 468.7 | 479.5 | 409.1 | 469.4 | 479.8 | 458.6 | 470 | 477.4 |
| K_1 | 456.9 | 415.5 | 442.1 | 454.6 | 416.5 | 438.7 | 456.9 | 422.9 | 435 | 450.5 |
| K_2 | 607.3 | 563.6 | 586.8 | 599.6 | 561.5 | 583.4 | 599.4 | 560.9 | 573.7 | 591.8 |
| W_1 | 522.9 | 484.5 | 505 | 513.8 | 483.8 | 502 | 514.4 | 483.5 | 496.3 | 508.7 |
| Richlite | 494.9 | 474.7 | 487.5 | 493.6 | 474.4 | 484.5 | 491.2 | 472.4 | 479.5 | 487.5 |

DAMPING RATIO AT NATURAL MODE 3 OF SAMPLES, FOR EACH TRAIL.

| Sample | Dry | 25/85 | 25/75 | 25/50 | 35/85 | 35/75 | 35/50 | 45/85 | 45/75 | 45/50 |
|---|---|---|---|---|---|---|---|---|---|---|
| F_1 | 0.68 | 1.05 | 0.85 | 0.77 | 0.98 | 0.82 | 0.66 | 0.88 | 0.79 | 0.69 |
| F_8 | 0.78 | 0.97 | 0.81 | 0.79 | 0.84 | 0.79 | 0.76 | 0.93 | 0.79 | 0.71 |
| F_9 | 1.00 | 1.02 | 0.75 | 0.68 | 0.90 | 0.74 | 0.69 | 0.85 | 0.74 | 0.64 |
| Bamboo | 0.57 | 0.9 | 0.90 | 0.70 | 1.27 | 1.22 | 0.63 | 0.97 | 0.97 | 0.67 |
| Rosewood | 0.48 | 0.85 | 0.46 | 0.38 | 0.81 | 0.48 | 0.37 | 0.50 | 0.52 | 0.36 |
| K_1 | 0.75 | 1.28 | 0.98 | 0.79 | 1.36 | 0.95 | 0.75 | 1.35 | 0.94 | 0.79 |
| K_2 | 0.87 | 1.12 | 0.96 | 0.80 | 1.16 | 0.91 | 0.83 | 1.11 | 0.91 | 0.84 |
| W_1 | 0.70 | 1.18 | 0.88 | 0.80 | 1.08 | 0.86 | 0.71 | 1.14 | 1.06 | 0.72 |
| Richlite | 0.88 | 1.20 | 1.27 | 0.89 | 1.23 | 0.94 | 0.92 | 1.04 | 1.09 | 0.89 |

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