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

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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 and a paper-phenolic resin based composite) keeping the Rosewood as the baseline.

1 INTRODUCTION

Musical instruments can be broadly classified into string instruments, woodwinds, brass and percussion [1]. Looking at the history of musical instruments, we notice 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 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. A typical acoustic guitar is shown in Figure 1. 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. Sound is produced due to the vibration of the air in the sound box. Many factors play a significant role in the final sound quality, the size of the hole, the material, 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.

Wood, due to its wide range of properties, abundance and ease of machinability, is being used in a multitude of applications. It is believed in the musical industry that ageing of these wooden musical instruments has a positive influence on the acoustic properties [2,3] and humidity and creep are considered to be the primary factors for this positive impact and experiments have been conducted to prove the hypothesis. Finally, the appearance of these wood plays a significant role. But 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.

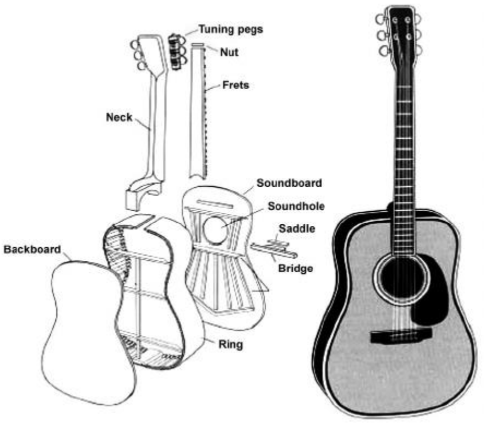

Figure 1: Acoustic Guitar

Probert [4] studied the use of carbon fibre composite as a replacement material for the sound box for an acoustic guitar by developing a simplified sound box model and compared it to Yamaha FG403S guitar. He could match the first ten natural frequencies with an error of 0.9% to 15.7%. Dominy et al. [5] tried to replace wood in a violin for improvement of the sound quality. Different core materials were also investigated such as polypropylene, polystyrene, balsa and even cardboard was experimented with [5-9]. They did not satisfy the damping properties of Sitka spruce that they were trying to mimic though they could meet the Haines et al. [10] criteria.

In using natural fibres, bast fibres (which include flax fibres) [11] are found to be recommended as a possible alternative. In the market, a hemp fibre composite guitar is manufactured and sold by Canadian Hemp Guitars. Phillips [12] developed a one-piece ukulele using flax fibre composite with balsa and foam as core materials. Similar studies were done by Marcadet et al. [13] 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. Study on alternate species of wood can also be found were the option of bamboo as a raw material was explored in many of musical instruments [13 – 17].

In this paper, we try to identify 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 per 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.

2 EXPERIMENTAL STUDY

Two different sets of experimental studies were performed. 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 parameter, natural frequency. The second study involved understanding the effect of humidity and temperature on the natural frequency and damping ratio.

2.1 Experimental Setup:

All the modal tests have been carried out as per ASTM standard, E1876-09 [18]. Free-free boundary conditions were used for testing the samples. A mini-hammer (PCB Piezotronics Model 086E80) and accelerometer (PCB Piezotronics Model 352A73) were used to excite and record the response of the samples. The information was conditioned (using PCB Piezotronics Model 482C) and collected using a National Instruments DAQ (Model USB 4431). Finally, the information was visualized using a MATLAB DAQ code that was developed for modal testing. Figure 2(a) shows the test setup that was used to carry out the tests.

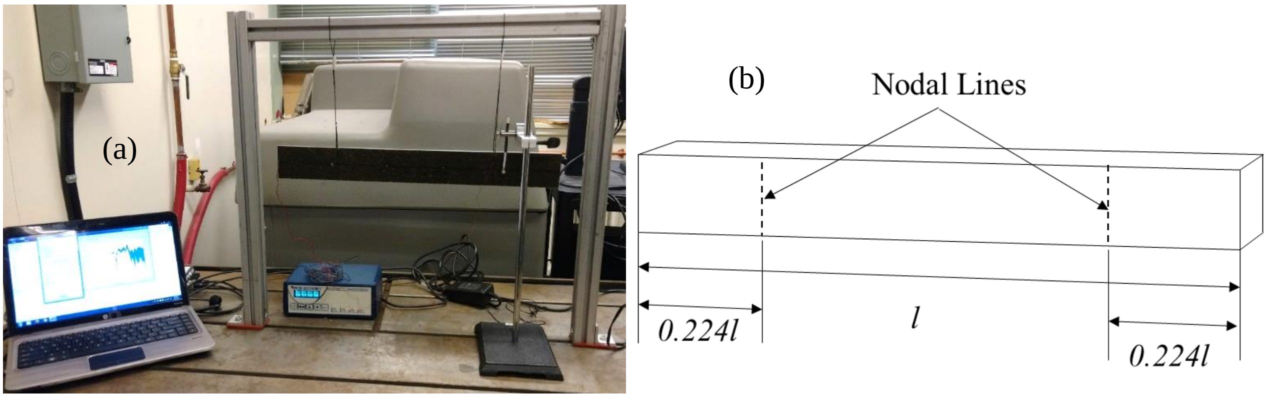

Figure 2: Test setup for the modal testing.

A lathe bed was used as the table to fix the support frame. Because a lathe bed is a solid block of metal, the amount of vibration that could be transmitted from the ground would be minimum thus isolating the test setup. Aluminium rods were used to make the frame which were fixed to the bed using T-head bolts. Silicon padding of 0.5cm was used between the frame and bed to absorb any vibrations from the devices that were placed on the lathe bed. Since the test was conducted in a small enclosed space, effects of air circulation were minimized. A custom-made hammer holder was made to lock the hammer movement after the first impact. As per ASTM standard, the sample must be hung at 0.224l (l being the total length of the sample) as shown in Figure 2(b), along the nodal line to prevent any distortion to the natural modes and additional damping to the system. Samples were hung as low as possible using nylon thread to facilitate free movement. The accelerometer was adhered to the sample using wax. The sample was excited at six equidistant points along the midplane.

The gain was set to 10 for both the sensors. The response was recorded after 2 secs from impact. A sample rate of 44100 samples/sec was used, and frequency bandwidth of 20 Hz to 22.05 kHz was recorded. The damping ratio was calculated using half-power bandwidth method.

2.2 Effect of 5 Parameters (E_1, E_2, E_f, thickness and density) on the Natural Frequency.

Table 1: 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

To perform the parametric study, Taguchi's Design of Experiment (DOE) was employed. 8 different trials had to be performed when we consider five parameters at two levels. The task of designing eight different laminates with a specified value of properties was difficult. Hence, an 8% allowance in the variation of the parameters was permitted to design the laminates reasonably. Tables 1 lists the values of the parameters that were considered.

2.3 Effect of Humidity and Temperature on the Acoustic Behaviour (Natural Frequency and Damping ratio)

Both Rosewood and flax fibre are susceptible to temperature and humidity thus it is vital to understand the implications for the acoustic response namely, natural frequency and damping ratio. 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. Three temperatures (25ºC, 35ºC and 45ºC) and three humidity levels (50% RH, 75% RH and >85% RH) were considered and, in total, 9 trials were conducted. Salt bath was used to attain the required humidity inside the conditioning chamber and a data logger (Omega OM-92) was used to record temperature and humidity. Before every conditioning run, the samples were dried for 6 hours (the duration was decided after a trial run) in the oven at 100ºC. The sample weights were measured before and after drying. Exactly after 24 hours of conditioning, modal testing was performed on the samples.

For the study, the samples were manufactured using FLAXPREG UD180 prepreg from Lineo and balsa as the core material, cured using an oven, at 140ºC for 2.5 hrs. The properties are tabulated in Table 2. Length and width were kept constant at 53.8cm x 6.45cm. 'B' in the table indicates use of balsa core of 0.8mm thickness. 3 more samples manufactured from flax fibre composite and balsa core, obtained from KU Leuven University, Belgium and by an intern in the lab were also tested. Here W_1 is the woven and UD combination and K_1 and K_2 are the samples from KU Leuven. The nomenclature employed in the table will be utilized in rest of the paper to refer to these samples.

Table 2: 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
W_1	18.79	3.5	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

3 RESULTS AND DISCUSSION

3.1 Effect of 5 parameters (E_1, E_2, E_f, thickness and density) on the Natural Frequency

The laminates that were tested for this study are F_1 to F_7 and K_2. Analysis of variance (ANOVA) was performed on the data collected from modal testing to understand the important parameters.

Table 3: 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

Table 3 shows the ANOVA parameters that were calculated for Mode 1. The error was calculated to be 7.82%. The error usually accounts for error in experiments performed or indicates that there might be other parameters which were not accounted for. 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. Surprisingly we find that for the first mode, modulus (E_1) in 1-direction has a negative influence. In ANOVA, when a parameter has very low or a negative impact it indicates that the parameter does not have any influence and it can be pooled to redistribute the percentage. Upon performing this step, the new ANOVA table is shown in Table 4.

Table 4: ANOVA results for natural Mode 1 after E_1 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

The error reduces from 7.82% to 5.88%. The percentage influence of the other parameters is increased by a small percentage. In ANOVA, the authenticity of the results can be calculated by using the standard variance ratio tables which are given for different degrees of freedom (DOF) at various confidence levels. Referring to this table the variance ratio that we have calculated gives a 95% confidence.

Table 5: 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 6: 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 5 and 6 show the ANOVA results for natural Mode 2 and Mode 3. The results are presented after the pooling of the insignificant terms are performed. The error for Mode 2 is calculated as 15.39% and 27.22% for Mode 3 and the confidence level drops to 90%. Another point to note is that we see an increasing trend in the error parameter, which could be result of excluding other parameters such as shear modulus. When we compare the results of all three modes, it is seen that importance of thickness continuously increases. Also, the influence of E_1 is seen more in the case of Mode 2 and Mode 3.

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

For this study, F_1, F_8, F_9, W_1, K_1, K_2, Rosewood, Bamboo fibre composite (Bamboo) and a paper-phenolic resin based composite from Richlite (Richlite) were used. The variation in natural Mode 1 for each trial is shown in the above Table 7. The N_1/N_2 terms in the table are to be read as; N_1 as temperature and N_2 as relative humidity.

Table 7: Natural Mode 1 frequency values for samples, for each trial.

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

Some of the samples do not show any change in Mode 1 at certain trial conditions, though there was change in their weight. For example, Rosewood did not have a change in its frequency 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. 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%. Like Rosewood, F_1, F_8, F_9 and Richlite have maximum variation ranging from 4.43% to 6.13%. 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 8: Damping ratio at natural Mode 1 of samples, for each trial.

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 trial is shown in Table 8. It is seen that none of the samples could match the damping properties of that of the Rosewood. We can also say that we do not see any trend in the variation. Percentage change in damping ratios for K_1 and K_2 was 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 from 65.57% to 83.82%. Richlite had the minimum in comparison to all the other samples.

To understand the effect of temperature and humidity separately, the results are plotted in graphs, plotting some of the samples tested. At a constant level of humidity, Figure 3(a) shows the effect of temperature variation on natural frequency, which is seen to be insignificant as the variation is less than 1% in all the samples. However, the similar trend is not seen in the case of damping ratio. From Figure 3(b), 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.

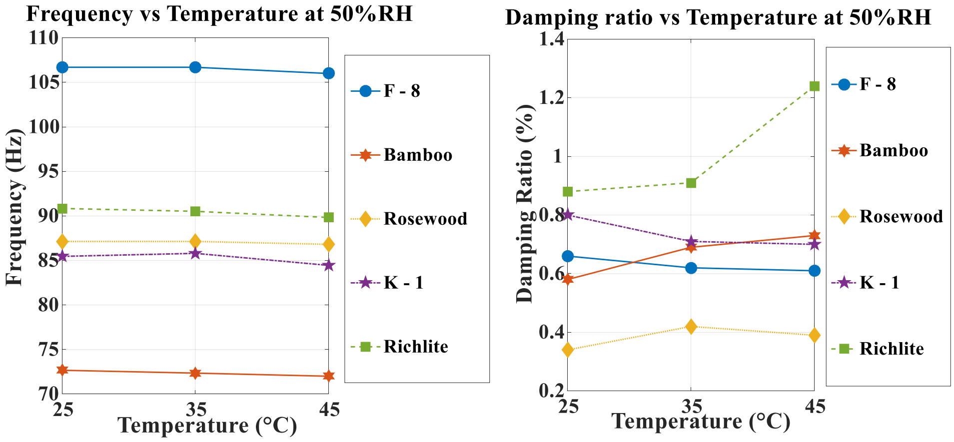

Figure 3: (a) Variation in natural mode 1 vs. Temperature, (b) Variation in damping ratio at mode 1 vs. Temperature. For both cases, data at 50% RH was used.

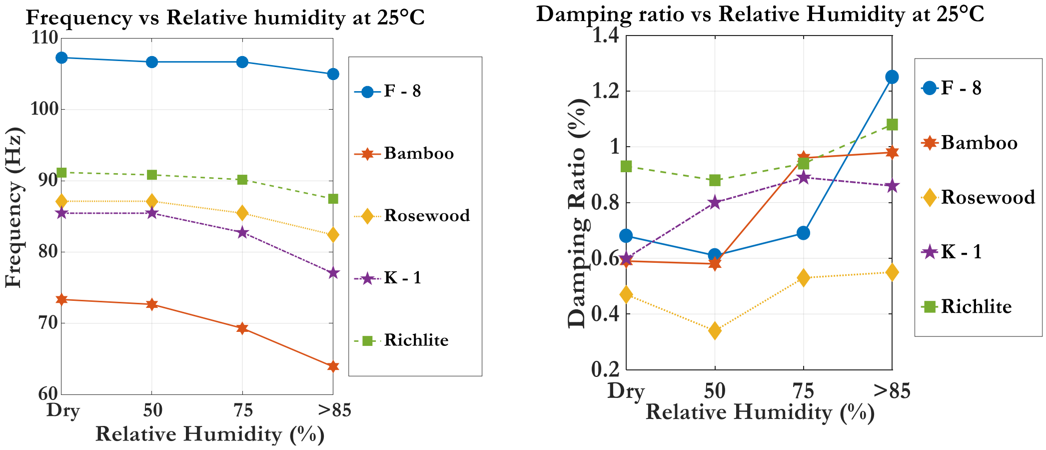

Figure 4: (a) Variation in natural mode 1 vs. Relative humidity, (b) Variation in damping ratio at mode 1 vs. Humidity. For both cases, data at 25°c was used.

Next, we look at the variation of natural frequency and damping ratio at varying humidity levels (Figures 4(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. In regard to damping ratios, we do not see a very clear trend, but overall the damping ratio has increased compared to what it was in the dry state. 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.

4 CONCLUSION

A systematic study was performed to identify the important properties for mimicking the acoustic behavior of Rosewood. It was found that for first natural frequency, flexural modulus, thickness, density and modulus E_2 are the critical parameters ranked as listed in descending order. The importance of thickness keeps increasing as we extend the calculations to higher modes. In the second study, it was found that all the samples were more sensitive to humidity than temperature. Rosewood, though absorbed the maximum amount of moisture compared to other samples did not have large variation in its properties. Flax composite samples did not have a gain of more than 3% by weight and it was found to be quite stable in comparison to Bamboo and Richlite, which shows that flax composites could be a better alternative. Damping ratio change did not have any noticeable pattern. Also, the damping was found to be higher for all sample in comparison to Rosewood.

For future work, it would be interesting to see if damping properties can be improved with a layer or layers of carbon fibre or glass fibre in the flax laminate. Further, to improve the E_1/E_2 ratio, we can look at different resin systems. Given that the fretboard undergoes machining and it is subjected to a lot of wear and tear, it would be good to perform wear resistance tests.

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