# FLAX FIBERS IN MUSICAL INSTRUMENT SOUNDBOARDS

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## SUMMARY

A flax fiber sandwich panel was developed for use as a musical instrument soundboard. The dynamic properties of the flax laminate were compared to those of the most widely used wood species. The dynamic Young's modulus, shear modulus and internal friction of both materials were used for comparison. A small prototype instrument was constructed using the studied flax laminate.

*Keywords: natural fibres; dynamic properties; acoustics; vibration*

## INTRODUCTION

Natural fibers have gained recent attention due to their renewability and other environmental benefits. The primary applications that have benefited from their development have been in the automotive industry. In this study, it was investigated whether a natural fiber composite could replace wood as soundboards in stringed musical instruments. The main reason for using composite materials for this application is for greater resistance to environmental effects. Soundboards based on carbon fiber reinforcement have already been successfully developed in other studies [1,2]. Natural fibers also seem like a good candidate since they have a very wood-like appearance and similar properties.

In order to evaluate the flax laminate, the dynamic properties were compared to those of wood. Freely supported beams were excited for specific modes using an impulse excitation device. The Young's and shear moduli were determined from flexural and the torsional modes respectively.

## BACKGROUND

Throughout history, certain species of wood have been known to possess good qualities for use as soundboards. The instrument's success has traditionally relied upon the skills of a luthier to select these species and choose sections that are free of defects. In recent times, researchers have determined what properties give these wood species their superior characteristics. It has been agreed upon that materials with a high specific modulus and low internal friction in the grain direction produce the best soundboards [3]. Ono et al further demonstrated that the stiffness in the cross-grain direction is also an important factor [3]. The shear modulus has been shown to govern the behavior in the high frequency range [1]. Thus all of these dynamic properties must be taken into consideration when developing a synthetic material to replace wood.

Other important factors are the density and strength of the material. It is critical not to exceed the areal density of a typical spruce soundboard in order to maintain the radiation efficiency of the instrument. A spruce soundboard of 2.5 mm thickness typically has an areal density ranging from 1.1 to 1.5 kg/m$^2$ [2]. These values were used as guidelines when developing a ply sequence for the flax sandwich panel. The material must also be strong enough to withstand the tension of the strings. Spruce has a bending strength of 80 – 130 MPa for 100 mm by 20 mm by 3 mm specimens [1].

## EXPERIMENTAL

The approach taken in this study was the same as previous studies. Sitka spruce was first characterized and then its dynamic properties were used as target values for the synthetic material [1, 2].

Modal testing has been used to characterize both the Sitka spruce and flax samples. ASTM 1287-01 [5] was followed to obtain the dynamic Young's modulus and shear modulus. This standard involved exciting freely supported beams at specific vibration modes using an impulse excitation. Young's modulus was determined from a flexural mode and the shear modulus from a torsional mode of vibration. The beams were supported at the node lines corresponding to the mode of interest.

### Materials

Flax fibers that were pre-impregnated with epoxy resin were used in this study. High quality Sitka spruce samples were also obtained for means of comparison. Balsa wood was used as a core material, with the flax fibers, due to its low density and low damping properties [6].

### Sample preparation

Fifteen samples were prepared for each material, including ten samples for the in-plane stiffnessess and five for the torsional stiffness. The ply sequence for the flax laminate was based on intuition and meant only as a first attempt. It comprised of two outer unidirectional layers and two inner woven layers all orientated in the 0 degrees direction. A 3/32 inch balsa core was used in the middle to increase the bending stiffness and give a final thickness similar to spruce soundboards.

The flax samples were manufactured on a heated press at 140°C for 30 minutes. Samples were then cut with the appropriate dimensions and orientations. The sample size was 2 cm x 8 cm to give appropriate length-to-thickness and width-to-thickness ratios to comply with beam theory assumptions. The thickness of the spruce samples varied between 3.2 mm and 3.3 mm. The flax samples varied between 2.7 mm and 3.1 mm in thickness. This larger variation in thickness was due impart to the variation of the balsa core thickness. Very small holes (0.042 inches) were drilled on the node lines to allow the specimens to be supported vertically. These small holes can be shown to have little effect on the dynamic properties [4].

## Experimental Setup

Both a non-contact excitation method and impulse excitation was used in order to minimize errors on the measured loss factors. The response of the beams was measured using a Polytec OFV-2000 Laser Doppler Vibrometer (LDV) and the excitation was generated using a steel ball hanging from a thread. The thread was 32 cm long and the ball was dropped from an angle of 15 degrees. This angle provided a good signal while still being close enough to consistently place the location of impact. The samples were supported in a steel frame suspended by fine fishing line. The steel frame assembly was placed on a damping isolation pad. The setup is shown in Figure 1.

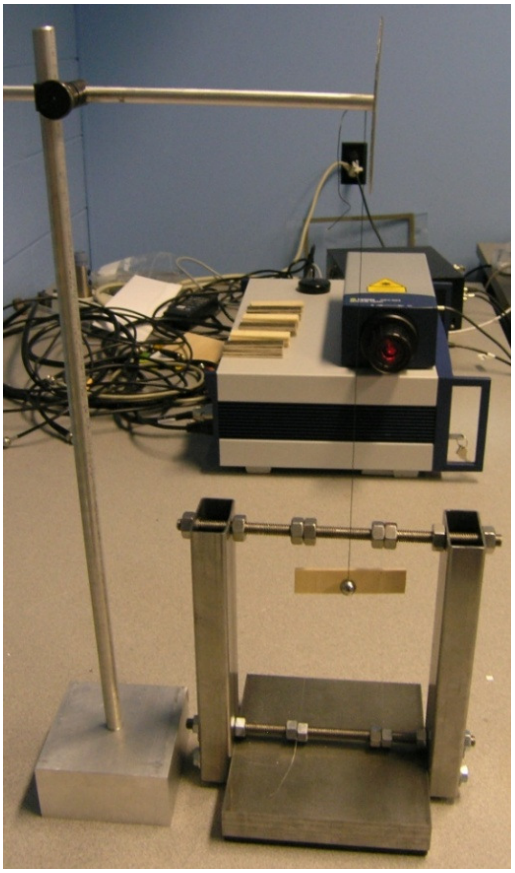

Figure 1: Modal testing setup

## Calculations

The dynamic young’s modulus was obtained from [5]:

$$E = 0.9465 \left(\frac{m {f_f}^2}{b}\right)\left(\frac{L^3}{t^3}\right)\mathrm{T} \qquad (1)$$

where m is the mass of the bar, $f_f$ is the resonant frequency in flexure, b is the width, L is length and T is a correction factor based on the thickness and width of the sample.

The shear modulus was calculated from [5]:

$$G = \frac{4Lmf_t}{bt}\left(\frac{B}{1+A}\right) \qquad (2)$$

where m is the mass of the bar, $f_t$ is the resonant frequency in torsion, t is the thickness, b is the width, L is length and A and B are correction factors.

The internal friction was obtained using the half-power bandwidth method, given by the following formula [6]:

$$\eta_r = \frac{{\omega_a}^2 - {\omega_b}^2}{2{\omega_r}^2} \qquad (3)$$

where $\omega_r$ is the resonant frequency and $\omega_a$ and $\omega_b$ are the frequencies at the two half power points of the mode in question.

## Results

Each specimen was tested until 5 resonant frequencies were obtained within 1% of eachother. An average of the five frequencies was then used to calculate the modulus. The following results were obtained.

Table 1: Results for x-direction samples

| | **$\rho$ (g/cm$^3$)** | **$f_x$ (Hz)** | **$E_x$ (GPa)** | **$Q_x^{-1}$x$10^{-3}$** | **$E_x/\rho$ (km/s)$^2$** | **$\gamma$ (kg/m$^2$)** | **VF$_f$ (%)** |
|---|---|---|---|---|---|---|---|
| **SX-1** | 0.440 | 2882.0 | 13.9 | 9.41 | 31.5 | - | - |
| **SX-2** | 0.421 | 2860.1 | 13.4 | 6.88 | 31.7 | - | - |
| **SX-3** | 0.445 | 2917.5 | 14.5 | 10.2 | 32.6 | - | - |
| **SX-4** | 0.442 | 2906.7 | 14.5 | 7.79 | 32.7 | - | - |
| **SX-5** | 0.424 | 2762.5 | 12.1 | 11.7 | 28.5 | - | - |
| **FX-1** | 0.642 | 2139.0 | 15.4 | 14.2 | 24.0 | 1.74 | 45.0 |
| **FX-2** | 0.624 | 2231.0 | 16.2 | 15.4 | 26.0 | 1.71 | 46.1 |
| **FX-3** | 0.674 | 2402.0 | 20.4 | 9.1 | 30.3 | 1.84 | 42.0 |
| **FX-4** | 0.612 | 2202.0 | 16.3 | 11.1 | 26.7 | 1.65 | 48.2 |
| **FX-5** | 0.703 | 2000.0 | 17.7 | 14.1 | 25.1 | 1.74 | 44.9 |

Note: Areal density, internal friction and fiber volume fraction represented by $Q_x^{-1}$, $\gamma$ and VF$_f$ respectively.

The specific modulus in the x-direction of the flax laminate was generally lower than Sitka spruce and the internal friction was higher. However, FX-3 had comparable specific modulus and internal friction. This seems to be due to its lower fiber volume fraction. This could be a result of better bonding between the fibers due to higher resin content. This suggests better control over the fiber volume fraction is necessary to reduce internal friction and increase specific modulus of the flax laminate.

The areal densities of the flax samples were generally above those of typical 2.5 mm thick spruce soundboards. Based on the material specifications, removal of one layer will give an areal density within the target range.

Table 2: Results for y-direction samples

| | **$\rho$ (g/cm$^3$)** | **$f_L$ (Hz)** | **$E_y$ (GPa)** | **$Q_y^{-1}$x$10^{-3}$** | **$E_{y/}\ \rho$ (km/s)$^2$** | **$\gamma$ (kg/m$^2$)** | **$VF_f$ (%)** |
|---|---|---|---|---|---|---|---|
| **SY-1** | 0.428 | 684.1 | 0.771 | 26.1 | 1.75 | - | - |
| **SY-2** | 0.429 | 689.3 | 0.778 | 21.4 | 1.85 | - | - |
| **SY-3** | 0.432 | 696.6 | 0.808 | 24.2 | 1.81 | - | - |
| **SY-4** | 0.431 | 703.0 | 0.801 | 25.0 | 1.81 | - | - |
| **SY-5** | 0.433 | 722.6 | 0.861 | 27.6 | 2.03 | - | - |
| **FY-1** | 0.595 | 1269.4 | 4.40 | 18.2 | 7.39 | 1.77 | 44.1 |
| **FY-2** | 0.581 | 1270.9 | 4.05 | 23.1 | 6.97 | 1.77 | 43.8 |
| **FY-3** | 0.590 | 1303.2 | 4.41 | 17.6 | 7.49 | 1.79 | 43.5 |
| **FY-4** | 0.600 | 1208.2 | 4.04 | 20.7 | 6.72 | 1.79 | 43.5 |
| **FY-5** | 0.597 | 1200.3 | 4.09 | 22.4 | 6.85 | 1.74 | 44.9 |

The modulus in the y-direction of the flax laminate is significantly higher than that of Sitka spruce as a result of the two woven layers. A laminate containing only one woven layer or only unidirectional layers would give closer properties to spruce in the y-direction. The internal friction is however comparable in the y-direction.

Table 3: Results for torsion samples

| | **$\rho$ (g/cm$^3$)** | **$f_T$ (Hz)** | **G (GPa)** | **$G_{/}\ \rho$ (km/s)$^2$** | **$\gamma$ (kg/m$^2$)** | **$VF_f$ (%)** |
|---|---|---|---|---|---|---|
| **ST-1** | 0.460 | 2581.3 | 0.836 | 1.82 | - | - |
| **ST-2** | 0.439 | 2695.6 | 0.829 | 1.89 | - | - |
| **ST-3** | 0.431 | 2632.3 | 0.856 | 1.98 | - | - |
| **ST-4** | 0.454 | 2563.2 | 0.775 | 1.71 | - | - |
| **ST-5** | 0.437 | 2629.5 | 0.764 | 1.75 | - | - |
| **FT-1** | 0.559 | 2485.7 | 0.762 | 1.19 | 1.73 | 45.2 |
| **FT-2** | 0.620 | 2524.1 | 0.79 | 1.27 | 1.87 | 41.0 |
| **FT-3** | 0.659 | 2342.4 | 0.673 | 0.998 | 1.84 | 41.9 |
| **FT-4** | 0.591 | 2335.3 | 0.674 | 1.1 | 1.70 | 46.5 |
| **FT-5** | 0.698 | 2372.7 | 0.672 | 0.955 | 1.84 | 41.8 |

It can be seen that the dynamic shear modulus is generally less for the flax laminate. This is due to the fact that most of the reinforcement is at the outer skins. The differences in shear modulus will likely lead to a variation in high frequency behavior [1]. To eliminate this effect, a more evenly distributed reinforcement should be used. This may be possible by using thin balsa layers in between the flax layers.

A summary of all the results for each material is shown in Table 3. Values are based on the average of all the specimens. The results for Sitka spruce were in good agreement with the values obtained in the literature [1].

Table 4: Summary of results

| | **$\rho$ ($g/cm^3$)** | **$E_x$ (GPa)** | **$E_{x/}\ \rho$ $(km/s)^2$** | **$Q_x^{-1}$ $x10^{-3}$** | **$E_y$ (GPa)** | **$E_{y/}\ \rho$ $(km/s)^2$** | **$Q_y^{-1}$ $x10^{-3}$** | **$E_x/E_y$** | **G (GPa)** |
|---|---|---|---|---|---|---|---|---|---|
| **Spruce** | 0.436 | 13.7 | 31.4 | 9.20 | 0.801 | 1.84 | 24.9 | 17.1 | 0.812 |
| **Flax** | 0.620 | 17.2 | 27.7 | 12.8 | 4.20 | 6.77 | 20.4 | 4.10 | 0.714 |

The most striking differences between the spruce and flax samples were the stiffness in the y-direction and the degree of anisotropy. This was due to the presence of woven layers in the flax samples. By eliminating some of the woven layers, this large variation can be reduced.

Overall, this ply sequence of the flax laminate can be improved to better mimic the dynamic properties of Sitka spruce. The results suggest that by modifying the ply sequence and fiber volume fraction a laminate with very similar dynamic and geometric properties can be produced. The changes necessary are to decrease the number of woven layers and also to obtain a fiber volume fraction of around 42%.

## DESIGN AND MANUFACTURING

The smallest instrument of the guitar family, a soprano ukulele, was constructed using the studied laminate. A small scale instrument was chosen to reduce tooling costs while still developing a suitable process for manufacturing an instrument of any size. The process uses a pressure bladder in the main air cavity and a foam core in the neck. The bladder applies 100 psi of pressure in the air cavity. The neck is sized to correspond to the same pressure when compressed in the mold. The use of a core in the neck was based on feedback from professional musicians who complain about the “feel” of hollow necks currently found in composite instruments on the market.

The various parts of the ukulele are shown in Figure 2 on the 3D computer model of the prototype.

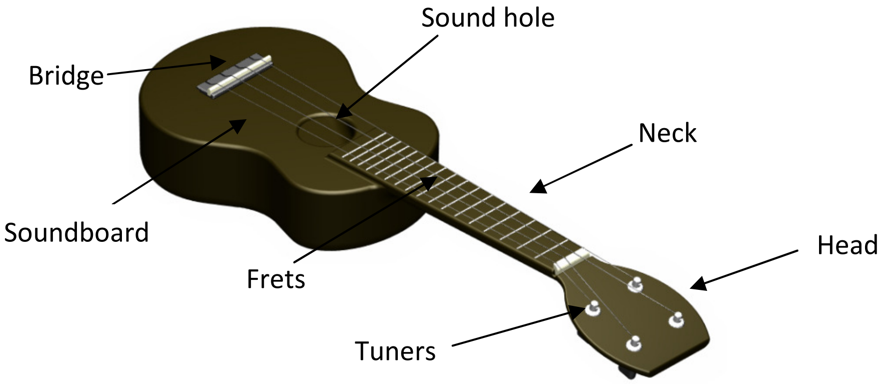

Figure 2: 3D model of prototype

## Mold design

Based on the 3D model, a two-piece mold was designed and manufactured using a CNC machine. The final mould is shown in figure 3. This mould produces a stringed instrument in entirely one piece. This is drastically different from how musical instruments have been traditionally made and more complex than how composite musical instruments are generally produced. The effect of this structural change on sound radiation will be the focus of a future study. The primary reason for choosing this mold design was to minimize post-machining which would be beneficial in a production setting. The bridge and fret locations were defined by small imprints on the mold surface to simplify installation.

Figure 3: CNC machined aluminum mold

## Manufacturing

The manufacturing process currently takes about ten hours to make a part from start to finish. Most of the time and effort was put into optimizing the process. The design of preforms was a large part of developing the manufacturing process. The final preforms imitate the grain orientations commonly found on stringed instruments. These shapes look similar to sections that a luthier cuts out to make a wooden instrument. The boundary around the soundboard was designed to contain fewer layers as to not inhibit the movement of the soundboard. The final performs are shown in Figure 4.

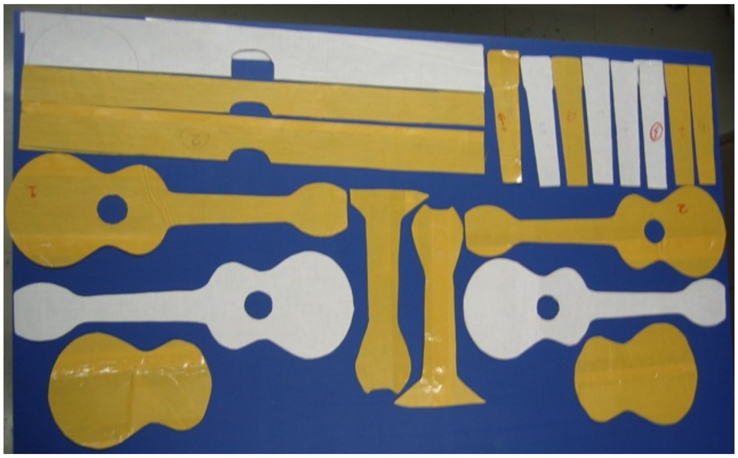

Figure 4: Preforms

## Post Machining

Post machining jigs were built to accurately locate the tuners and sound hole. The sound hole fixture consisted of a thin piece of steel machined to the outer contour of the soundboard with the sound hole cut into the correct location. This was then clamped to the instrument and a dremel tool was used to make the hole. The size of the sound hole was calculated based on the assumption of a Helmholtz resonator. The Helmholz resonance is given by:

$$f_0 = \left(\frac{c}{2\pi}\right)\sqrt{\frac{1.85r}{V}} \qquad (4)$$

where c is the speed of sound in air, r is the sound hole radius and V is the air cavity volume. The frequency of the air cavity should be “tuned” just below the lowest note on the instrument. This corresponds to 261.63 Hz for the soprano ukulele. For the volume of the air cavity given in the 3D computer model, the radius should be about 0.95 in.

The tuner jig was based on a common design used by machinists to drill holes quickly and accurately. A concave shape of the head was machined into a steel block and then drill bushings were fit into the correct locations. The block then fits into place on the head the drill bit is easily guided into the correct locations. The instrument before post-machining is shown in Figure 5.

Figure 5: Ukulele before post-machining

## CONCLUSION

Flax fiber composites have potential to act as suitable stringed instrument soundboards. The specific modulus and internal friction of the laminates show a strong dependency on fiber volume fraction and ply sequence. This suggests that a suitable laminate can be produced by altering these parameters. Modal testing was a good non-destructive method for obtaining the elastic constants and damping of the materials.

## ACKNOWLEDGEMENTS

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