

BIO-COMPOSITE MATERIAL APPLICATIONS TO MUSICAL INSTRUMENTS

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ABSTRACT

Bio-composite materials suitable for replacing wood for use in musical instruments were developed. The mechanical properties of Sitka spruce, the most widely used wood species for this application, were taken as a benchmark when developing the new materials. The materials were characterized by static and dynamic methods to determine the dynamic Young's modulus, shear modulus, internal friction and static mechanical properties. Based on the material characterization, a hand layup process with a two-part closed mould and internal pressure bladder was developed and a total of six prototype ukuleles were manufactured. The results show that the bio-composite material can meet all the necessary criteria for a soundboard material and that an efficient manufacturing process can be developed for producing composite musical instruments.

KEYWORDS: Natural fibres; dynamic mechanical properties; composite musical instruments; vibrations; acoustics

RÉSUMÉ

Des matériaux bio-composites dans le but de remplacer le bois pour les instruments de musique ont été développés. Les propriétés mécaniques de l'épinette de Sitka, une espèce de bois couramment utilisée pour cette application, ont été utilisées comme référence dans l'élaboration de nouveaux matériaux. Ces derniers ont été caractérisés par des tests mécaniques statiques et dynamiques afin de déterminer le module d'élasticité, le module de cisaillement, la friction interne et les propriétés mécaniques statiques. Les résultats de caractérisation ont permis de développer un procédé de fabrication avec un moule en deux parties et un sac pressurisé. Six prototypes de ukulélés ont été fabriqués. Les résultats montrent que le bio-composite peut répondre aux critères nécessaires pour un matériel de table d'harmonie et qu'un processus de fabrication efficace peut être développé pour produire des instruments de musique en matériaux composites.

MOTS CLÉS: Fibres naturelles; propriétés mécaniques dynamiques; instruments de musique en composites, vibrations, acoustique

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LIST OF SYMBOLS

<u>Symbol</u>	<u>Description</u>
E	Young's modulus
E_x	Longitudinal Young's modulus
E_y	Transverse Young's modulus
E_s	Longitudinal shear modulus
h	Thickness
ρ	Density
Q_x^{-1}	Longitudinal internal friction
Q_y^{-1}	Transverse internal friction
γ	Areal density
c	Speed of sound
V	Volume
a	Radius of sound hole
L	Length
T	String tension
μ	String mass per unit length
m	Mass
f_f	Resonant frequency in flexure
f_t	Resonant frequency in torsion
b	Width
A, B	Dynamic shear modulus correction factors
ω_r	Resonant angular frequency
ω_a, ω_b	Angular frequencies of half-power points

1. Introduction

In relatively recent times, the development of composite materials has led to superior performance for many applications. An often overlooked application that has benefited greatly from their development is musical instruments. The inherent orthotropic behavior of composite materials makes them a suitable replacement for wood that is traditionally used in this application [1]. For this reason, composite guitar and violin soundboards were developed as early as 1975 [1]. Several composite musical instruments can now be found in the marketplace ranging from cellos to flutes and these instruments have been a more common sight in the hands of professional musicians. Yo-Yo Ma now chooses to play a carbon fibre cello at some of his live performances due to its greater stability (Figure 1-1). For this reason, he planned to play one at the inauguration of President Barack Obama, however, he did not out of concern he might distract viewers with its appearance [2]. This suggests that a composite material with a closer resemblance to wood may be desirable for professional musicians required to perform in formal settings.



Figure 1-1: Yo-Yo Ma playing a carbon fibre cello [3]

In recent studies, there are several reasons why composite materials have been used to replace wood in musical instruments:

- Better resistance to environmental effects - Musicians often have to make costly repairs due to wood cracking from humidity and temperature changes. Composite materials are very stable to environmental changes and are a better investment for long term use.
- Less variability - Selection of wood species and sections that are free of defects has traditionally relied upon the skills of a luthier. Composite materials offer the possibility of producing consistent musical instruments without the worry of wood defects that can be detrimental to the sound.
- Lower production time – Composite materials offer greater possibilities in design that allow the manufacturer to reduce production time and cost by reducing the number of parts an instrument is built from.
- Endangered wood species – Some wood species that were commonly used in musical instruments are now in limited supply. Most notably, Brazilian rosewood which was the most widely used species for the back and sides of stringed instruments, is now listed in the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES) database and its use is tightly controlled [4]. Composite materials offer the possibility of mimicking the behaviour of unique wood species such as Brazilian rosewood.

1.1 Introduction to bio-composites

Bio-composites are composite materials that are reinforced with natural fibres derived from plant, animal and mineral sources. For a material to be classified as a bio-composite, any type of matrix can be used including conventional petroleum derived polymers [5]. If a sustainable matrix is used in conjunction with natural

fibres, the final material is then classified as a “green” composite [6]. Since natural fibres are sustainable, bio-composites will likely be less costly than their carbon fibre counterparts in the near future.

Bio-composite materials have gained recent attention due to growing environmental concerns. They are currently primarily used as body paneling in the automotive industry [7] but some sporting goods and other applications have also been developed. A flax based bicycle and tennis racket that are currently available on the market are shown in Figure 1-2.

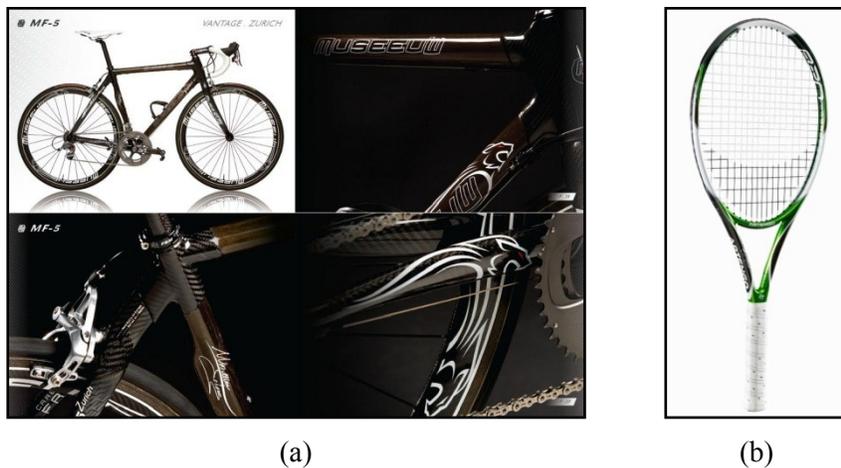


Figure 1-2: Flax based sporting goods (a) Museeuw MF-5 bicycle [8] (b) Artengo 820 tennis racket [9]

1.2 Overview of the guitar

Stringed musical instruments come in several forms and almost every country has one that is a unique part of its cultural history. In the western world, the guitar is one of the most commonly played and familiar sounding. The modern day guitar has its origins from the sixteenth century Spanish Vihuela [10]. Guitars along with most other stringed instruments operate in the same way. Sound is created by an acoustic structure that is excited by strings under tension. The structure or “body” of the instrument usually consists of two vibrating membranes connected by sides, an acoustic cavity and a neck where the performer places their fingers. These elements are coupled to the strings by means of a component called the

“bridge”. The strings do not produce much sound on their own, due to their small area, but they transmit energy to the rest of the structure that is coupled with the surrounding air. The primary parts of the guitar are shown in Figure 1-3.



Figure 1-3: Parts of the guitar [11]

Several stringed instruments are closely related to the guitar and are said to belong to the guitar family of musical instruments [12]. The soprano ukulele is the smallest instrument of this family and was selected as the prototype instrument for this study since its structure is almost identical to the guitar and its small size reduced tooling costs.

1.3 Motivation

The primary motivation of this research was to investigate if a high quality stringed musical instrument could be made from bio-composites. Due to the superior mechanical properties of carbon fibre, limited research has investigated the use of other reinforcement fibres for this application. The inherent wood-like characteristics of bio-composites make them seem like ideal candidates for replacing wood. They would possibly solve the aesthetic problem and have closer acoustic properties to wood since both are based on cellulose fibres. Another motivation of this research was to reduce the production time and craftsmanship that it currently takes to build a musical instrument by taking advantage of the inherent benefits of composite materials.

1.4 Objectives

The objectives of this research were selected to both assess the feasibility of using a bio-composite material as a soundboard and also to develop a manufacturing process to produce low-cost musical instruments. The objectives were as follows:

- 1) Perform static and dynamic mechanical characterization on a flax/epoxy bio-composite
- 2) Assess the feasibility of using bio-composites as the soundboard of a stringed musical instrument
- 3) Develop a manufacturing process to produce low-cost stringed musical instruments from composite materials
- 4) Compare a bio-composite stringed instrument to one of known high quality made out of wood

1.5 Thesis Organization

To achieve the above objectives, the thesis was divided into the following chapters. First, Chapter 2 is a literature review that describes previous research that has been done in developing alternative materials for the soundboards of stringed instruments. Chapter 2 also provides a brief overview of engineering

acoustics in the context of designing stringed musical instruments. Following the literature review, Chapter 3 is a description of the studied materials as well as the testing procedures that were used to characterize them. Chapter 4 and 5 discuss the design of the prototype stringed instrument and the corresponding tooling. Chapter 6 and 7 describe the manufacturing and post-machining processes respectively that were developed to build the prototype ukuleles. Finally, Chapter 8 discusses the evaluation of the final prototypes.

2. Literature Review

To successfully develop a soundboard from bio-composites, it was required to know which mechanical properties lead to a good soundboard and also which non-traditional materials have been investigated in the past. Furthermore, in order to build a prototype, it was required to gain a general knowledge of engineering acoustics in the context of designing stringed instruments. As a result, the main literature that was reviewed can be divided into three categories; soundboard criteria, use of non-traditional materials and musical acoustics.

2.1 Soundboard criteria

The mechanical properties that lead to a good soundboard have been known in the scientific community for over a half a century. The quality of stringed instruments has been shown to strongly depend on the frequency response [13]. This frequency response in turn depends on the mechanical properties of the material. Based on this assumption, criteria have been developed that govern the use of non-traditional materials based on their mechanical properties. The first work in this area was performed by John Schelleng [14]. He determined that for the flexural behavior of two homogeneous plates to be the same, their stiffness per unit length and density per unit area must be the same. This can be summarized by the following two relationships.

Equation 2-1: Schelleng stiffness criteria

$$E_1 h_1^3 = E_2 h_2^3$$

Equation 2-2: Schelleng areal density criteria

$$\rho_1 h_1 = \rho_2 h_2$$

where E_i is the Young's modulus, h_i is the thickness and ρ_i is the density. Subscripts 1 and 2 represent the two materials that have the same flexural behaviour.

The criteria proposed by Schelleng imply that even if the same stiffness cannot be achieved by a substitute material, the thickness can be altered so that the bending stiffness remains the same. However, if the areal density criterion is exceeded in doing so, the given material may not be a good substitute for wood. Schelleng also demonstrated why Sitka spruce (*picea sitchensis*), the wood traditionally used for violin and guitar soundboards, is superior for this purpose. Sitka spruce has a very low density, high specific modulus and low internal friction. For this reason, Sitka spruce is typically used as the benchmark when developing a substitute material. The mechanical properties of Sitka spruce, along with other woods commonly used in musical instruments are shown in Appendix A.

Haines *et al* later extended the work of Schelleng to account for the use of a non-homogeneous material. Their criteria were derived from the flexural equations of motion for a flat plate. The criteria were essentially the same as those proposed by Schelleng with two additional criteria; high degree of anisotropy and low internal friction. Low internal friction is desirable so that the sound from the musical instrument does not die too rapidly. The importance of the degree of anisotropy criteria was later demonstrated by Ono *et al* using the frequency response functions of various plates. It was shown that plates with a large variation of in-plane stiffnesses respond better to a wider range of frequencies [15]. By contrast, isotropic plates only respond well to a limited range of frequencies.

Hanies *et al* proposed the following quantitative values based on a typical 2.5 mm thick spruce soundboard [1].

1. Ratio of x-direction to y-direction bending stiffnesses of at least 12
2. Ratio of x-direction bending stiffness to areal density of at least 12×10^6 (m/s)²
3. Areal density between 1.1 and 1.4 kg/m²
4. Logarithmic decrements in both in-plane directions generally increasing with frequency

Haines *et al* determined that for a composite sandwich structure to satisfy these criteria, a sufficiently high stiffness fibre must be used with a very low density core material. If a core material is not used, the areal density limit would be surpassed before the required bending stiffness was reached.

Although most research has focused on the properties in the x-direction (*along-the-grain* or *fibre* direction), Ono *et al* investigated the importance of the y-direction (*across-the-grain* or *transverse* direction) and shear properties. They determined that the properties in the y-direction play an important role in the materials frequency response [15]. Wood used for soundboards has an average cellulose microfibril angle of 5 degrees which leads to some reinforcement in the y-direction [16]. Therefore to accurately mimic the frequency behaviour of wood, the properties in the y-direction must be taken into consideration. Ono *et al* also demonstrated that the behavior in the high frequency range is strongly dependent on the shear modulus of the material [16]. Laminates with only surface reinforcement inherently have a lower shear modulus and lead to a variation in high frequency behavior. The author's address the manufacturing difficulties in producing evenly distributed fibers without exceeding the low density of wood.

In general, researchers have agreed that materials with a low density, high specific modulus and low internal friction in the x-direction are best for soundboards. These three factors can be summarized the following criterion proposed by Ono *et al* [17].

Equation 2-3: Ono soundboard quality criteria

$$\eta = \frac{Q_x^{-1} \cdot \gamma}{E_x}$$

where Q_x^{-1} , E_x and γ are the internal friction, Young's modulus and areal density respectively.

2.2 Use of non-traditional materials

The work of Schelleng and others led to the development of several non-traditional soundboard materials. Advanced composite materials account for the majority of these new soundboard materials. As discussed above, composite materials are a good replacement for wood due to their inherent orthotropic properties and superior stability.

2.2.1 *Advanced composite materials*

The first composite soundboard was developed by Daniel Haines and Carleen Hutchins in conjunction with C.F Martin Inc in 1975 [1]. This soundboard was a sandwich panel using carbon fibre/epoxy as the outer skins and cardboard as the core. They also considered using polystyrene and polypropylene as the core, however, these materials failed to lead to the low damping of Sitka spruce. The final sandwich structure met all of the Haines *et al* criteria.

A later study performed by McIntyre and Woodhouse created a sandwich structure with comparable stiffness and lower damping than spruce [18]. This sandwich panel used balsa wood as the core material. Lower internal friction was obtained than the cardboard core sandwich panel in the Haines *et al* study. This suggests balsa wood may be a good core material in conjunction with fibres that have higher internal friction than carbon.

Significant work was also performed by Ono *et al* to develop a soundboard substitute based on polyurethane foam reinforced with unidirectional carbon fibres [16, 19, 20]. Several ply sequences were investigated based on the author's previous work on soundboard wood characterization. Their recognition of the importance of the shear modulus led them to develop substitutes that had fibres that were very well distributed [16]. Furthermore, their studies on the properties of wood in the y-direction led them to reinforce some experimental laminates in the y-direction [20]. They also experimented with sandwich panels reinforced

only at the outer skins. Of all the laminates that were tested, the surface reinforced sandwich panels performed best in listening tests [20].

At the same time of this study, researchers in the United Kingdom were attempting to develop a carbon fibre violin that exceeded the sound quality of a wooded one [21]. During the course of that study, it was determined that using a lightweight foam core in a sandwich structure led to the soundboard skins vibrating independently. The final carbon fibre prototype did not exceed the quality of a wooden violin but work was ongoing to improve the material.

2.2.2 *Other non-traditional materials*

Although carbon fibre based composite materials have dominated the non-traditional materials that have been investigated, some other interesting materials have been considered. A study conducted by Yano *et al* investigated the use of Japanese cedar to create a laminated material suitable for instrument back plates [22]. Back plates generally have lower specific mechanical properties and are primarily selected for their appearance [23]. Japanese cedar has poor mechanical properties and grows very quickly thus making it a better alternative to endangered wood species like Brazilian rosewood. The final laminated material had very similar dynamic properties to Brazilian rosewood.

Balsa wood was also recently used to create a violin soundboard based on the Schelleng scaling criteria by Waltham [24]. The prototype violin demonstrated a very similar frequency response to one built from Spruce thus validating the scaling criteria. There was however a mismatch in internal friction and the balsa violin had a higher volume output. For this reason the final instrument was deemed not to be acceptable for a professional musician.

An extensive study was also performed on the possible use of bamboo grass fibre in a variety of musical instruments [25]. Bamboo was found to be suitable for instruments where wood species with a high density and low internal friction are

typically used, however, it was found to be not acceptable for soundboards where a very low density is required.

2.3 Musical acoustics

In order to successfully design a stringed instrument a general knowledge of musical acoustics is necessary. Stringed instruments can be seen as coupled vibrating systems where all elements must be understood in order to produce a working instrument. In this study, focus will be specifically on the structure of the guitar and closely related instruments. When the strings of the guitar are plucked or struck, they transfer energy to the bridge and soundboard which in turn transfer energy to the sides, back plate and air cavity. At low frequencies, the soundboard transfers energy to the back plate through the sides and air cavity. At high frequencies the sound is radiated primarily by the soundboard and bridge [10].

2.3.1 Air cavity

The air cavity is critical for the low frequency response of a stringed instrument. It can be approximated as a neckless Helmholtz resonator with a large face. The resonant frequency is given by [10]:

Equation 2-4: Resonant frequency of neckless Helmholtz resonator

$$f_0 = \frac{c}{2\pi} \sqrt{\frac{1.85a}{V}}$$

where c is speed of sound, a is the radius of sound hole, V is the volume of air cavity and f is the resonant frequency.

The volume of the air cavity and radius of the sound hole are usually selected so that this frequency corresponds to one of the low open string notes. For the guitar it is typically around 98 Hz (G note) and for the soprano ukulele it is usually around 260 Hz (C note) [12], however, in practice it is always placed slightly

below these frequencies as to not affect the volume balance of the individual notes [12].

2.3.2 *Strings*

The strings are the primary interface between the performer and the musical instrument. Traditionally, strings were made from sheep's gut however modern strings are usually made from nylon or steel. The frequency at which a string vibrates is a function of its length, mass and tension. This frequency is given by:

Equation 2-5: Resonant frequency of vibrating string

$$f = \frac{1}{2L} \sqrt{\frac{T}{\mu}}$$

where T is the string tension, L is the length of the string, μ is the mass per unit length of the string and f is the resonant frequency.

While performing a musical piece, the frequency of a string is changed by altering its length. Metal inserts known as “frets” are positioned so that when the string is pushed against the fingerboard, it gains a new effective length and the desired frequency is produced. The spacing of the frets is based on the musical scale that the instrument is designed for and there are several types of musical scales all over the world. In western music, a scale known as the equal temperament scale has been historically used. The equal temperament scale divides an octave into 12 intervals where each note is $^{12}\sqrt{2}$ times higher in frequency than the previous note [26]. Two adjacent notes are said to be a “semitone” apart while two notes that are separated by one note are said to be a “tone” apart.

2.3.3 *Impedance matching*

Another important concept in designing a stringed instrument is impedance matching. For a wave to efficiently travel from one medium to another, the impedances of both materials must be similar [27]. In the context of a stringed

instrument, the ratio of the string and soundboard impedances is critical. The string impedance and soundboard impedance are given by the following equations [27]:

Equation 2-6: String impedance

$$Z = \sqrt{\mu T}$$

Equation 2-7: Soundboard impedance

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

where μ is the mass per unit length of the string, T is the string tension, E is the x-direction stiffness and ρ is the density.

Unfortunately, it is not so straight forward as to simply match the impedances of the strings and soundboard. If the impedances match perfectly, all of the energy will be transmitted too quickly and the sound will die out rapidly. On the other hand, if there is a large increase or decrease in impedance, the vibration will be completely reflected and little sound will be produced. As a result, a balance must be achieved so that enough of the energy is transmitted to the soundboard while enough is retained in the string so that it remains vibrating for a sufficient amount of time. This usually corresponds to a soundboard impedance of a few thousand times greater than the string impedance [27].

3. Material Characterization

The first step in this project was to select appropriate fibres, matrix and core materials in order to meet the requirements of a soundboard. After selecting appropriate materials, a full static and dynamic characterization was performed to compare the mechanical properties of the bio-composite with those of Sitka spruce.

3.1 Material selection

Wood is a remarkable material due to its low density and high specific modulus so it is no easy task to select another material to replace it. In general terms, wood can be seen as a natural composite material, with cellulose fibres surrounded by a lignin and hemicellulose matrix [28]. The low density of wood comes from its high porosity, typically around 60% for spruce [29]. It would initially seem possible to replace it with an equally porous bio-composite since these materials are also normally based on cellulose fibres. This approach was not feasible since the microstructure of wood is very complex and both microscopic and macroscopic properties contribute to its high mechanical properties [28]. Even though the layer angles in the cell wall of wood (Figure 3-1) are much the same as a composite material ply sequence, it would be very difficult to recreate this complex microstructure with existing manufacturing technology.

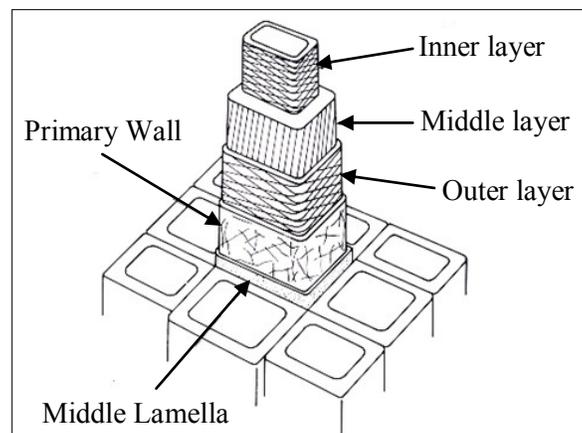


Figure 3-1: Cell wall microstructure of wood [30]

Since it was not feasible to recreate the microstructure of wood, the approach of developing a sandwich structure was taken. To meet the criteria necessary for a soundboard it was critical to select an appropriate fibre, matrix and core material. In the past, it would have been difficult to make an appropriate soundboard based on natural fibres but with the quality of these fibres increasing it is now more realistic. The following sections will discuss the fibres, matrix and core materials that were considered in this study.

3.1.1 Fibre

After surveying several types of natural fibres, it was found that a category known as bast fibres, which come from the stems of certain plants, had the highest specific mechanical properties and thus the most potential as reinforcement. The properties of bast fibres along with several other fibres are shown in Appendix B. Of the various bast fibre producing plants, Ramie (*Boehmeria nivea*) produced the stiffest and strongest fibres. For this reason, it seemed like an ideal candidate for this application, however, its production was limited due to the high cost of extracting its useful fibres as a result of its high gum content [31].

The bast fibre that was most readily available in useful form came from the flax plant (Figure 3-2). Of the flax materials currently available, three were considered in this study; unidirectional prepreg, woven prepreg and dry woven fibres (Figure 3-3). Flax fibres pre-impregnated with epoxy resin had the most potential based on the supplier's specifications, but due to their higher cost dry fibres were also considered. The prepreg material was produced by Lineo NV of France and was available in varying areal densities of fibres. The woven dry fibre was produced by C.R.S.T also of France and was only available in one areal density (500 g/m²).



Figure 3-2: Common flax (*Linum usitatissimum*) [32]

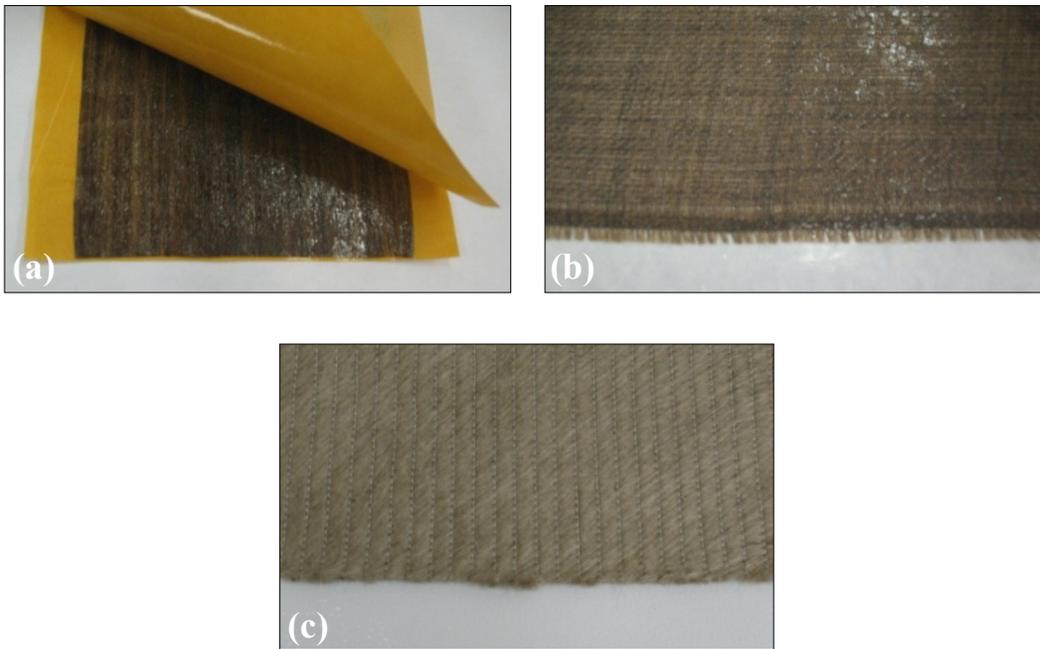


Figure 3-3: Flax materials used in this study (a) FUD-200 unidirectional prepreg
(b) FFA-200 woven prepreg (c) CRST-500 woven dry fibre

3.1.2 *Matrix*

Since the prepreg already had an epoxy resin system built in, a matrix only needed to be selected for dry fibre. It was initially desired to select a sustainable matrix to produce a composite that could be classified as “green”. Of the types of sustainable resins, poly-L-lactic-acid (PLLA) was the most widely available but had a low Young’s modulus of only 1.3 GPa [6]. Acrylated epoxidized soybean oil (AESO) was also considered but had a stiffness less than half of conventional epoxy [33]. Due to the difficulties in finding a sustainable matrix with adequate mechanical properties, a conventional resin system was finally selected.

Selection of an appropriate resin system also depended on the manufacturing process. In this study, a resin infusion process was used to make the dry fibre samples which required a resin system with a viscosity below 500cPs and a fairly long working time [34]. The vacuum-assisted-resin-transfer-moulding (VARTM) system was chosen because it was a low-cost production method. A resin system that was designed for this process was finally selected (Derakane Momentum 411-350).

3.1.3 *Core*

To reach the required bending stiffness without exceeding the areal density limit of the soundboard, it was necessary to select a very lightweight core material. The core material also influenced the damping of the final laminate, so this was another critical factor. A core with very low damping was desired to counteract the inherent damping effects of the flax material. Based on the work of McIntyre and Woodhouse, balsa wood was shown to lead to a laminate with excessively low damping in conjunction with carbon fibres [18]. For this reason, balsa wood was selected as the core material so that in combination with the flax fibres it might lead to an acceptable damping factor. Typically, balsa wood used for core material has the grain oriented normal to the fibre direction to aid with out-of-plane compressive strength, however, for this study it was more desirable to have the grain oriented in the fibre direction to give better mechanical properties for the

soundboard. Balsa strips typically used for model airplanes were selected for the core. There were some initial concern as to how well the balsa would bond to the flax prepreg but from initial samples it proved to bond very well.

3.2 Sample preparation

To investigate the effect of processing on the final material properties, samples were made from three methods; vacuum bagging, hot press and vacuum-assisted-resin-transfer-moulding (VARTM). A summary of the processing parameters is given in Table 3-1 where the cure cycles were selected based on the recommendations of the material specifications (Appendix C).

Table 3-1: Summary of sample processing methods

Process	Material	Pressure (atm)	Cure cycle
Vacuum Bag	- FUD200 - FFA200	1	30 min at 140°C
Hot Press	- FUD200 - FFA200	7	30 min at 140°C
VARTM	- C.R.S.T 500	1	24 hrs at ambient Post cure: 2 hrs at 120°C

3.2.1 Prepreg

The flax prepreg samples were manufactured on a hot press (Figure 3-4a) and also by vacuum bagging techniques. The amount of pressure applied on the hot press was selected based on the maximum air line pressure that was used to pressurize an internal pressure bladder during the manufacturing process of the prototype ukuleles (7 atm). For both the vacuum bag and hot press samples, the cure cycle was a 2°C/min heating ramp to 140 °C for 30 min with a cooling rate of 2.5°C/min. For this cure cycle, a glass transition temperature of between 135°C and 145°C was expected based on the flax prepreg specifications (Appendix C). The tool that was used to press the prepreg samples consisted of two nested

aluminum plates (Figure 3-4b). This mould was not sealed so resin was able to bleed off during processing. For the vacuum bagging, a perforated release film followed by a bleeder cloth was used on top of the flax prepreg.

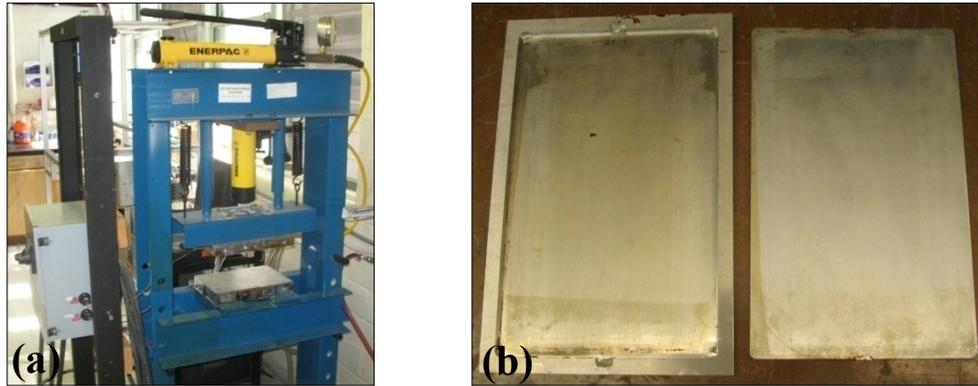


Figure 3-4: Hot press setup for manufacturing testing coupons (a) hot press setup (b) tool plates for making coupons

3.2.2 *Dry fabric*

The dry woven flax fibre samples were prepared using a vacuum-assisted resin-transfer-moulding (VARTM) setup (Figure 3-5). Derakane Momentum 411-350, an epoxy vinyl ester resin suitable for VARTM, was selected as the matrix. The resin was infused through the dry fibre using a vacuum pot at the outlet. The infusion finished well before the resin gelled which implied that the viscosity of the resin was low enough and that the permeability of the dry flax fibre was sufficiently high.

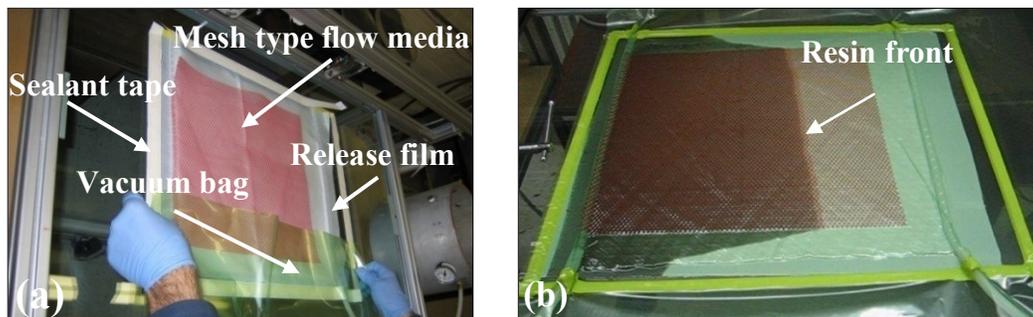


Figure 3-5: Vacuum-assisted-resin-transfer-moulding setup (a) initial preparation (b) during infusion process

3.2.3 Specimen cutting

Cutting the bio-composite samples presented a couple problems that were generally not encountered when cutting conventional composite materials. In the end, the VARTM samples were cut by water cooled tile saw and the cured prepreg samples were cut with a Fein multi-master tool (FMM 250Q). Initially, the prepreg samples were also cut by the water cooled saw but water damage was immediately apparent. This was likely due to a high presence of voids and high fibre volume fraction as will be further discussed in Section 3.5. Bio-composites that have a high void content are more susceptible to water damage and higher fibre volume fractions make this issue even more problematic [5]. Water absorption could be a negative aspect during operation of the part so attention should be paid to minimize the void content if a bio-composite material is going to be directly exposed to water. Musical instruments are not directly exposed to water but they are commonly played in humid environments.

The dimensions for the static testing specimens were selected based on the work of Shokrieh [35] and are given in Table 3-2.

Table 3-2: Static testing specimen dimensions

Test type	Thickness (mm)	Width (mm)	Length (mm)
Fibre direction tension	2	15.0	25.0
Transverse direction tension	2	25.0	15.0
Woven tension	2	25.0	25.0
Shear	3.0	13.7	15.2
Compression	3.4	25.0	14.0

For the dynamic test specimens, the dimensions were selected to comply with beam theory assumptions as well as to place the resonant frequencies in an acceptable range (3.00 mm x 20.0 mm x 80.0 mm). To support the specimens

during testing, very small holes were drilled on the node lines of the vibration mode of interest (Figure 3-6). These holes can be shown to have little effect on the measured dynamic properties [18]. For the flexural mode, the holes were drilled at 22.4% of the length from both ends. For the torsional mode, they were drilled at half of the length and also half of the width.

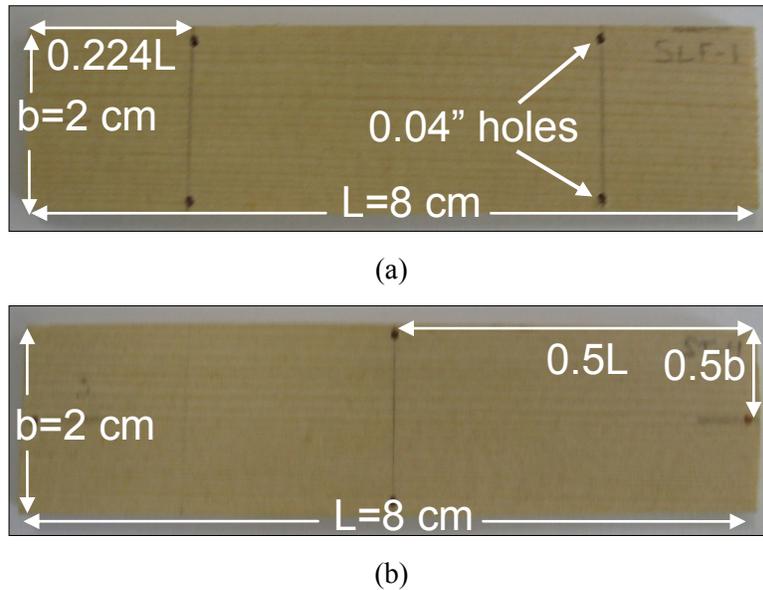


Figure 3-6: Dynamic testing specimen geometry (a) flexural mode (b) torsional mode

3.3 Static testing

To obtain all the required material properties for the finite element model and to make an initial evaluation of the bio-composite material, it was necessary to perform a full static mechanical characterization. This involved three types of testing; tensile, compression and shear.

3.3.1 Tensile testing

Tensile testing was performed on all samples in accordance with ASTM D3039 [36]. The testing was performed on a 100kN MTS® testing machine (Figure 3-7). A loading rate of 5 mm/min was used for the fibre direction and 1 mm/min for the matrix direction. A total of five specimens were tested for each test case and an average of all the results was used to obtain the final material properties.

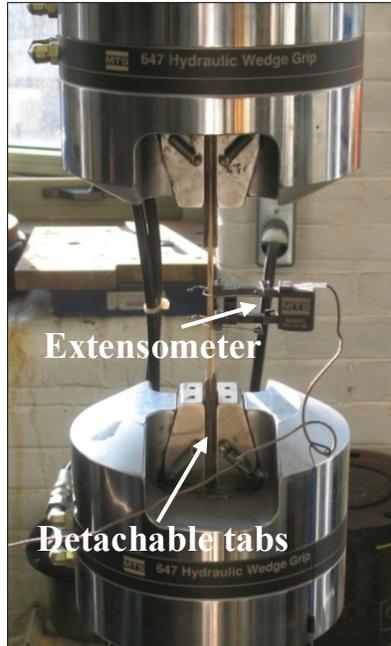
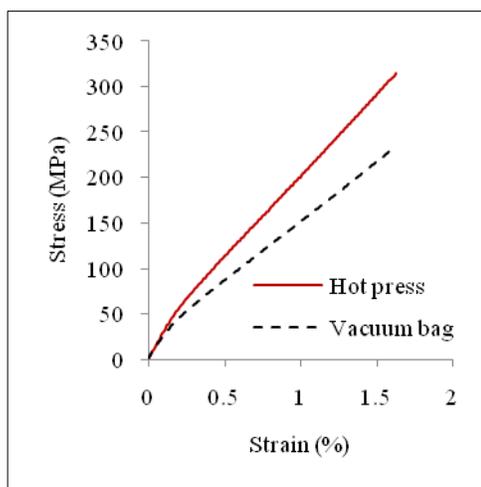
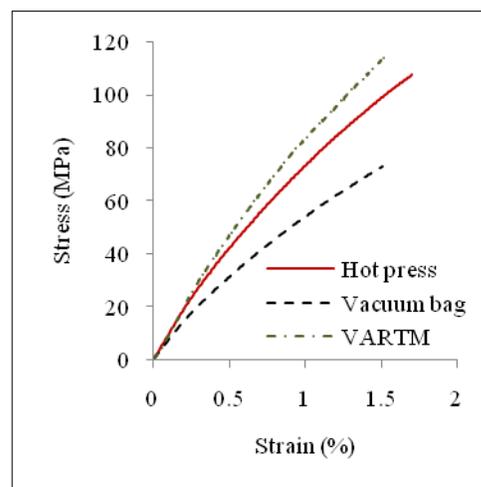


Figure 3-7: Tensile testing setup

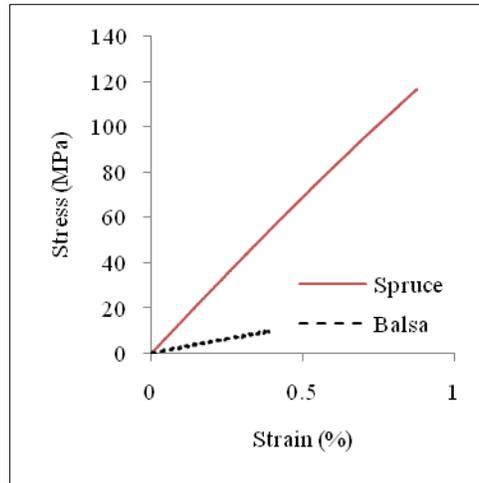
Detachable steel tabs were used in place of the bonded tabs that were recommended in the ASTM standard. This was deemed acceptable because of the relatively low mechanical properties of the flax based material. This tab configuration resulted in consistent failure in the gauge section so bonded tabs proved not to be necessary. Averages of the resulting stress-strain curves for the tensile testing are shown in Figure 3-8.



(a)



(b)



(c)

Figure 3-8: Average stress-strain curves from tensile testing (a) unidirectional (b) woven (c) wood

The resulting curves were bilinear for the unidirectional prepreg and non-linear for the woven materials. The bilinear behavior was likely due to micro-cracking of the matrix [36] and the non-linear behavior was likely due to the non-linear elastic behavior of the sheared matrix [37]. For each case, the initial slope was used to determine the stiffness. For both of the wood samples, the behavior was linear with failure occurring in a brittle manner similar to the flax prepreps. A summary of the tensile properties for all the materials is given in Table 3-3.

Table 3-3: Mechanical properties obtained from tensile testing

	Process	E_x (GPa)	E_y (GPa)	X_T (MPa)	Y_T (MPa)	V_f (%)
FUD200	Vacuum bag	23.2 ± 1.9	3.44 ± 0.51	215 ± 31	17.5 ± 1.2	37.8 ± 4.3
FFA200	Vacuum bag	7.91 ± 0.25	7.91 ± 0.25	73.1 ± 2.9	73.1 ± 2.9	35.6 ± 0.4
FUD200	Hot press	28.2 ± 1.6	3.31 ± 0.20	286 ± 38	11.8 ± 1.9	54.7 ± 4.1
FFA200	Hot press	10.4 ± 0.66	10.4 ± 0.66	108 ± 1.74	108 ± 1.74	49.8 ± 0.9
CRST500	VARTM	8.71 ± 1.21	8.71 ± 1.21	97.7 ± 9.8	97.7 ± 9.8	30.1 ± 2.2
Spruce	-	13.6 ± 0.52	0.611 ± 0.11	90.2 ± 3.9	4.61 ± 0.87	-
Balsa	-	1.76 ± 0.54	0.0534 ± 0.016	8.76 ± 2.8	3.92 ± 1.0	-

The fibre volume fraction given in Table 3-3 was calculated from:

Equation 3-1: Fibre volume fraction

$$V_f = \frac{\frac{m_{fibre}}{\rho_{fibre}}}{\frac{m_{fibre}}{\rho_{fibre}} + \frac{m_{matrix}}{\rho_{matrix}}}$$

where the mass of the fibre was calculated from the areal density of the fabric multiplied by the number of layers and area of the samples. The mass of the matrix was obtained from the difference of the total sample mass and fibre mass. The densities of the fibre and matrix were 1.45 g/cm³ and 1.15 g/cm³ respectively.

The vacuum bag specimens had a roughly 25 percent decrease in stiffness and strength due to a lower fibre volume fraction. The relationship between fibre volume fraction and Young's modulus is shown in Figure 3-9.

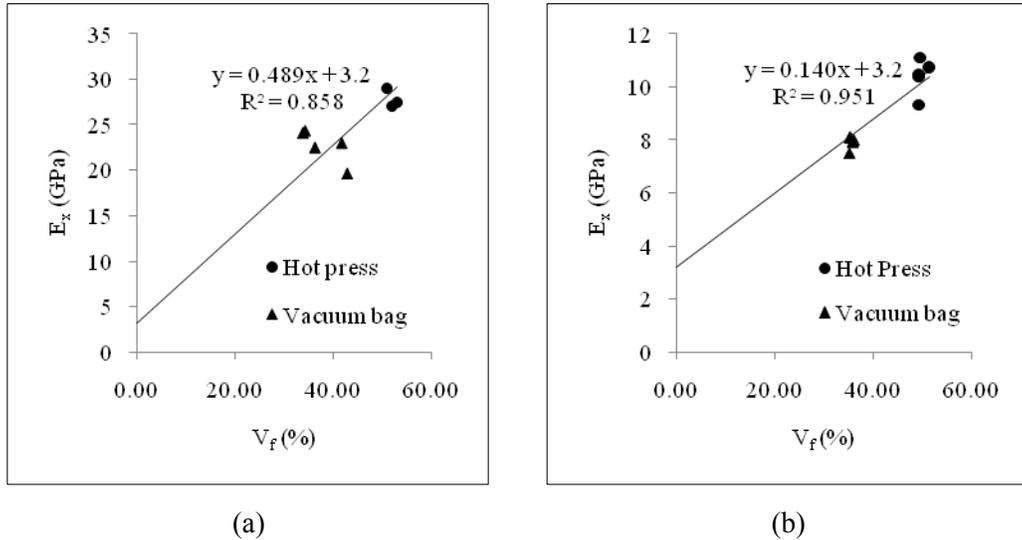


Figure 3-9: Young's modulus versus fibre volume fraction for prepreg samples
(a) unidirectional (b) woven

An unexpected result from this testing was that the VARTM samples had a higher stiffness than the vacuum bag woven samples even though they had a much lower fibre volume fraction. The dry fibre is less costly and requires very little equipment to process so when unidirectional becomes more readily available it

will likely be better for this application. However, at the time of this study, the unidirectional prepreg manufactured at 100 psi had the best mechanical properties and also the degree of anisotropy necessary to develop a successful soundboard.

Due to the large difference in bulk density of the materials it was more useful to compare their specific properties (Figure 3-10). To determine the density of a given sample, the volume was first determined by measuring the width and thickness at three points and taking an average. The length was only measured at one point as recommended by the ASTM standard. The density was finally obtained from dividing the calculated volume by the mass of the sample.

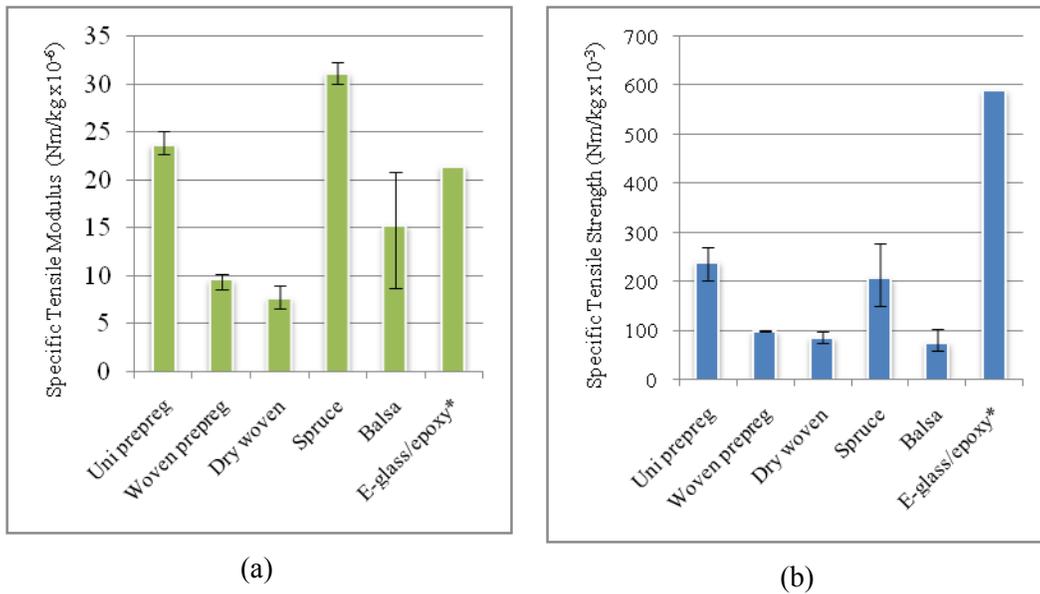


Figure 3-10: Specific tensile properties of studied materials *[38] (a) specific tensile modulus (b) specific tensile strength

It can be seen in Figure 3-10 that spruce has a higher specific Young's modulus in the grain direction than all of the other materials. The specific modulus of the unidirectional prepreg was however slightly higher than typical E-glass/epoxy but the E-glass/epoxy was far superior to all the materials in specific strength.

Based on the results of the tensile testing, it was concluded that the flax prepreg, processed by the above methods, did not lead to a suitable soundboard material.

However, by creating a sandwich structure with the low density and low damping balsa core it was feasible to satisfy all of the Haines *et al* criteria [1].

3.3.2 Compression testing

Due to the bending moment applied by the bridge on the soundboard of the instrument, there are fibres in the soundboard that are both in tension and compression. Since composite materials generally have lower properties in compression, it was important to obtain the compressive strength of the materials to determine accurate failure criteria from the finite element model. Compression testing was only performed on the flax prepregs manufactured on the hot press since that was the final material and pressure that was used to manufacture the prototype ukuleles. Five samples were tested for each test case and an average was taken for the final result. The specimens were supported in detachable steel tabs with a gauge length of 1 cm and a loading rate of 1 mm/min was applied. Two failure modes were observed with this setup; buckling and kinking (Figure 3-11). Pure compressive fibre failure was likely not observed due to the relatively low modulus of the natural fibres [38].

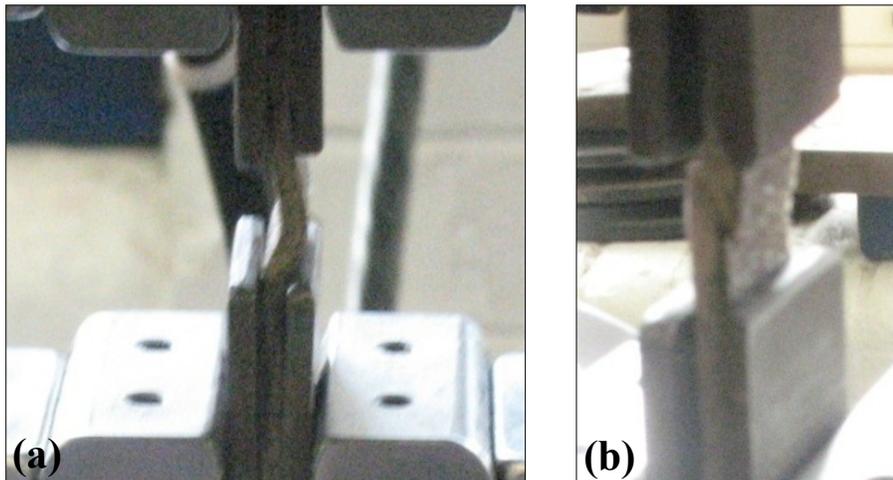


Figure 3-11: Failure modes observed during compression testing (a) buckling (b) kinking

The specific compressive strength of the bio-composite was comparable to literature values for spruce (Figure 3-12). Balsa wood had a fairly high compressive strength so that was another benefit of using it as the core material.

The compressive strengths of the flax/epoxy laminates (Table 3-4) were significantly lower than typical E-glass/epoxy.

Table 3-4: Compressive strengths of flax prepregs

	X_c (MPa)	Y_c (MPa)
FUD-200	95.6 ± 3.4	41.2 ± 1.9
FFA-200	71.3 ± 3.0	71.3 ± 3.0

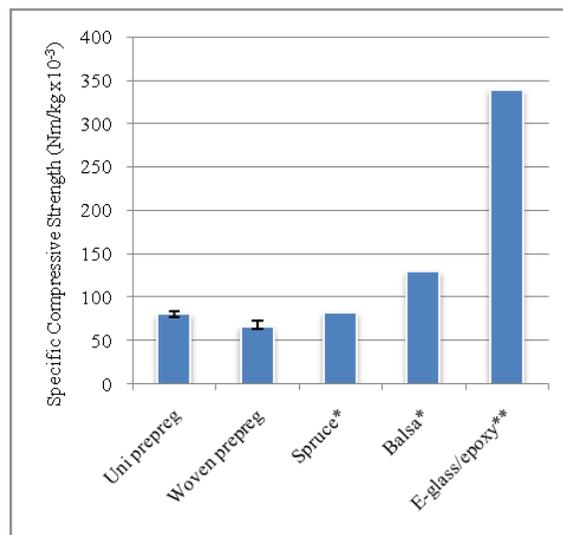


Figure 3-12: Specific compressive strength of studied materials * [39] ** [40]

3.3.3 Shear Testing

As discussed in the literature review, it was found that there is a high correlation between the shear modulus and the high frequency behavior of a soundboard [16]. Using a sandwich structure inevitably leads to a reduction of in-plane shear properties so this factor had to be taken into account. This effect was minimized by using a balsa wood core that had some contribution to the shear properties. To obtain the shear properties, a three-rail test fixture developed by Eilers [41] was used with a 100kN MTS® testing machine. A total of four cross ply specimens were tested for both the unidirectional and woven prepreg. A woven shear sample along with the test fixture is shown in Figure 3-13.

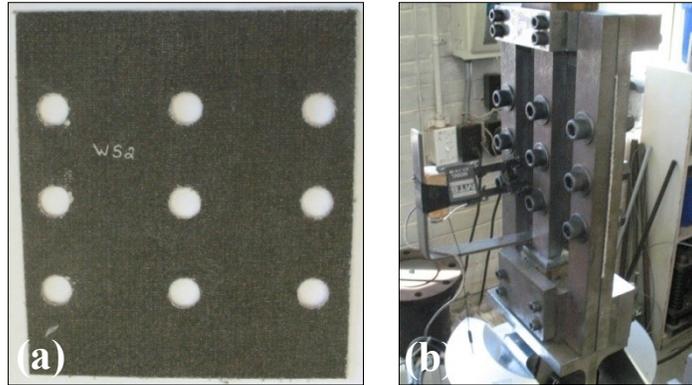


Figure 3-13: Shear testing setup (a) cross-ply specimen (b) three-rail test fixture

In order not to damage the extensometer, the specimens were only loaded to a strain of 1 mm to obtain the shear modulus. The extensometer was then removed and the specimen was loaded until failure to obtain the shear strength. From this method, the shear properties could be determined but a complete stress-strain curve could not be generated. The resulting shear properties are given in Table 3-5 and the specific properties are presented in Figure 3-14.

Table 3-5: Shear properties obtained from three-rail test fixture

	E_s (GPa)	S (MPa)
FUD-200	5.2 ± 0.74	27.1 ± 1.1
FFA-200	3.39 ± 0.32	23.9 ± 1.6

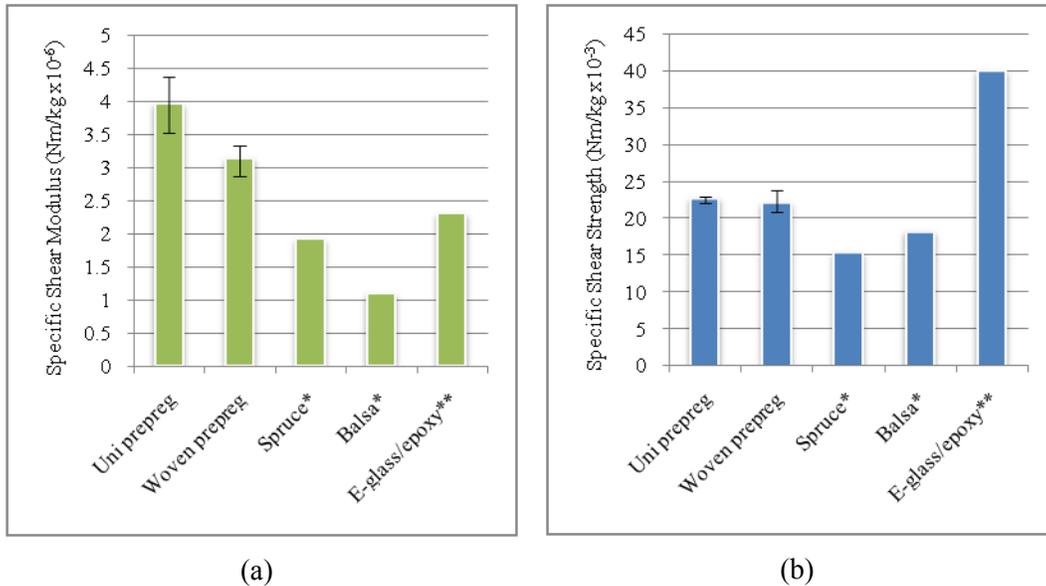


Figure 3-14: Specific in-plane shear properties of studied materials * [39] ** [40]
 (a) specific in-plane shear modulus (b) specific in-plane shear strength

The results of the shear testing showed that the flax materials had a higher specific shear modulus than all of the other materials. However, by combining the flax prepreg with balsa wood it was possible to make a sandwich structure with similar overall shear properties to spruce. The specific shear strength of the flax materials was greater than both wood species but all were much lower than typical E-glass/epoxy.

3.4 Dynamic testing

Although static testing provided a good initial assessment of the ability of the bio-composite material to act as a soundboard, it could not determine the internal friction or dynamic elastic properties. These properties define the dynamic behavior of the final material, thus were critical for an application that was a coupled system of vibrating elements. To obtain these properties, dynamic testing was performed in accordance with ASTM E1876-09 [42]. This standard involved exciting small beam specimens in flexural and torsional modes of vibration to determine the dynamic Young's and shear moduli respectively. Several other methods of obtaining these parameters from orthotropic plate samples have also

been investigated in the literature [18, 43-46], however, at the time of this writing no standardized test existed.

The first step in the dynamic testing was to build a support structure for the small beam specimens. The final setup was designed to isolate the specimens from ambient vibrations (Figure 3-15). A non-contact excitation and detection device was selected to minimize errors on the measured loss factors. The excitation device consisted of a small steel ball hanging from a thread that was swung from a constant angle of 15 degrees. The response of the beams was measured with a laser Doppler velocimeter (Polytec OFV-2000). The sample beams were supported between two steel side columns attached to a large steel block. Fishing line was then strung between the holes in the prepared samples and attached to sections of threaded rod to provide free-free boundary conditions.

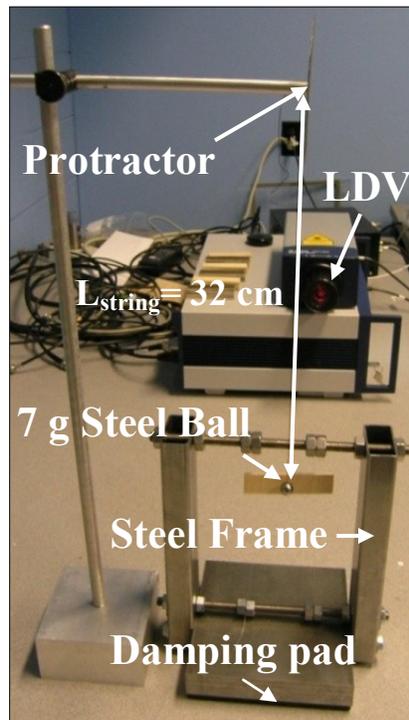


Figure 3-15: Dynamic test setup with laser Doppler velocimeter

Based on the results of static testing, two different sandwich structures along with Sitka spruce samples were characterized. These ply sequences were chosen to satisfy the stiffness, areal density and degree of anisotropy criterion for the

soundboard and back plate. The lower limit of the number of plies was restricted by the required mechanical properties and the upper limit was limited by the maximum allowable areal density. The amount of unidirectional and woven fabric was governed by the degree of anisotropy requirement. To meet the degree of anisotropy requirement and not exceed the areal density of a typical spruce soundboard, it was determined that a maximum of two unidirectional flax layers could be used. The thickness of the core necessary to attain the required bending stiffness was then determined using classical laminate theory. It was found that a 1.89 mm thick balsa core led to a sandwich panel that matched the bending stiffness of a 2.5 mm thick spruce soundboard. These calculations were performed by means of ZenLAM* software [47]. The final ply sequence for the soundboard was $[0_u]_s$ with a core thickness of 1.89 mm. For the remainder of this text, subscript “u” in the ply sequence will denote the use of unidirectional prepreg and subscript “w” will denote the use of woven prepreg.

To develop a ply sequence for the back plate of the instrument, literature values for the mechanical properties of maple were taken as a benchmark (Appendix A). To meet the properties of maple, two additional woven layers were added to the soundboard ply sequence. It was determined that a core thickness of 1.64 mm led to the bending stiffness of a 2.5 mm thick maple back plate. The areal density was slightly exceeded with this ply sequence, however, this was not deemed to be a problem since the back plate has been traditionally selected for its appearance and not its mechanical properties [23]. The final back plate sequence was $[0_u / 0_w]_s$ with a core thickness of 1.64 mm.

For all of the materials, 15 samples were cut for a total of 45 samples. Ten were cut in the fibre direction and five were cut perpendicular to the fibre direction. Five of the fibre direction samples were used for the flexural mode of vibration and the other five were used for the torsional mode. This was done to avoid

* ZenLAM is a software that calculates ply stresses, strains and failure criteria using classical laminated plate theory

drilling holes on sections of the samples that did not correspond to a node line. The specimens were then excited on a node line that corresponded to another mode of vibration to avoid exciting the wrong mode. The laser Doppler velocimeter measured the response of the beams and the data was used to calculate the dynamic mechanical properties. These calculations are described below.

For the flexural mode of vibration, the dynamic Young's modulus was calculated from [42]:

Equation 3-2: Dynamic Young's modulus

$$E = 0.9465 \left(\frac{mf_f^2}{b} \right) \left(\frac{L^3}{h^3} \right)$$

where m is the mass of the sample, f_i is the resonant frequency in flexure, t is the thickness, b is the width and L is the length.

For the torsional mode of vibration, the shear modulus was determined from [42]:

Equation 3-3: Dynamic shear modulus

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

where m is the mass of the sample, f_i is the resonant frequency in torsion, t is the thickness, b is the width, L is the length and A and B are correction factors based on the specimen geometry.

The damping of the material was calculated using the half power bandwidth method and is given by [48]:

Equation 3-4: Quality factor

$$Q = \frac{\omega_a^2 - \omega_b^2}{2\omega_r^2}$$

where Q is the quality factor, ω_r is the resonant frequency and ω_a and ω_b are the frequencies at the half power points. The inverse of the quality factor is known as the loss factor (Q^{-1}) and designates the amount of internal friction in a given material [49]. To measure the resonant frequencies, time domain data was obtained from the laser Doppler velocimeter and was converted to the frequency domain using the fast-Fourier transform function in Matlab® (Figure 3-16).

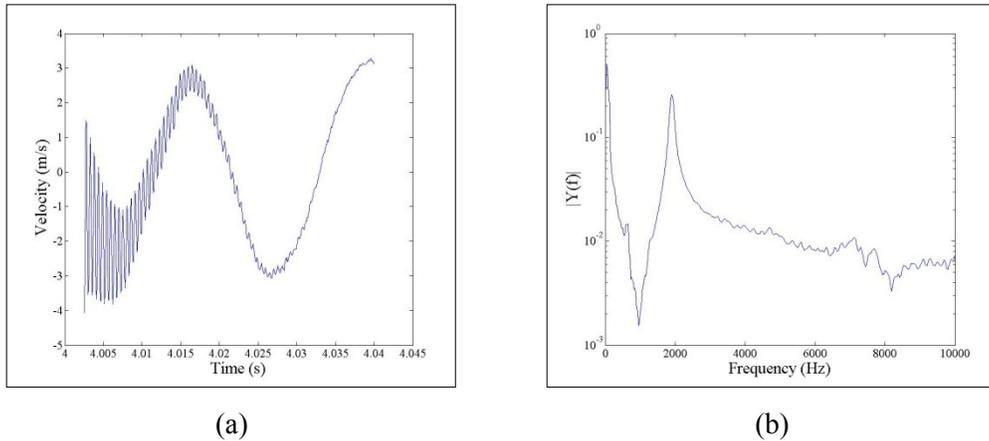


Figure 3-16: Sample response from dynamic testing (a) time domain (b) frequency domain

It can be seen that the time domain signal contained two main frequencies. A higher frequency superimposed on a much lower frequency. The lower frequency signal was the rigid body motion of the beam and the higher frequency signal resulted from the vibration mode in question. The two were differentiated in the frequency domain so that the dynamic mechanical properties could be calculated from the resonant frequency of the vibration mode. The rigid body mode was not considered, however, it could have been used to determine the mass of the vibrating object [48].

An average of all the specimens was finally taken to determine the dynamic mechanical properties. The calculated stiffnesses for the sandwich structure corresponded to the engineering constants for apparent stiffness in flexure. A summary of the results is given in Table 3-6.

Table 3-6: Dynamic testing results for flax sandwich structures and spruce

	E_x (GPa)	$Q_x^{-1} \times 10^{-3}$	E_y (GPa)	$Q_y^{-1} \times 10^{-3}$	E_s (GPa)
Sitka spruce	13.7 ± 0.5	8.02 ± 1.9	0.801 ± 0.035	24.9 ± 2.5	0.812 ± 0.040
Flax soundboard	16.6 ± 1.2	8.43 ± 2.7	1.08 ± 0.13	20.1 ± 2.0	1.03 ± 0.072
Flax back plate	17.2 ± 0.9	9.95 ± 2.9	4.20 ± 0.19	20.4 ± 2.5	0.714 ± 0.057

The results for the spruce agreed well with those obtained by Ono *et al* [50]. The flax soundboard had comparable internal friction to spruce as well as a sufficiently high apparent Young's modulus.

3.5 Void content

Of the several types of composite defects, it is widely agreed that voids are the most detrimental to the mechanical properties of the composite [51]. Voids originate mainly from trapped air on the fibre surfaces but also from air bubbles and volatiles trapped in the resin [51]. Voids can also grow from the diffusion of air or water vapor and by combining with neighboring voids [52]. To gain some insight on the void content of the samples, they were analyzed under a microscope. Specimens from all three manufacturing methods were cut and polished. The resulting images explained the water absorption problems and also why the woven prepreg samples had lower mechanical properties than the dry fibre samples. From visual inspection, it was found that the prepreg samples had a significantly higher presence of voids compared to the dry fibre samples manufactured by VARTM (Figure 3-17).

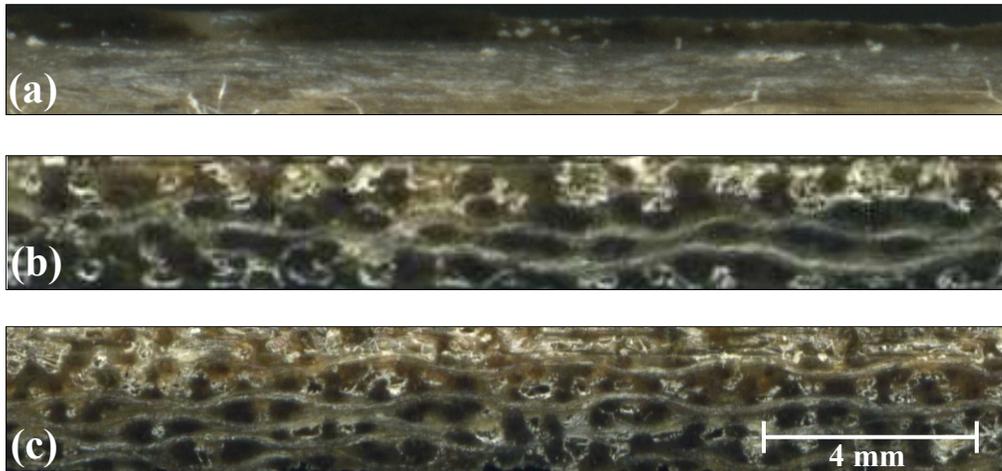


Figure 3-17: Cross sections of flax samples showing void content (a) dry fibre (VARTM) (b) woven prepreg (hot press) (c) woven prepreg (vacuum bag)

The dry fibre sample had few visible voids while both prepreg samples had very noticeable quantities. Due to the water absorption problems, it was likely that the diffusion of water and combining of neighboring voids caused the large size of some of the voids.

Aside from the negative impact on the water absorption problem, it was uncertain if a high presence of voids was in fact a problem for this application. Since wood is itself a highly porous material, it could have been beneficial to try and recreate this porosity. A high concentration of voids would have reduced the bulk density of the composite material and brought it closer to wood, however, to recreate the level of porosity found in wood would have required a significantly higher void content than that observed. Even with this level of voids, the bulk density of the cured flax prepreg was around 1.1 g/cm^3 , significantly higher than softwood species such as Sitka spruce.

3.6 Results comparison

The results of the dynamic and static testing implied that the flax and balsa sandwich structure could meet all of the Haines *et al* criteria [1]. Based on the criteria, four key properties were compared; bending stiffness, areal density, level of internal friction and degree of anisotropy.

3.6.1 Bending stiffness

The bending stiffness in the x-direction was the most important property to match. Based on the material characterization, the flax sandwich structures had a higher overall apparent stiffness than both wood species (Figure 3-18). Given this information, the bending stiffness could be easily matched to a wooden soundboard by adjusting the core thickness.

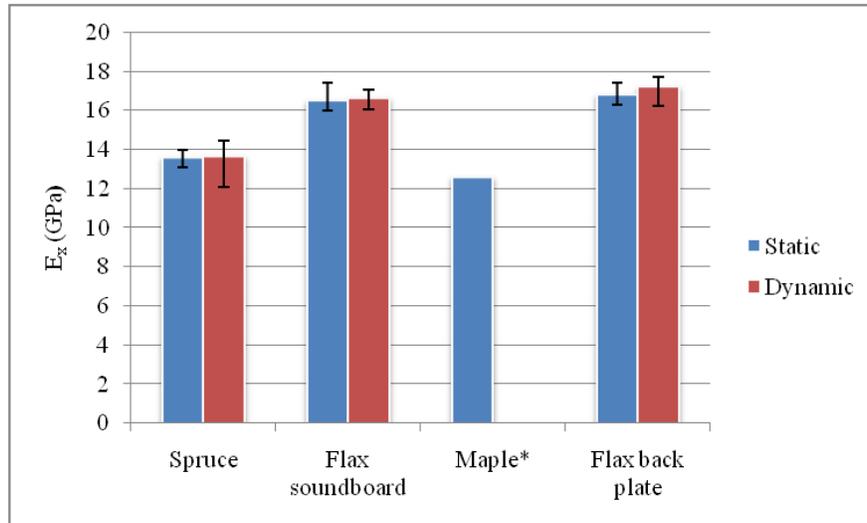


Figure 3-18: Young's modulus in x-direction of soundboard materials * [39]

It has been shown in previous studies that there is a high correlation between the static and dynamic Young's modulus of wood in the low frequency range [53]. The results from this study seem to agree well with this observation. There was also a high correlation between the static and dynamic stiffnesses of the flax sandwich structures.

3.6.2 Areal density

The resulting areal densities of the sandwich structures were a direct function of the ply sequences that were selected. Based on the areal density and degree of anisotropy requirement of the soundboard, only two layers of unidirectional prepreg could be used with the balsa core. This led to an areal density in the lower range of typical spruce soundboards (0.95 to 1.18 g/cm^3) [16]. For the back plate, two additional woven layers were added which resulted in a slightly higher

areal density than typical maple back plates. The areal densities of the sandwich structures and their wooden counterparts (based on a thickness of 2.5 mm) are shown in Figure 3-19.

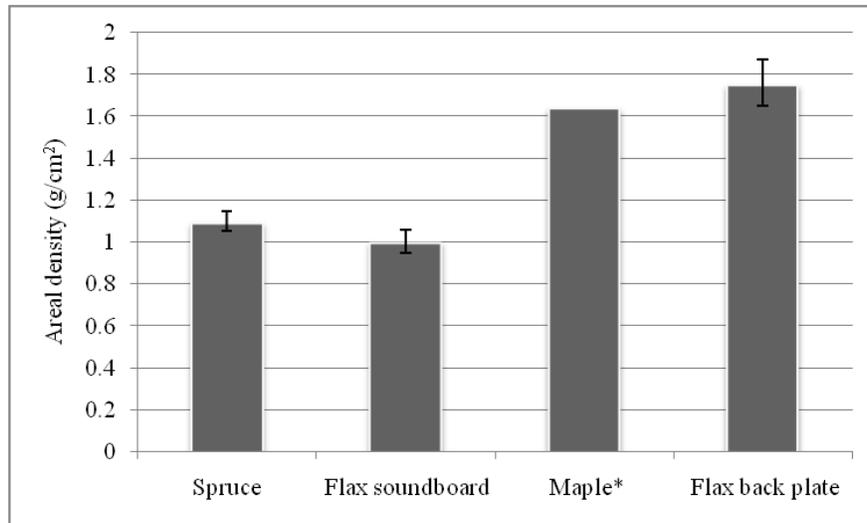


Figure 3-19: Areal densities of soundboards * [39]

3.6.3 Internal friction

The level of internal friction was a major concern from the beginning of this study since the flax prepregs were known for having high damping properties [8]. This can be a positive attribute in applications where damping of vibrations is critical but for stringed instruments it is desirable to have relatively low damping. As discussed above, the balsa wood core was selected to counteract the damping effects of the flax prepregs and resulted in similar overall damping when compared to spruce and maple (Figure 3-20).

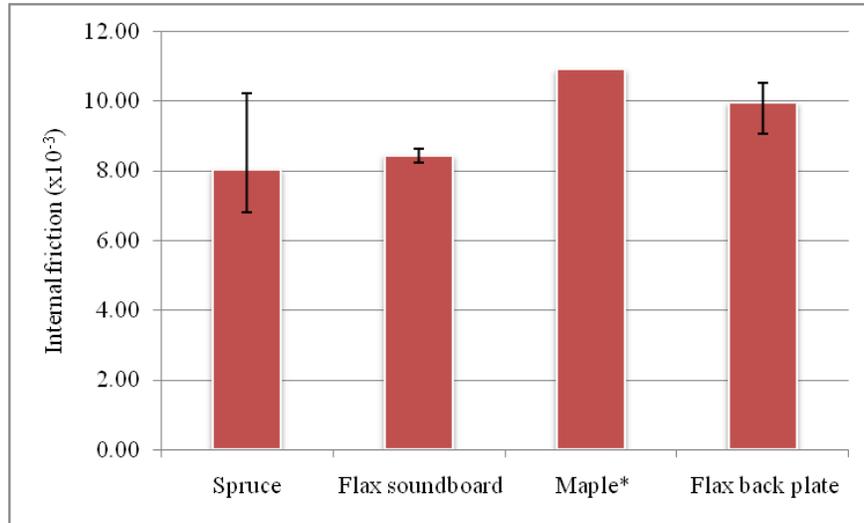


Figure 3-20: Internal friction in x-direction of soundboard materials * [39]

3.6.4 Degree of anisotropy

Similar to the areal density, the degree of anisotropy was primarily a function of the ply sequence that was selected. By using appropriate combinations of unidirectional and woven layers the degree of anisotropy could be controlled very well. The resulting degree of anisotropy for the flax soundboard was comparable with spruce (Figure 3-21). The degree of anisotropy for the back plate was lower than maple but this was not deemed to be a serious problem.

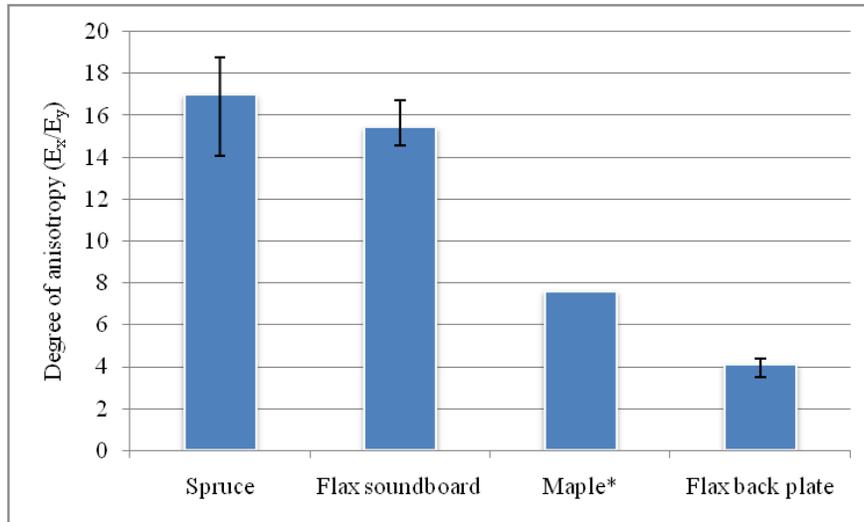


Figure 3-21: Degree of anisotropy of soundboard materials * [39]

3.7 Summary

The flax prepreg in general had better specific shear and compressive properties than the spruce, however, it was inferior in the most important property for a soundboard; the specific Young's modulus in the fibre direction. For this reason, it did not meet all of the Haines *et al* criteria on its own. However, by creating a sandwich structure with a balsa core, all of the soundboard criteria were satisfied.

The flax prepreg was also shown to have better specific stiffness than typical E-glass epoxy in tension and shear. This suggests that the flax/epoxy composite could replace E-glass/epoxy in stiffness driven applications. On the other hand, the flax material had significantly lower specific strength than E-glass/epoxy so would not be suitable for replacing it in strength driven applications.

4. Prototype Design

After the material characterization suggested that the bio-composite had potential to act as a soundboard, a small prototype was designed and manufactured. Due to the cost of tooling, it was desired to select a small musical instrument to develop a manufacturing process that could be adapted to any size. Since the focus of this study was on the structure of the guitar, the smallest instrument of the guitar family was selected, namely, the soprano ukulele.

4.1 Computer model

Based on ukulele dimensions that have been developed over the years, a 3D computer model was created using NX6 software (Figure 4-1). The dimensions and structure of the instrument were based on the acoustic requirements for this type of instrument. The two primary fixed requirements were the volume of the air cavity, so that the Helmholtz resonance was properly “tuned”, and the length of the neck.



Figure 4-1: Rendered image of prototype computer model

The main body of the prototype was modeled using an extruded section based on a sketch of the soundboard geometry. The neck and headstock were modeled using a swept section with varying cross section geometry. Edge blends were

finally implemented to make all transitions smoother. The edge blends were important since the fibres would have difficulty conforming to right angles. The general dimensions of the prototype along with a full size guitar are presented in Table 4-1 where the component names correspond to those shown in Figure 1-3.

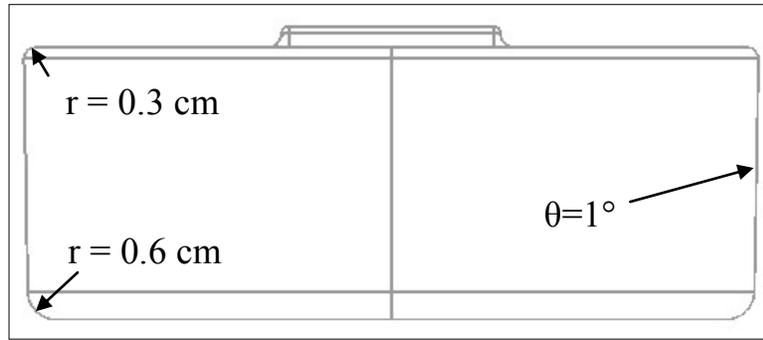
Table 4-1: Prototype and classical guitar dimensions

	Prototype	Classical Guitar*
Upper bout radius (cm)	13.7	29.0
Lower bout radius (cm)	17.1	37.5
Body length (cm)	23.8	48.5
Body depth (cm)	6.35	10.5
Scale length (cm)	34.4	67.0
Overall length (cm)	50.8	98.0
Sound hole diameter (cm)	4.72	9.05

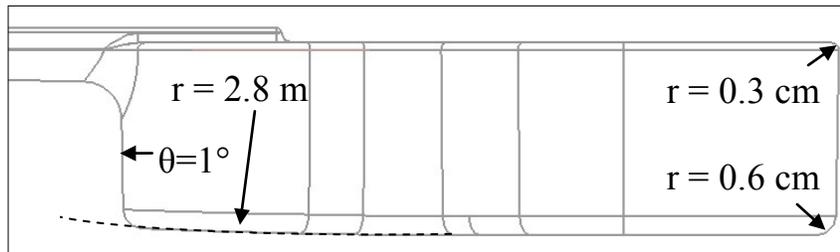
* [12]

It should be noted that the back of stringed instruments are usually slightly curved. This results in a greater number of vibration modes and leads to a richer sound [12]. This design feature was incorporated into the prototype and can be seen in Figure 4-2. The following design features were also included based on the use of composite materials instead of wood:

- Draft angles - To easily de-mould the part it was necessary for the prototype to be drafted in both halves of the mould. Usually the sides of wooden stringed instruments are not drafted but in this case a very small draft angle of 1 degree was incorporated (Figure 4-2). Such a small angle was chosen as to not affect how comfortable the instrument was to play.



(a)



(b)

Figure 4-2: Draft angle and curvature details for prototype design (a) rear view
(b) side view

- Reduced complexity – One significant advantage of using composite materials was that the instrument could be designed with far fewer pieces than typical guitars. In this case, the prototype was designed in entirely one piece. It is uncertain what affect this change had on the sound radiation properties but it is possible that it was beneficial.
- Elimination of “heel” - Another advantage of using composite materials, was that there was no need for a “heel” that is usually required on stringed instruments to connect the neck to the main body (Figure 4-3). The heel can be a nuisance for performers since it gets in the way when the musician is trying to play notes high up the fingerboard.

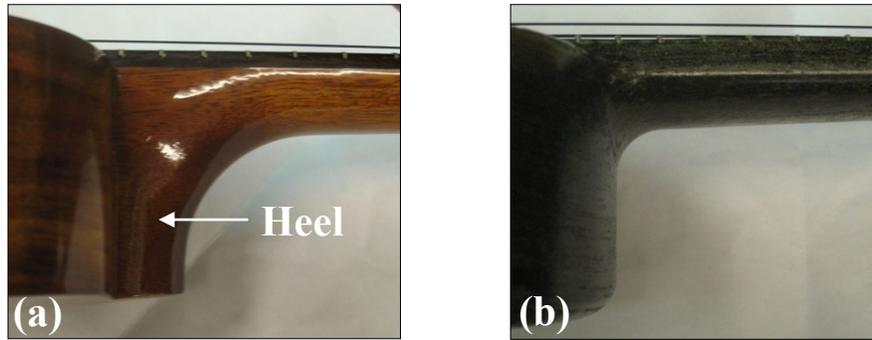


Figure 4-3: Illustration of neck joint (a) traditional “heel” design (b) “heel-less” design

The final computer model bore many similarities to a traditional instrument but with much advancement based on the benefit of using composite materials. This style of design could be extended to other musical instruments that are commonly made from several pieces.

4.2 Finite element modelling

The results of the material characterization were input into an ANSYS finite element model in order to optimize the design of the small prototype. The main purposes of the finite element model were to see if the structure could withstand the tension of the strings and also to predict some of the key resonant frequencies.

4.2.1 Meshing

The structure of the soundboard and back plate of the model were meshed using SHELL181 elements and the bridge was meshed using SOLID186 elements (Figure 4-4). The two components were then bonded together using CONTA174 and TARGE170 elements with perfectly bonded boundary conditions. The boundary conditions for the shell elements were based on previous work on predicting the resonant frequencies of guitar soundboards by Elejabarrieta *et al* [54]. In that study, the effect of free and “hinged” boundary conditions was investigated. The free conditions were meant to predict the resonant frequency during the building phase of stringed instruments when the soundboard was not attached to the structure. The “hinged” boundary conditions were used to predict the resonant frequency after the instrument was built when the soundboard was

attached to the structure. In this study, only the hinged boundary conditions were imposed since at no point during the manufacturing process was the soundboard in a free state where it could be tested. For the loading, a force of 30 Newton was applied at four points on the bridge to simulate the string tension. The material properties that were input into the model were obtained from the mechanical characterization.

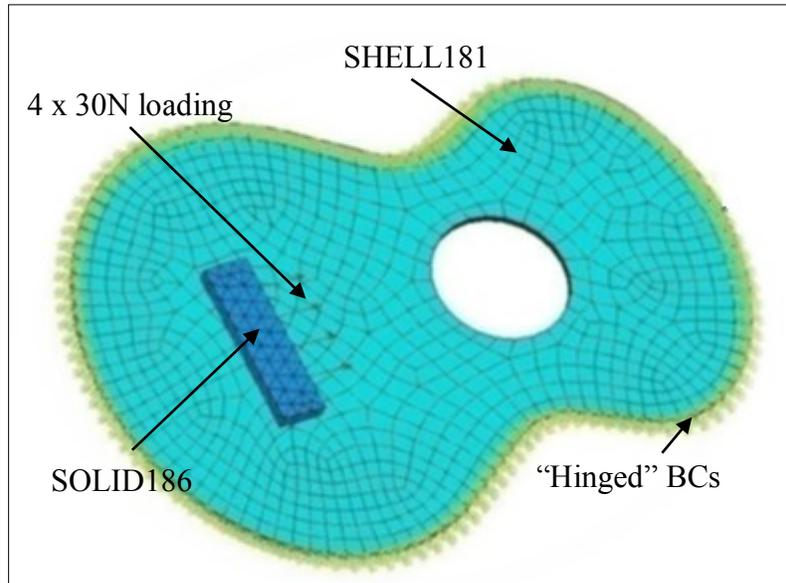


Figure 4-4: Finite element model of prototype soundboard

The ply sequences that were input into the model were based on the results of the static and dynamic testing. The final soundboard ply sequence was $[0_u]_s$ and the final back plate ply sequence was $[0_u/0_w]_s$ with balsa core thicknesses of 1.89 mm and 1.64 mm respectively.

4.2.2 Structural analysis

Since there were inherent stresses on the structure of the prototype as a result of the string tension, it was critical to determine the safety factor and also the amount of deflection. Initially an analysis of the full instrument was performed to locate the main areas of stress concentration. It was found that the main areas of concern were located around the bridge on the soundboard. Since the soundboard

could not be reinforced with extra layers due to the areal density requirement, this was the focus of the finite element analysis.

To determine the safety factor and mode of failure on the soundboard, a plot was generated of the maximum-stress failure criterion (Figure 4-5). The analysis predicted a safety factor of 7.38 and deflection of 0.33 mm (0.013 in) with a final mode of failure of fibre compression. This mode of failure occurred because the strength in compression for the flax material was much less than in tension. The final safety factor was still sufficiently high so there was no risk of the body failing. The deflection was however slightly above that of a typical ukulele (0.25 mm) [12] but normally soundboards have stiffening members called “braces” to attain such low deflections. For this reason, similar braces were added into the prototype during the manufacturing process.

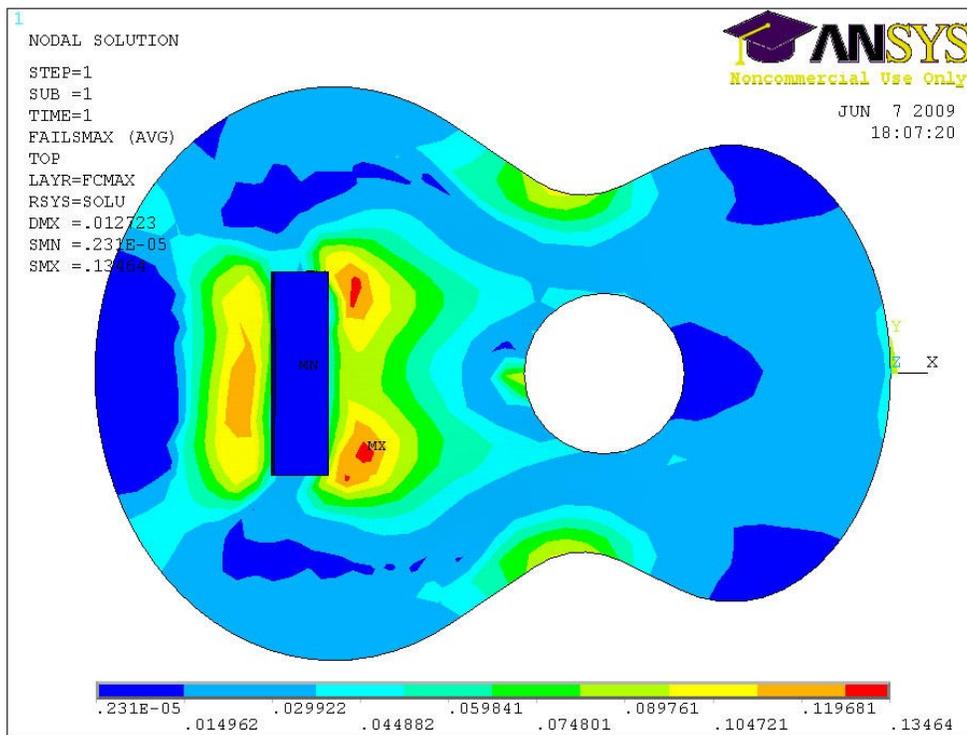
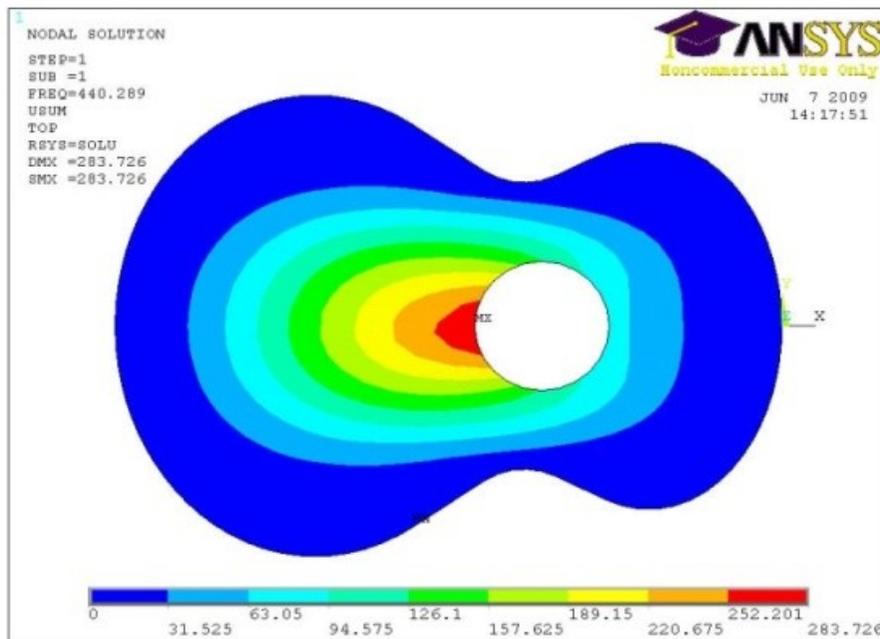


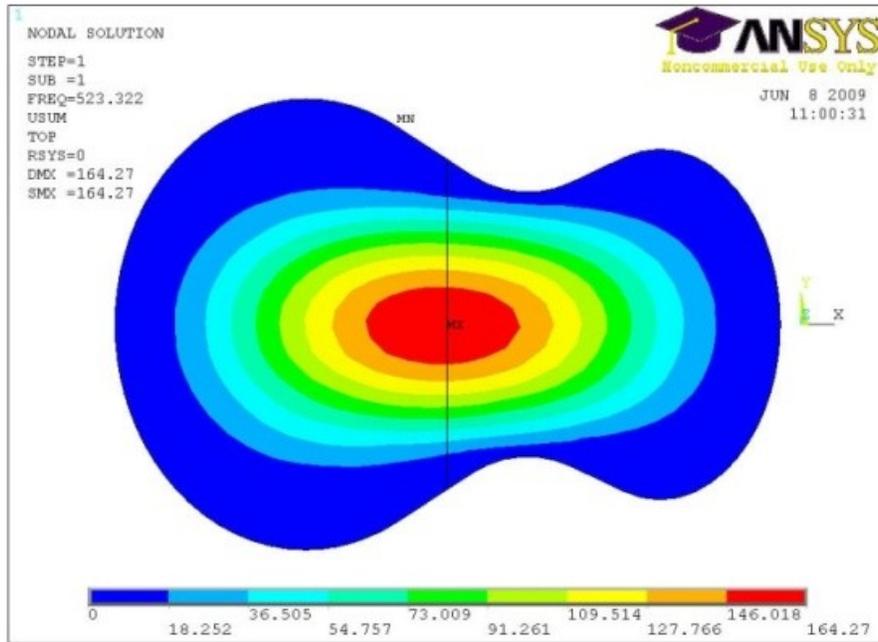
Figure 4-5: Maximum-stress failure criteria for prototype under string tension

4.2.3 Modal analysis

Traditionally, stringed instrument builders have “tuned” the fundamental resonant frequency of the soundboard and back plate to frequencies that correspond to notes of the open strings. This fundamental resonant frequency is commonly called the “tap tone” in the stringed instrument building community [12]. With the development of finite element modal analysis it is now possible to attempt to predict these frequencies based on the geometry and material properties. In this study, it was attempted to predict the thickness of balsa core required to produce the desired fundamental resonant frequency. For a ukulele, the soundboard is commonly tuned to 440Hz (A note) and the back plate is tuned to 523Hz (C note). Using these as target values, the required thickness of the balsa core was determined to be 2.5 mm for the soundboard and 3 mm for the back plate. Due to the low density of the balsa core, this increase in thickness added very little to the areal densities. The displacement magnitudes of the soundboard and back plate at the fundamental resonant frequency are plotted in Figure 4-6.



(a)



(b)

Figure 4-6: Fundamental resonant frequencies of soundboard and back plate
 (a) soundboard (440 Hz) (b) back plate (523 Hz)

5. Mould Design

One of the most significant steps in producing a composite part is the development of a mould. The resulting composite part will only be as good as the mould that produced it. A major step in designing a good mould lies in selecting an appropriate tooling material. Several materials can be used to make a mould but an appropriate one must be selected based on the requirements of the part. These requirements include the dimensional tolerance, heating rates, durability of the tool, coefficient of thermal expansion and cost [34]. The most critical property of any tooling material is the coefficient of thermal expansion (CTE). It is most desirable to have the CTE of the tooling material match the CTE of the composite being moulded. If there is a mismatch between the fibre and tooling CTE, residual stresses may occur in the part during cooling. One method to compensate for the difference in CTE between the mould and the tool is to incorporate a “shrink factor”. If the size of mould can be determined at its greatest expansion point, a “shrink factor” can be determined for the required size at ambient temperatures [34].

5.1 Computer model

Based on the computer model, a two-part closed mould with an internal pressure bladder and core was designed using the NX6 module “Mold Wizard” (Figure 5-1). This module involved selecting parting regions on the CAD model to create the two-part mould. Since draft angles had been taken into consideration in the initial CAD model it was straightforward to define the parting regions.

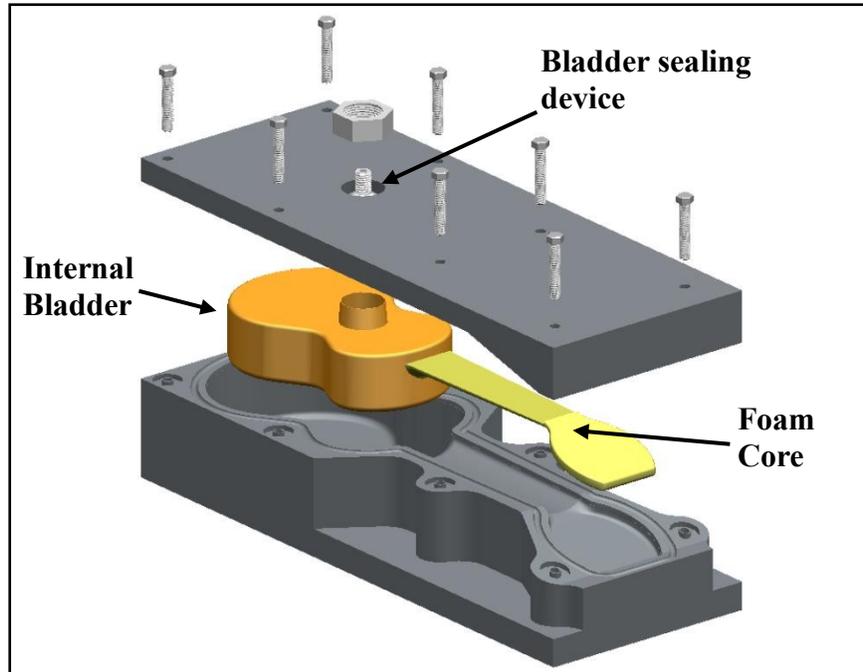


Figure 5-1: Computer assembly of two-part closed mould with inserts

After the initial creation of the two part mould, the following design features were added:

- Knife edge tool – This design feature was based on the work of O’Flynn [55] and helped to avoid pinching of the fibres in between the two mould halves. This concept is illustrated along with the actual knife edge tool in Figure 5-2.

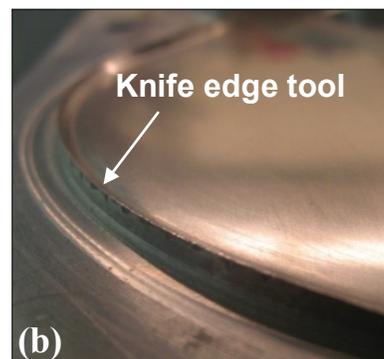
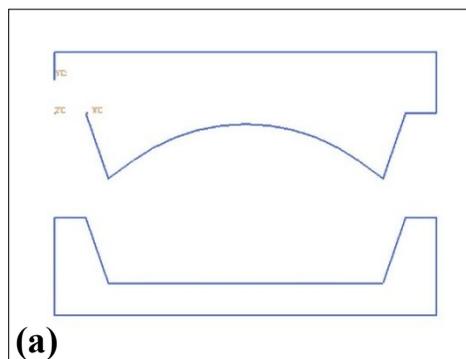


Figure 5-2: Illustration of knife edge tool included in mould design (a) section of initial concept (b) actual knife edge tool

- O-ring grooves - O-rings are known to be the best way to seal a mould since they do not rely on a high machining tolerance [34]. An O-ring groove was added around the entire contour of the part for optional sealing of the mould and they were also placed around the threaded holes to ensure that they were not filled with resin during the manufacturing process (Figure 5-3).

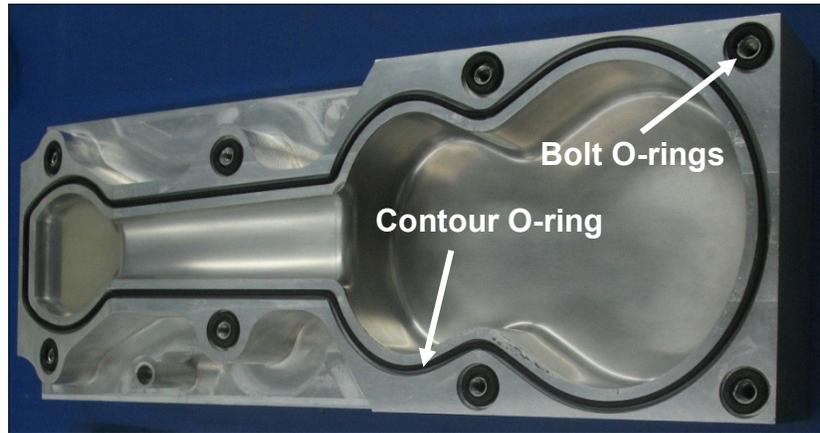


Figure 5-3: Placement of O-rings in prototype mould

- Internal pressure bladder and core – An internal pressure bladder and foam core (Figure 5-4) were developed to apply pressure in certain sections of the mould. Details of the manufacturing of the bladder and core are discussed in Section 5.3 and Section 6.1.4 respectively.

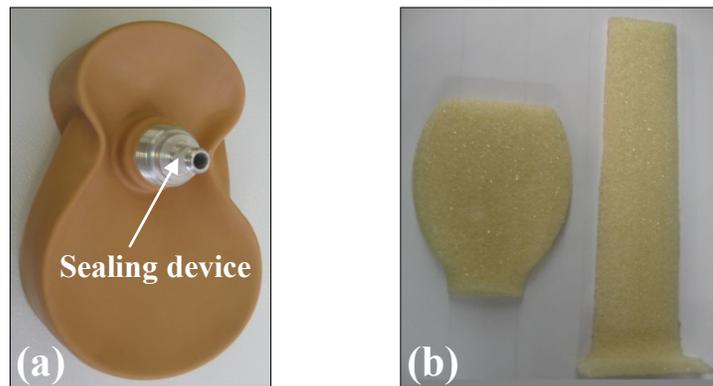


Figure 5-4: Pressure application inserts in mould design (a) latex pressure bladder
(b) foam core

- Bladder sealing device – This device sealed the internal pressure bladder in the main body of the mould (Figure 5-5). It was placed in a tapered inlet on the mould to help seal the bladder under application of pressure (Figure 5-5a). The device proved to work very well and was able to withstand the maximum air line pressure of 7 atm with no detectable leaks. A custom nut and washer were added to hold it in place during mould assembly and two O-rings were also added to better seal the inlet.

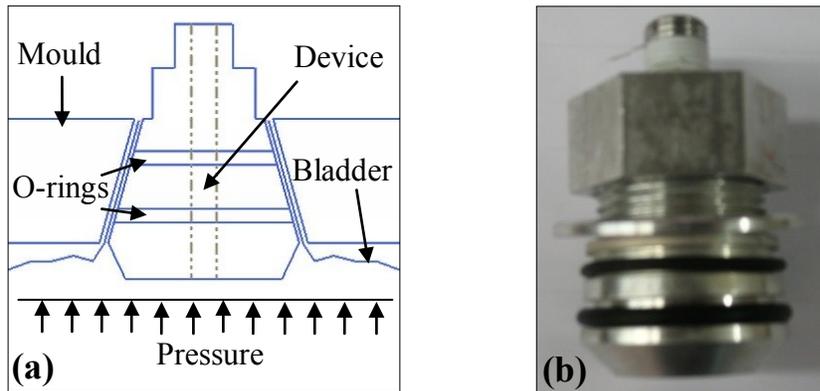


Figure 5-5: Internal pressure bladder sealing device (a) initial concept (b) actual device

5.2 Machining and finishing

After the two part mould was designed, it was machined from aluminum 6061 on a Milltronics® Partner MB20 vertical CNC machine (Figure 5-6). Aluminum 6061 has a much high CTE compared to composite materials, but it was selected for its durability and relatively low cost. Since the geometry of the part was quite complex, ball end mills had to be used to machine most of the surfaces. Ball end mills left small “scallops” that needed to be sanded off (Figure 5-7). Flat and tapered end mills were used wherever possible to minimize the presence of scallops and the amount of sanding required.



Figure 5-6: CNC machining of prototype mould

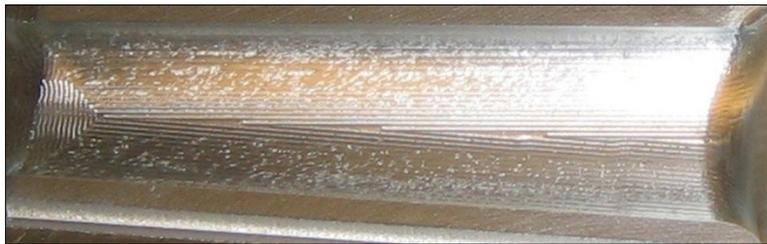


Figure 5-7: “Scallops” left by ball end mills during CNC machining

After the mould was machined, it was sanded using graduated roughness of sandpaper from 240 grit to 2000 grit. This was followed by a polishing with DuPont® Polishing Compound. The mould had to be periodically re-sanded and polished after it was damaged during manufacturing of parts. The surface finish of the mould was critical since even the slightest defects on the mould surface would show up on the final parts. The final sanded and polished mould is shown in Figure 5-8.

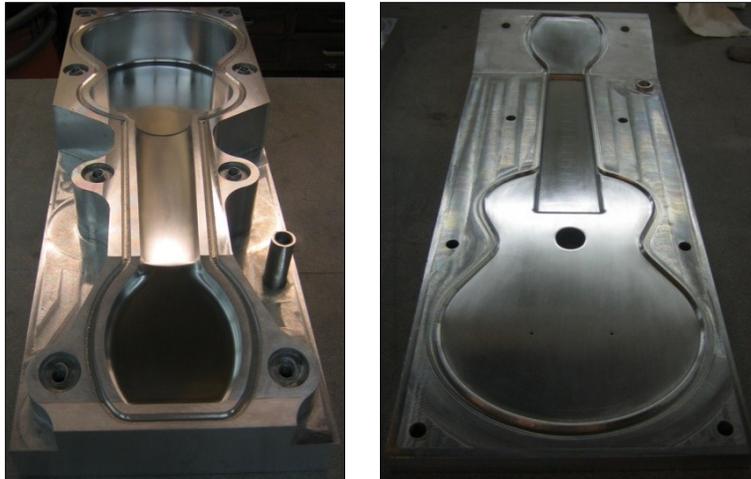


Figure 5-8: Two-part mould after sanding and polishing

5.3 Pressure bladder

It is common practice to mould hollow composite structures with a flexible internal bladder that is pressurized with air. Due to the hollow nature of stringed musical instruments, it was decided to include a pressure bladder in the mould design. Developing a working bladder was a critical part of the manufacturing process and proved to be a challenge. Due to the complex geometry and size of the part, creating a bladder was not as straightforward as for smaller parts. During the course of this study two types of bladders were experimented with; latex and silicone.

5.3.1 Latex bladder

Based on the work of Thouin, it was initially desired to make the pressure bladders out of latex. He had great success using custom latex bladders to mould a bicycle stem [56]. This type of bladder is made by dipping a tool into a mixture of hot water and latex to form a bladder based on the tool geometry [57]. The dipping process is carried out by Piercan USA Inc, a company that specializes in custom latex bladder [57]. The material selected for the dipping tool must be able to withstand temperatures above 115 °C and impervious to water. Ideally, a metallic material should be selected, however, for prototype work it is recommended to use a casting resin. The dipping tool must also be designed with

a large enough opening so that the bladder can be stretched off. The manufacturers website recommends to limit this stretching to around 500% but it states that stretching up to 700% can be accommodated [57].

For the dipping tool material, two types of polyurethane tooling were experimented with; RenCast® 6430 and RenShape® 473. Based on the work of Thouin [56], a small mould was made to create several mandrels from the polyurethane casting resin RenCast® 6430. The small mould was machined to 60% of the size of the prototype mould cavity (Figure 5-9a). This percentage was chosen to facilitate easier moulding of the dipping tools and to reduce cost. An issue arose when pores occurred on the surface of the moulded dipping tools (Figure 5-9c) but they were easily filled with a few layers of a gel coat (RenGel® 3260). The resulting tools were suitable for the dipping process and latex bladders were successfully produced.

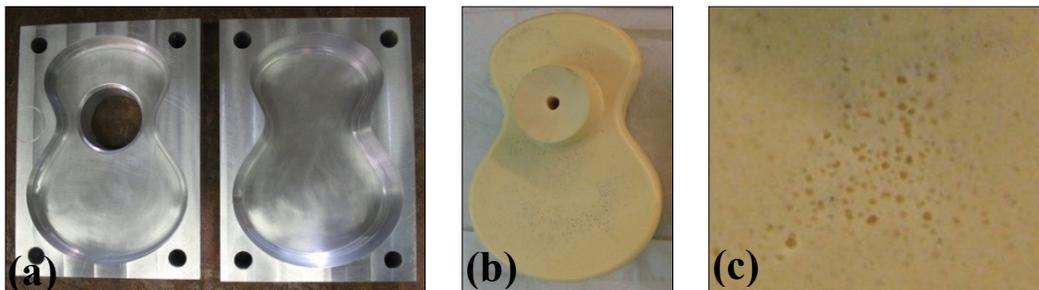


Figure 5-9: Polyurethane dipping tools used for making custom latex bladders (a) two-part aluminum mould (b) de-moulded dipping tool (c) resulting surface porosity

Even though the above tools were suitable for the dipping process, an unrelated problem arose as a result of their small size. The latex had a maximum elongation of 900% but the bladders had a tendency to inflate unevenly which resulted in them breaking before they filled the mould cavity. As a result of this size problem, a larger dipping tool scaled to 90% of the body volume was manufactured. Due to the difficulty and high cost of moulding a larger sized tool, it was machined from RenShape® 473, a polyurethane tooling board. This material was simple to machine and free of pores which reduced the manufacturing time to make the dipping tool. To machine the tools, a stock block

was placed in a vice on a vertical CNC machine and a contour was machined until just above the position of the vice. The excess stock from the bottom of the part was then removed with a band saw. The completed dipping tool is shown in Figure 5-10.

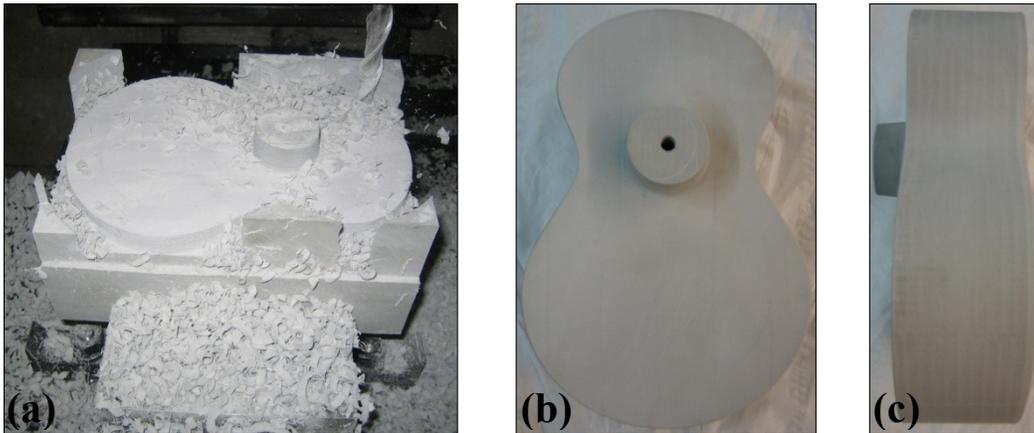


Figure 5-10: Final design of polyurethane dipping tool (a) CNC machining (b) top view (c) side view

5.3.2 *Silicone bladder*

Due to the difficulties encountered while making the latex bladders, a method was devised to make bladders from the existing two-part closed mould. This was done using Air Tech® MultiBag liquid silicone that was designed to be painted onto a tool surface to create a flexible reusable vacuum bag. In this study, it was attempted to coat the surfaces of a two-part closed mould to produce an internal bladder with the entire part geometry. This type of bladder had a few advantages; low cost, no need for additional tooling and rapid production time. To make the silicone bladders, three layers of the liquid silicone were first applied to both mould halves and allowed to fully cure. A large bead of the liquid silicone was then placed around the parting line of the mould and the mould was closed. The closed mould was then inverted so that the liquid silicone would flow to the other mould half and connect the two sides. The silicone bladder is shown inside the mould in Figure 5-11.

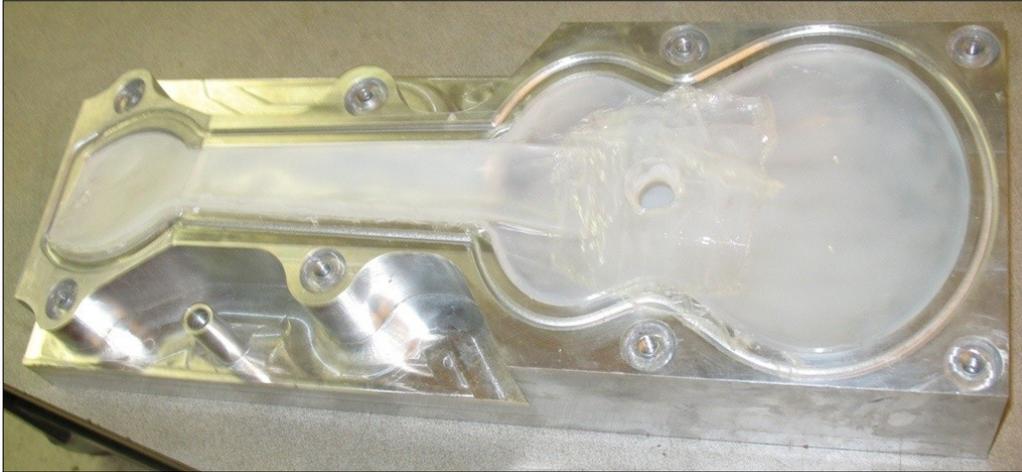


Figure 5-11: Silicone bladder inside of the mould

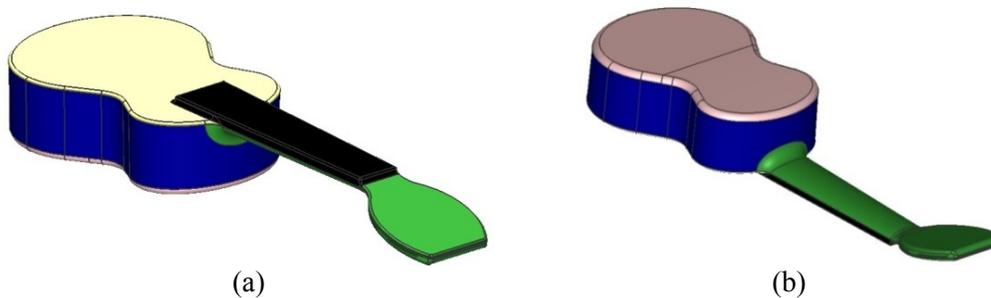
One issue that arose from using the existing mould was that the final size of the silicone bladder was too large. Ideally, a bladder should be slightly smaller than the tool so that when it expands no resin ridges are produced. The silicone bladder left large resin ridges on the inside of the prototype that potentially had a negative influence on the sound quality. Furthermore, it had a tendency to break at weak points which was a serious problem during manufacturing of the prototypes. For these two reasons (size problem and sensitivity to failure under pressure) this bladder was deemed not acceptable for this manufacturing process.

6. Manufacturing

After the two-part mould was completed, a hand layup manufacturing process was developed with the prepreg materials. A total of six parts were manufactured and improvements were made to the process after each one. The two biggest variables in the manufacturing process were the preforms and the cure cycle.

6.1 Preforms

Development of the preforms was the most challenging part in producing the manufacturing process. The final preforms were generated by the “flat pattern” function in NX6 based on the areas shown in Figure 6-1. These preforms were specifically designed to produce the same grain orientations as those on wooden musical instruments to further help mimic the frequency response. The surfaces on the prototype were divided into five groups; soundboard, backplate, neck and headstock, sides and fingerboard.



		Ply sequence	Core thickness (mm)
Soundboard		$[0_u]_s$	2.5
Back Plate		$[0_u / 0_w]_s$	3.0
Neck and Headstock		$[0_u / 0_w / 0_w / 0_u]_s$	variable
Sides		$[0_u / 0_w]_s$	0
Fingerboard		$[0_u / 0_u / 0_w / 0_w / 0_w / 0_w]_s$	0

(c)

Figure 6-1: Details of preform design for prototype ukulele (a) top view (b) rear view (c) ply sequences

6.1.1 Soundboard

The soundboard preforms were straightforward to design since there was no curvature. They were designed to include both the neck and headstock to reduce the total number of preforms. Based on the required ply sequence, only two preforms needed to be developed. The inner preform was made to be slightly smaller for easier placement. The final soundboard preforms along with the balsa core are shown in Figure 6-2.



Figure 6-2: Soundboard preform design

6.1.2 Back Plate

The back plate preforms were also not difficult to design but had some problematic curvature at the corners. The back had a similar layup to the soundboard with the addition of two woven layers. It proved to be simplest to cut the back plate preforms separate for the rest of the structure. This added to the total number of preforms but was much easier to layup. The final back plate preforms along with the balsa core are shown in Figure 6-3.



Figure 6-3: Back plate preform design

6.1.3 Sides

The sides of the prototype had the same ply sequence as the back plate without the balsa core. Normally the same wood species are selected for the sides of an instrument as those for the back plate, so ideally a balsa core would have also been included in this section, however, due to the limited drapability of the balsa strips this was not feasible. In the future, a balsa core could be steam moulded to the correct shape similar to how a wooden hockey stick is curved.

One key feature of the side preforms was the addition of extra material (“tabs”) on the top of the woven preforms to bond the upper half of the mould to the lower half. The extra material is marked by the dashed boxes in Figure 6-4 and it will be further discussed in Section 6.3.

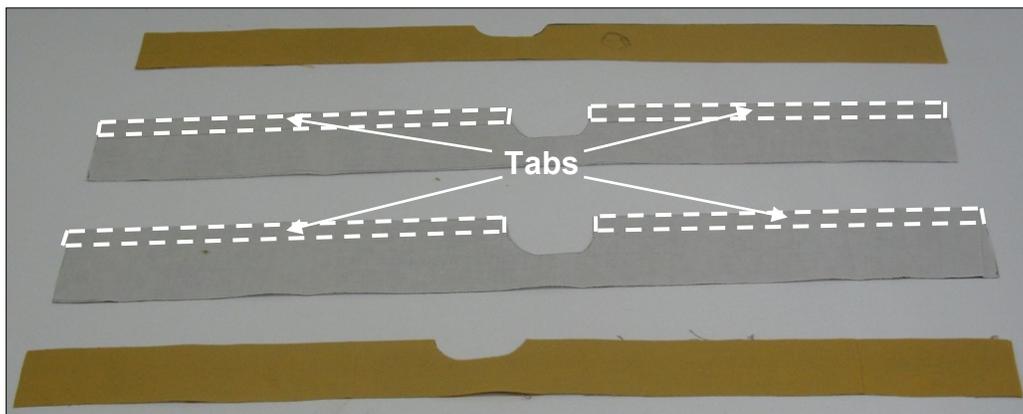


Figure 6-4: Side preform design

6.1.4 Neck and headstock

The neck and headstock preforms were a bit more difficult to define since they required extra layers to reduce the deflection. Cores were added in this region to both apply pressure during manufacturing and also to increase the bending stiffness of the neck. The cores were CNC machined from very low density DIAB® foam core. All the dimensions of the foam core were sized to 94% of the mould cavity size except for the length of the neck which was sized to 100%. This scaling was small enough to be easily inserted into the layup while large enough to apply sufficient pressure.

A similar modification to that added in the side layup, was added in this region to bond the lower half of the mould to the upper half. Extra material was added around the contour of the woven preforms for this purpose. The final neck preforms and foam core are shown in Figure 6-5.

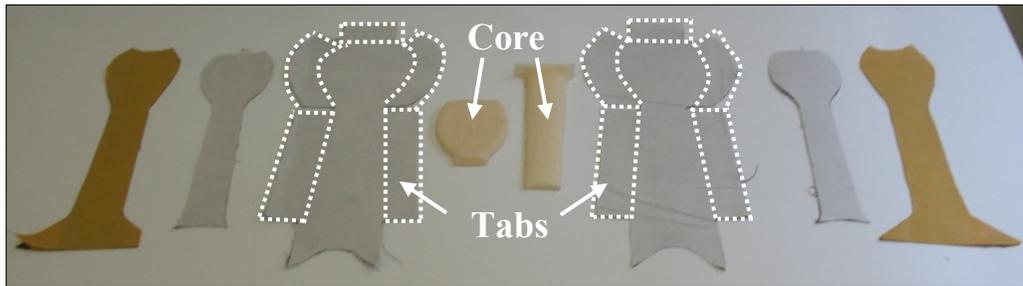


Figure 6-5: Neck and headstock preform design

6.1.5 Fingerboard

The fingerboard ended up being the most troublesome area in the mould to develop preforms. Two types of layups were experimented with during the development of the manufacturing process (Figure 6-6).

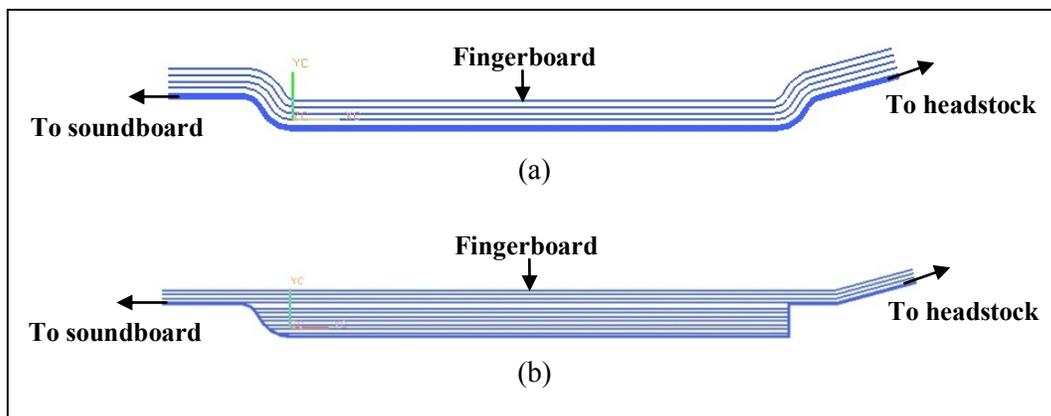


Figure 6-6: Layup designs for fingerboard (a) hollow design (b) thickness design

It was initially desired to use layup in Figure 6-6a, a more or less hollow fingerboard with only enough thickness to cut the fret slots. This was done to allow the fibres to follow a smooth contour from the soundboard to the headstock and reduce the required number of preforms. The main problem with this layup was that a specially contoured nut was needed to fit the tangent curves located at the transition to the headstock. It was not feasible to machine a specially

contoured nut for each prototype so the layup in Figure 6-6b was devised so that a typical rectangular cross section nut could be installed easily. This layup built the fingerboard up in thickness much like what would be found on existing guitars. To facilitate this layup, a mould insert was made to change the tangent curves into a right angle (Figure 6-7). The final fingerboard performs (Figure 6-7d) were based on cross sections of the CAD model at thickness intervals of 0.28 mm, which corresponded to the ply thickness of the cured flax prepreg.

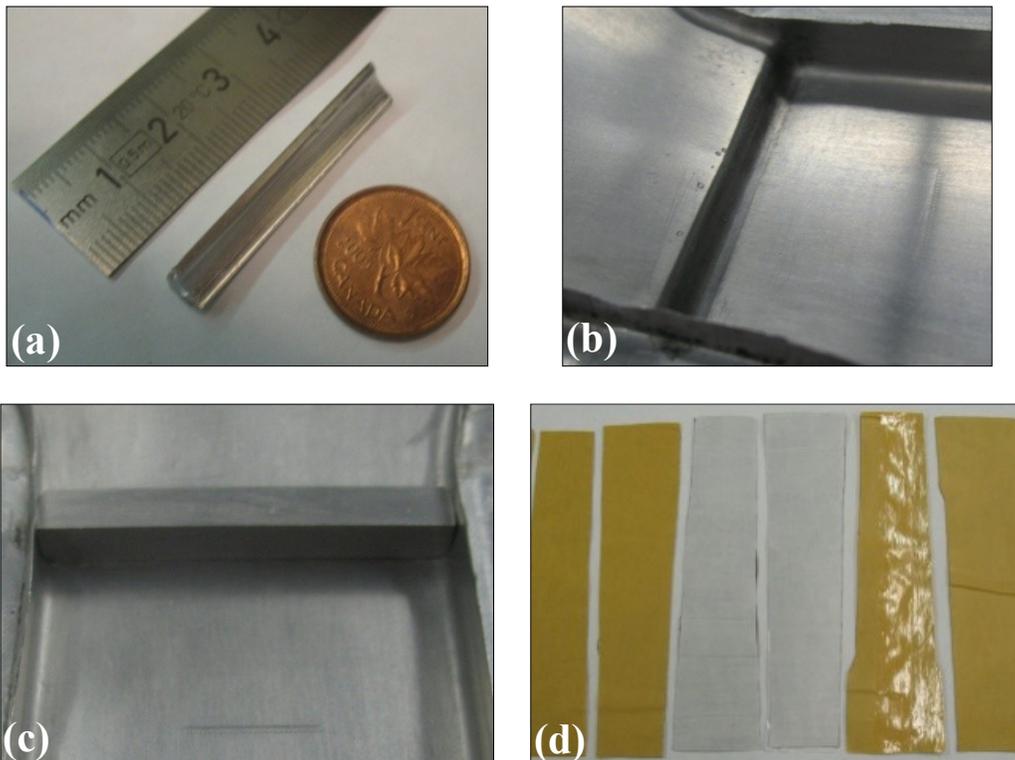


Figure 6-7: Mould insert developed for fingerboard preforms (a) insert after machining (b) mould without insert in place (c) mould with insert in place (d) preforms designed for use with insert

6.2 Cure cycle

The cure cycle that was selected was based on the recommendations of the prepreg manufacturer (Appendix C). The processing times that were provided were quite rapid but the actual curing time was much greater due to the large size of the mould.

6.2.1 Temperature lag

It was initially acknowledged that the large size of the aluminum mould would lead to a heating delay. To gain more insight into the thermal behavior of the mould, a thermocouple was placed inside of the empty mould and another was placed in the air of the oven while the whole setup was subjected to a cure cycle (Figure 6-8). The thermocouple was fed through the bladder sealing device and attached to the bottom of the cavity, where the greatest temperature lag would likely occur, to mimic the conditions of the mould during processing (Figure 6-8a).

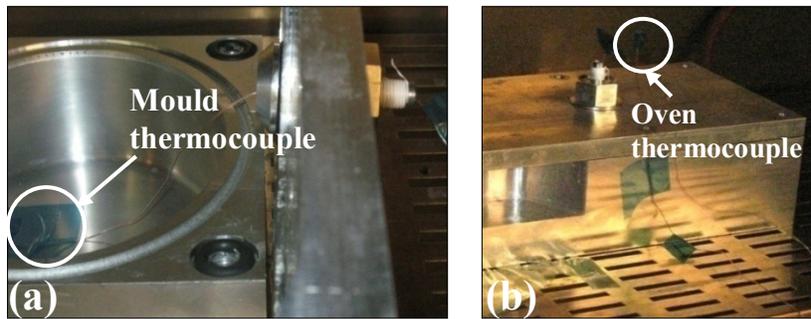


Figure 6-8: Thermocouple setup for mould heating study (a) position of mould thermocouple (b) position of oven thermocouple

The thermocouples were hooked up to a data acquisition system and a general cure cycle of ramps, holds and overshoots was run to simulate all possible features that could be added to the cure cycle (Figure 6-9). The heating and cooling rates were selected based on the specifications of the material.

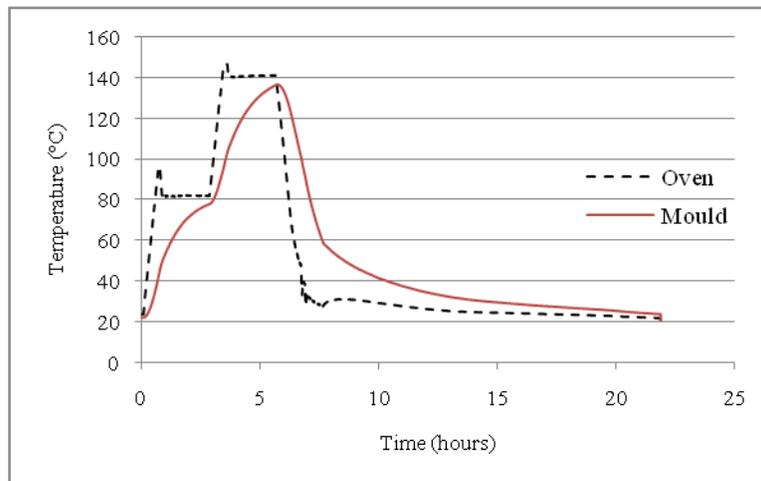


Figure 6-9: Thermal behavior of two-part closed mould and convection oven

The results showed that the internal mould temperature lagged dramatically behind the air temperature of the oven. It took the mould approximately an extra 2.5 hours to reach the initial hold of 80°C and a further extra 2.5 hours to reach the final cure temperature of 140°C. The overshoots proved to be a good method of reducing the time for the mould to reach the target temperatures. Based on this data, a better cure cycle was proposed for the prototype mould being heated in a convection oven (Figure 6-10).

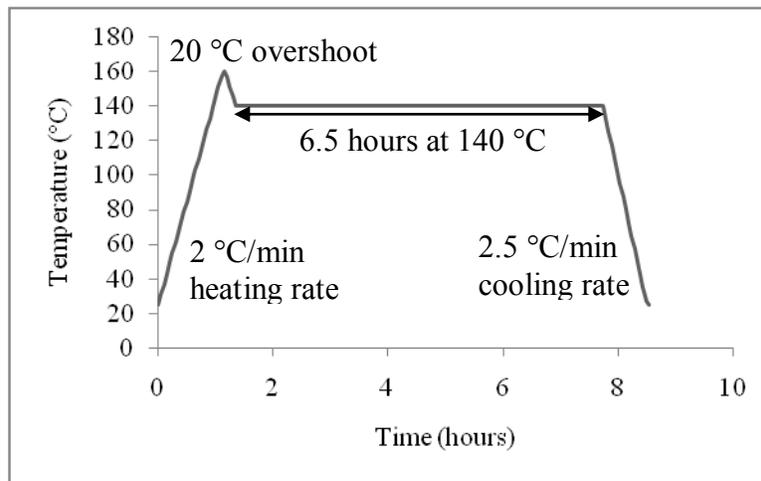


Figure 6-10: Cure cycle from mould heating study

6.3 Manufacturing process development

Developing the manufacturing process was a large part of this study. Several challenges had to be overcome during the manufacturing of the six prototypes. A couple techniques were developed along the way to improve the manufacturing process. The most significant developments were as follows:

- Tabs to bond two halves of the mould – As discussed in the Section 6.1.3 and Section 6.1.4, extra material was incorporated in the preforms to facilitate bonding of the two halves of the mould. For the neck and headstock, two large tabs were incorporated so that they could be folded over the cores (Figure 6-11a). A similar technique was used in the body section where small tabs were cut from the extra material (Figure 6-11c).

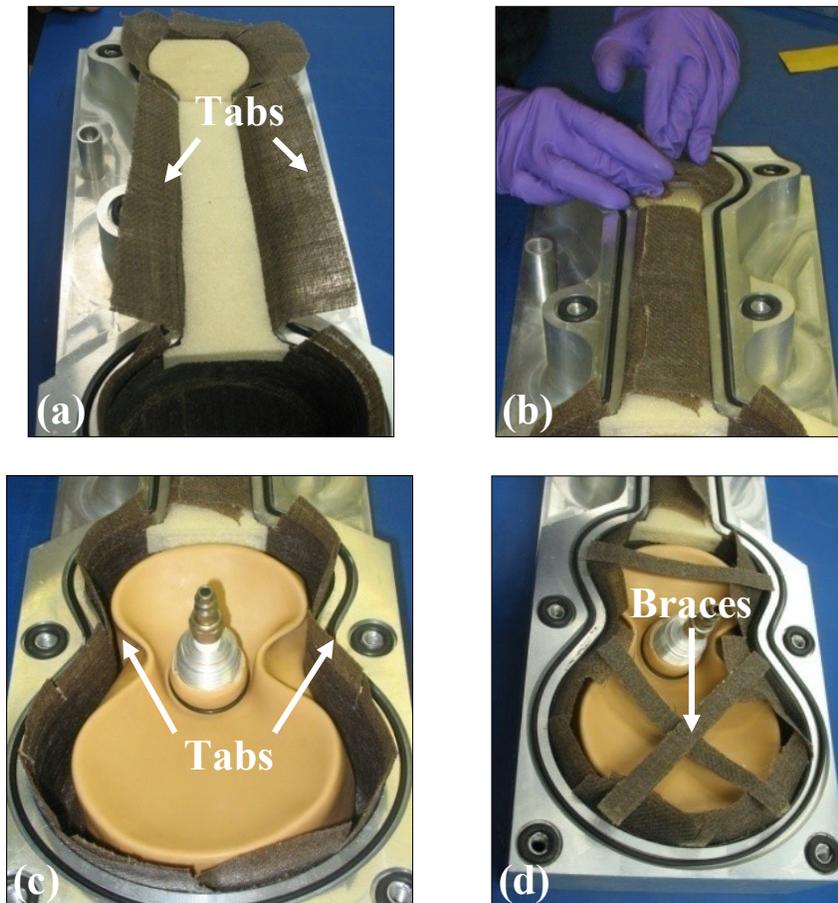


Figure 6-11: Bonding tabs and bracing installation (a) core insert with tabs (b) core tabs being folded (c) internal bladder tabs after being cut (d) attached bracing and bladder tabs

- Bracing – Based on the results of the finite element modeling, it was necessary to include braces in the soundboard to reduce the deflection. Braces are normally attached after the soundboard is manufactured but with this process it was possible to incorporate them directly into the layup (Figure 6-11d). The braces were bonded on the tabs in the main body and were made three woven layers thick with dimensions of 1.5 cm x 15 cm. One issue with including braces, is that they have a big effect on the resonant frequencies and mode shapes of the soundboard [10]. Due to time limitations, the effect of the bracing pattern on these parameters was not investigated.

Complete steps in the manufacturing process are presented in Appendix D. The process took two people approximately ten hours to complete including the time of cutting the preforms. With an automatic fibre cutting machine and some more improvements to the process, the total time could likely be reduced to less than four hours. This does not include the curing time, but taking that into consideration, the manufacturing time is still much less than a high quality wooden instrument which is normally around 40 to 60 hours [58].

6.4 Recurring defects

During the development of the manufacturing process, a few defects were found to be recurring and difficult to avoid. These defects generally occurred in the same areas with the most problematic area being the smaller radius of curvature of the sides of the instrument. In this region, two major types of defects could be observed; fibre bridging and resin rich regions (Figure 6-12).



Figure 6-12: Recurring defects on prototypes

6.4.1 Fibre bridging

From the first prototype, it was noticed that fibres had a tendency to “bridge” around the sides of the instrument. This was a result of the fibres having insufficient length to conform to the contour of the mould so they tended to skip from one point to another (Figure 6-13). Even with fairly high application of

pressure, this type of defect could not be overcome due to the relatively high stiffness of the flax fibres. The best way to minimize this type of defect was to take extra care when placing the fibres around the sides of the instrument to ensure there was sufficient length to follow the entire contour. By the final prototypes, this type of defect was no longer a serious problem.

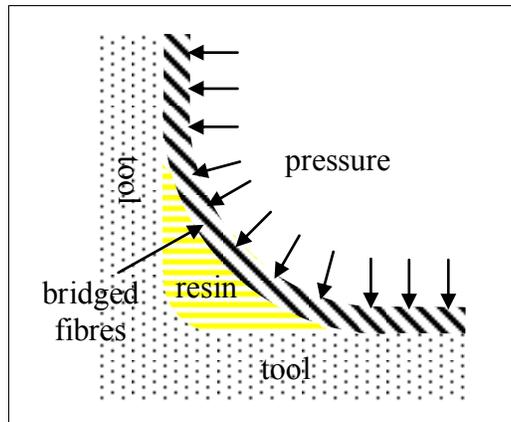


Figure 6-13: Illustration of fibre bridging

6.4.2 Resin rich regions

Resin rich regions are regions of composite parts that contain an excessive amount of resin. In this case, they seemed to be directly related to the fibre bridging as depicted in Figure 6-13. Sections of the mould where the fibres tended to bridge also tended to have an excessive region of resin. This type of defect was also a result of uneven pressure application. Early designs of the pressure bladder and core inserts did not apply even pressure throughout the part and as a result, sections that were under lower pressure had a tendency to build up greater amounts of resin. After the design of the inserts was modified, and sufficient care was taken during the layup, this type of defect was minimized.

7. Post Machining

After the parts were de-moulded there were still several components that needed to be installed. These components were the bridge, nut, fret, tuning machines and sound hole. It was initially desired to incorporate the latter three components directly into the mould but this proved to be unnecessary due to the added complexity.

7.1 Tuning machines

The tuning machines are the mechanisms that tighten the strings and are normally installed on the headstock of the instrument. For the prototypes, tuning machines were obtained from the luthier supplier Stewart Macdonald (product #0175). These machines required an installation diameter of $1\frac{1}{32}$ inches. To facilitate quick and accurate drilling of the holes a simple drill jig was manufactured (Figure 7-1a). This jig fit into place on the headstock of the instrument and acted as a guide for the drill bit. The holes were drilled using a brad point drill bit specially designed for drilling composites that led to very little delamination of the composite part.



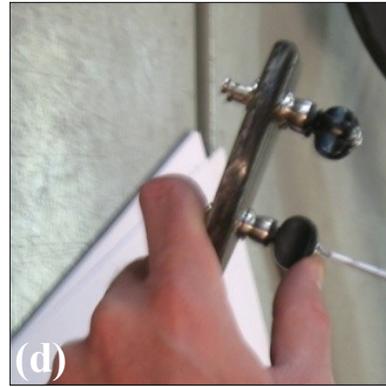


Figure 7-1: Installation of tuning machines (a) drill jig (b) holes being drilled on headstock (c) brass fittings (d) tuning machines being installed

Due to fact that the strings apply a force normal to the surface, and that the foam core provides very little stiffness in that direction, it was decided to reinforce this area with small metallic inserts. To make the inserts, a small brass pipe was cut into sections (Figure 7-1c) and then fit into the holes before the tuning machines were installed.

7.2 Sound hole

It is important that the diameter of the sound hole be cut properly so that the Helmholtz resonance is in the correct range and the low frequency response of the instrument is adequate. The diameter of the sound hole was calculated using Equation 2-4 where the volume was obtained from the CAD model. Based on the calculated diameter (4.72 cm), a trimming jig was machined so that the sound hole could be cut with a Dremel® tool. The trimming jig consisted of an eighth inch thick piece of sheet metal machined to the outer contour of the soundboard with the sound hole in the correct location (Figure 7-2a). This jig was aligned and clamped to the soundboard while the Dremel® tool machined of the excess material. Final trimming and sanding was required to smooth the edges of the sound hole.

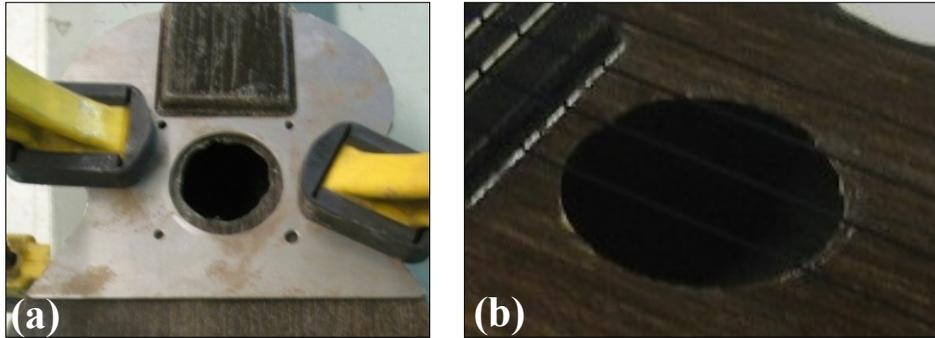


Figure 7-2: Post-machining jig for trimming sound hole (a) clamped sound hole jig
(b) trimmed sound hole

7.3 Fret installation

It was critical to accurately place the frets so that the final musical instrument functioned properly. Frets typically come in the form of a long wire from which small pieces are cut and installed. The frets have a barbed cross section that hold in place into very narrow grooves. The fret wire used in the prototypes was obtained from Stewart MacDonald (product #0764). This fret wire had an installation groove diameter of 0.58 mm (0.023 inch).

To accurately place the fret slots it is best to use a horizontal milling machine with correctly spaced saw blades. This is what is normally done in a production environment so that all the slots can be cut with one pass [59]. However, without access to such a machine, it was necessary to cut the grooves with a vertical CNC milling machine (Figure 7-3a).

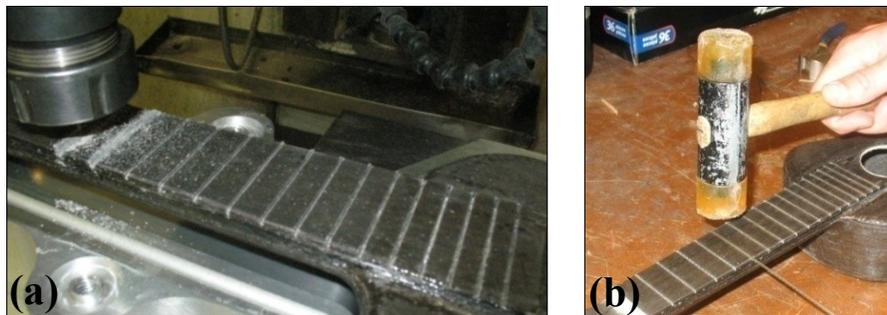


Figure 7-3: Installation of fret wire (a) CNC machining of slots (b) fret wire being hammered into place

As discussed in Section 2.3.2, the spacing of the frets for most western instruments is calculated based on the equal temperament scale. An online fret spacing calculator was used to determine the fret positions based on a scale length of 34.4 cm ($13\frac{9}{16}$ inches) [60] and the grooves were cut with a 0.58 mm diameter carbide end mill. Machining composite materials can be quite difficult but the flax based composite did not pose any serious problems being machined by small carbide end mills.

7.4 Bridge and nut

The final step was to place the bridge and nut of the musical instrument. It is critical that these components be placed properly since the fret spacing is calculated based on their positions. The nut was relatively easy to place after the addition of the mould insert which marked its placement. Luthiers commonly use wood glue to bond these components so that they can be removed if necessary with the application of heat. This glue is unfortunately not designed for bonding to composites so a quick setting five minute epoxy was used (MA-300). This adhesive worked well for the prototypes, but in production a type of glue that would allow for repairs should be used.

The bridge was placed using a paper template that was printed out from the CAD model (Figure 7-4). Special care was taken to make the sure the template was correctly aligned before the bridge was glued in place.



Figure 7-4: Template used for attaching the bridge

7.5 Finishing

It is common practice to finish commercial composite parts with paint or a lacquer after they are de-moulded. This finish does not normally lead to performance loss for most applications but for musical instrument it can have a negative influence on the sound quality. For this reason, instrument builders take pride in their finishing techniques and it was long thought the quality of Stradivarius violins were the result of a “secret formula” of varnish. This theory was, however, disproven after it was shown that the varnish was the same as that used by furniture makers of the time [61]. Another study performed by Ono *et al* investigated the effect of varnish on the acoustics of musical instrument soundboards. It was found that the application of varnish reduced the sound power level at low frequencies (<300Hz) and either increased or decreased it at high frequencies (>3 kHz) depending on the stiffness in the y-direction of the soundboard [62]. To finish the prototypes in this project, a traditional method known as “french polishing” was selected which involved applying several thin layers of shellac, a natural secretion of the lac bug, dissolved into denatured alcohol. A premixed shellac solution, Bullsye® Shellac, was obtained which dried in about twenty minutes so application of several layers was very efficient. The completed prototypes bore little resemblance to Sitka spruce but did have some similarity to rosewood and walnut (Figure 7-5).



Figure 7-5: Completed flax prototype

8. Final Evaluation

To conclude this study, it was appropriate to perform a sound quality evaluation of the final prototypes. It was decided to conduct blind listening tests with the help of volunteers. Three of the prototypes had all of the necessary components installed and were capable of being tested. Due to time limitations, a full analysis of the transient and frequency response was not performed.

8.1 Listening tests

Arguably the best test that can be performed to evaluate the quality of a stringed instrument is to listen to it. The human brain can detect small differences in sound that would be difficult to detect even with costly measurement equipment. With the help of twenty volunteers, a series of blind tests were conducted to compare the sound of the three completed prototypes with a high quality soprano ukulele made from Hawaiian Koa (Kamaka HF-1). In order to have an objective listening environment, the blind tests were conducted in a critical listening studio provided by the Center for Interdisciplinary Research in Music Media Technology (CIRMMT). To test the ukuleles, a major scale was played on each one and participants were asked to rate them from best to worst. The scale was played on both low and high strings of the instruments to evaluate how well they responded over a large frequency range. In total four instruments were tested; three of the prototypes and the Hawaiian Koa ukulele (Figure 8-1). The key differences in the soundboards of these instruments are summarized in Table 8-1.

Table 8-1: Summary of ukuleles that were subjected to the listening tests

	Soundboard material	Soundboard ply sequence	Core thickness (mm)
Hawaiian Koa	Hawaiian Koa	-	-
Flax-1	Flax/balsa/epoxy	$[0_u]_s$	2.5
Flax-2	Flax/balsa/epoxy	$[0_u / 0_w]_s$	2.5
Carbon fibre	Carbon fibre/epoxy	$[0_u / 0_w]_s$	0



Figure 8-1: Ukuleles that were subjected to listening tests

The only difference between the two flax prototypes was the soundboard ply sequence. Flax-1 was expected to perform better than Flax-2 since it met all of the Haines *et al* criteria. Flax-2 had two additional woven layers and as a result it exceeded the areal density limit. The carbon fibre prototype did not meet all the requirements either since it did not have a core material. This prototype was designed to be similar to composite instruments that were available on the market at the time of this study [63, 64]. The results of the blind tests are given in Figure 8-2.

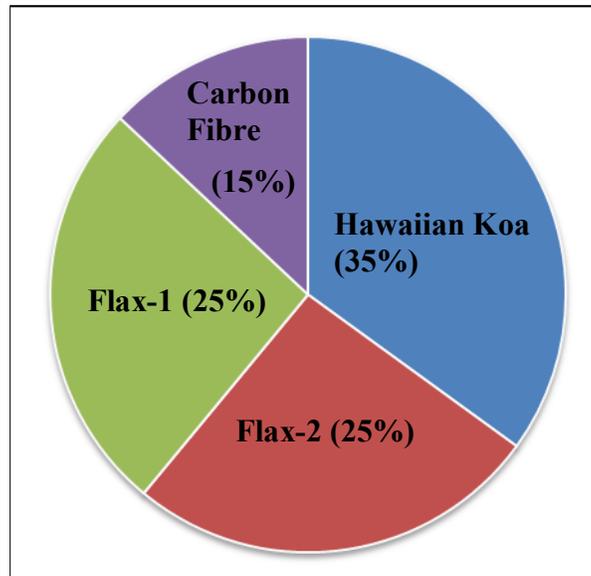


Figure 8-2: Results from blind listening tests

The results show that the Kamaka Hawaiian Koa ukulele was preferred by most listeners. Those listeners stated that it produced a louder sound and had a better response to lower frequencies on the musical scale. The flax ukulele was favored by some listeners who stated that it had a “more clear” sound compared to the wooden instrument. Unexpectedly, the two flax ukuleles performed the same even though Flax-2 had an inferior design. The main complaints about the flax prototypes were that they had a lower sound output and insufficient low frequency response. The damping was, however, comparable to the wooden instrument.

For the carbon fibre prototype, it was generally agreed that it had a very “thin” sound and that the damping was too high. Apart from those problems, it had a very high sound output which led some participants to favor it. If the carbon fibre soundboard had included a core material it is likely that it would have performed much better.

The results from the blind listening test suggest that there are still improvements that need to be made to the flax musical instrument before it can match the sound quality of a wooden one. The flax soundboard was preferred by some participants but the sound output level and low frequency response problems need to be addressed before it can match the sound quality of a wooden soundboard.

9. Conclusions

Due to the broad nature of this study, several conclusions can be drawn from the various stages. First, the initial material characterization indicated that a bio-composite sandwich structure based on flax and balsa wood could meet all of the Haines *et al* criteria for a soundboard substitute material. Based on the results of the material characterization, a hand layup manufacturing method in conjunction an internal pressure bladder and core was successfully developed and a total of six prototype ukuleles were made. Three of these prototypes were evaluated by blind listening tests and it was concluded that the bio-composite material had some potential to act as a soundboard but still did not produce the same sound quality as wood. This suggested that further work was needed to improve the properties of the substitute material.

9.1 Major contributions

A few major contributions were made during the course of this study that were primarily a result of its interdisciplinary nature:

- Innovative manufacturing process for stringed instruments - A start-to-finish manufacturing process was developed to produce repeatable composite stringed instruments in entirely one piece. At the time of this writing, no other stringed instruments could be found that were made in such a way from either wood or composite. It is possible that this type of structure has benefits for the acoustic properties of musical instruments.
- Mechanical characterization of flax/epoxy composite - Another important aspect of this research was the full characterization of a flax/epoxy composite. Both static and dynamic test methods were performed to see if the material could meet the criteria required for a soundboard material. It is hoped that the results of this characterization will assist future efforts in using this type of material in other applications.

- Dynamic testing - The use of dynamic testing was also an important contribution. Static testing methods are very common for characterizing composite materials but the use of dynamic testing to obtain the elastic properties is not nearly as common. The results of this study show that the mechanical properties of orthotropic materials can be readily obtained from these non-destructive test methods.

9.2 Future work

Due to the time limitations of this study there are several things that remain to be investigated:

- Evaluation of sound quality – The sound quality of the prototype was evaluated by simple listening tests but a more in depth analysis should be performed. Both the transient and frequency responses of the prototypes should be investigated to determine the cause of the problems that were observed during the listening tests.
- Manufacturing – There are more cost effective methods of manufacturing a composite stringed instrument. A resin infusion method such as resin-transfer moulding (RTM) should be explored in the future with a lower cost dry fabric. The manufacturing process could still incorporate the two-part mould and preform designs that were developed in this study.
- Application to other musical instruments – Focus in this study was placed on the suitability of this material to act as a stringed instrument soundboard. It could also have potential in other categories of musical instruments where higher density wood species are more desirable.

APPENDICES

Appendix A – Mechanical properties of various wood species

Soundboard wood species

Species	Density (kg/m ³)	Young's modulus (GPa)	Specific Modulus (Nm/kgx10 ⁻⁶)	Tensile Strength (MPa)	Degree of Anisotropy
Sitka Spruce	360	9.9	27.5	65.0	12.8
Engelmann Spruce	350	8.9	25.4	64.0	7.81
Douglas fir	480	13.4	28.0	85.4	14.7
Western red cedar	320	7.7	24.1	51.7	12.3
Redwood	400	9.2	23.0	69.0	11.5

[39]

Back plate wood species

Species	Density (kg/m ³)	Young's modulus (GPa)	Specific Modulus (Nm/kgx10 ⁻⁶)	Tensile Strength (MPa)	Degree of Anisotropy
Sugar maple	630	12.6	20.0	109	7.58
Brazilian rosewood	860	18.1	21.0	131	7.80
Black walnut	550	11.6	21.1	101	9.43
Honduras mahogany	450	9.70	21.6	79.3	9.35

[39], [22]

Appendix B – Mechanical properties of various natural fibres

	Fibre	Density (g/cm³)	Tensile strength (MPa)	Young's modulus (GPa)	Specific modulus (Nm/kgx10⁻⁶)	Price (Euro/kg)
Bast fibres	Flax	1.40-1.50	343-1035	27.80	19-53	2.29-11.47
	Jute	1.30-1.50	187-773	3-55	2-37	0.12-0.35
	Ramie	1.50	400-938	44-128	29-85	1.44-2.40
	Hemp	1.40-1.50	580-1110	3-90	2-60	0.57-1.73
	Kenaf	1.22-1.40	295-930	22-53	18-38	0.53-0.61
Leaf fibres	Banana	1.30-1.35	529-914	7.7-32.0	6-24	0.7-0.9
	Abaca	1.50	980	72	48.1	0.81-0.92
	Pineapple	1.52-1.56	170-1627	6.21-82	4-53	0.36-0.72
	Henequen	1.49	430-580	10.1-16.3	7-11	0.38-0.67
	Sisal	1.30-1.50	507-855	9.0-28.0	7-19	0.70-1.02
Non natural (for comparison only)	E-glass	2.50-2.55	2000-3500	73.0	29	1.25
	Aramide	1.40-1.45	3000-3150	63.0-67.0	45-48	7.2
	Carbon	1.40-1.75	4000	230.0-240.0	164-171	12.0

[31]

Appendix C – Recommended cure cycles for Lineo prepregs

Cure Temperature (°C)	Time (min)	Glass Transition Temperature (°C)
110	120	113-122
120	60	125-134
130	30	127-136
130	60	135-145
140	15	134-144
140	30	135-145
140	60	135-145
150	15	128-136
150	30	135-146

* For a heating rate of 2°C/min and cooling rate of 2.5°C/min

Appendix D – Manufacturing steps



a) Cut preforms



b) Apply release agent



c) Insert fingerboard



d) First soundboard layer



e) Balsa core



f) Final soundboard layers



g) First side layer



h) Remaining first layers



i) Woven layers



j) Back plate balsa core



k) Remaining layers



l) Insert foam cores



m) Prepare bladder



n) Cut body tabs



o) Fold neck and headstock tabs



p) Attach tabs and braces



q) Assemble mould



r) Air pressure and cure



s) De-mould



t) Post-machine and finish

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