Naturally Gnarly:
The all-natural surfboard.

BREE 495 Final Report

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Executive Summary

As an alternative for the use of synthetic materials in the production of fiber-reinforced composite structures, it has been proposed to use flax fibers and soy-based epoxies in applications where they are suitable. The proposed design within this report is to build a surfboard using a non-woven, needle-punched flax mat produced by the Composites Innovation Center as a source of fiber-reinforcement. This fiber has been used in combination with a commercially available soy-based epoxy called Ecopoxy®. The goal is to demonstrate the viability of using such materials as a cost-competitive, structurally appropriate and environmentally friendly lamination material.

In order to complete the surfboard design, multiple core material options were explored. Since cores are generally made of synthetic plastic foams, it was in our interest to research other available options that fit within our goals. Three naturally-derived materials were suggested for our design: Ecocradle™, foam grown via processes using fungal mycelium to degrade agricultural waste, balsa wood, which has been proven as a high performance material for cores in marine applications, and lastly corrugated cardboard, which is readily available at no cost and has the potential for structural applications. After thoroughly considering our options, corrugated cardboard was chosen to be the most suited to our needs.

The design was thus based on the materials defined above. The core design consisted of combining multiple strips of cardboard, aligned vertically, into a solid core that could then be shaped to our needs. The core could then be laminated using the flax fiber/Ecopoxy® laminate. As far as specific design with regards to shape, we decided to limit our scope to a generic design. In this way, it was possible to focus more on the proof of concept rather than surfing performance, which could not cover in this report.

Before conducting a structural analysis, we were required to determine the mechanical properties of the materials chosen. Testing was performed using the Instron Universal Testing Machine, allowing us to produce the tests required for our analysis. Tensile, compressive and flexural tests were used on sample specimens and average properties were computed. The materials showed strengths as expected and seemed appropriate.

Using the properties determine during testing, a structural analysis of our design was performed based on compression, bending and impacts due to surfing and handling. Assumptions were made to account for unknown loading during the dynamic processes in surfing. Based on our assumptions, the analysis performed showed that the materials would perform adequately for our purpose.

In order to complete our design process, we had to address the issue of construction methods. Based on our choice of materials, a method of construction was proposed for the core and for the lamination. The core would be built by gluing strips of cardboard together using carpenter’s glue and shaped with a power planer. The lamination would be performed through the use of hand lay-up and vacuum-bagging. In order to validate these methods and further test our design, a prototype was constructed. The prototype construction showed flaws in our methods and design, largely due to ineffective core construction and incompatibility between the cardboard core and the laminate.

Cost, biodegradability and overall environmental effects were also considered. Since the design needs to be revised, the cost is not relevant at this time. Biodegradability of the laminate is assumed to be very low, but proper testing should be performed to validate or refute this claim. The environmental impacts of producing the design are expected to be much lower than conventional surfboards.

In the end, it has been shown that flax fibers and soy-based epoxies have a strong potential for use in structural applications. However, it is necessary to apply them to designs that cater to their properties and allow them to perform competitively with other synthetic options. Technological advancements and increased availability of materials will be required for this to happen.

Introduction

In our previous work, it was shown that flax fiber mats, in combination with soy-based epoxies, have the potential to replace more conventionally used synthetic fibers and epoxies in mid-strength laminate applications [1]. The goal is to reduce the dependence on petroleum-derived products, which have high energy requirements, are not renewable, and are not easily degraded. As a proof of concept, it was decided that the flax mat and soy epoxy (Ecopoxy®) would be used as the laminate in the design of an all-natural surfboard. Preliminary calculations using values obtained from literature showed that these materials were suitable candidates for our design. The goal of this paper is thus to complete the design of the surfboard and conduct an in depth structural analysis in order to either accept or reject our claims. The design of a surfboard requires us to address the issue of choosing an appropriate core material. This will be done in the following section. Once the core material of choice has been selected we can decide upon a suitable design for the board. Also addressed within the report is the issue of construction feasibility. In order to properly assess this issue, a prototype was built using methods which we have proposed and outlined in the report.

The Core

The surfboard design generally follows the concept of a sandwich structure, which incorporates high strength face sheets with a lightweight, lower-strength core material. The structure can thus be compared to an I-beam, with the faces playing the role of the flanges. The role of the core is thus to support the faces with regards to the loads that they do not resist[2]. For the application to a surfboard, the required properties for the core are good resistance to compression, adequate strength in bending and light weight. Furthermore, it is our desire to use a material that is natural, renewable and cheap. The aim is thus to create a product that is functional and has reduced environmental impacts as compared to conventional surfboards, all while avoiding becoming cost-prohibitive.

Most commonly surfboard cores or blanks are made of a certain type of stiff and light plastic foam such as polystyrene. It is therefore appropriate to search for a material which has comparable properties.

Ecocradle™

The first material considered is a type of foam that is created using fungal mycelium to digest agricultural residue. Ecocradle™ has been shown to have ideal properties for our purpose, including comparable mechanical properties to synthetic foams, good moisture resistance, light weight and good biodegradability. It also has been estimated to require ten times less energy to produce compared to synthetic foams[1]. Our contact at Ecovative Design has however informed us that the product is not yet available in the size required. Furthermore, the foam is apparently not easily shaped using sanding equipment and thus would need to be grown in a mold to the desired shape for the surfboard. This would no doubt increase the cost. This option can therefore not be pursued at this time. We would however like to keep it in mind since it would be an ideal candidate if the production could be catered to our needs. Our contact has informed us that they are looking to prototype boogie boards in the coming months so it is possible that they may be able to fulfill our needs sooner than later. Regardless, we will consider other options at this point in time.

Balsa Wood

Balsa wood is very well established as a core material in many different applications. It has very good mechanical properties and is easy to work with. Its downfalls with respect to our application are its weight and cost. Balsa has higher density than foams, meaning that building a core entirely out of balsa would produce a very heavy board. In order to compensate, it was proposed that a more complex design incorporating balsa into a bulkhead system could be a potential solution. However, further inquiries into the price of balsa demonstrated that our cost would become prohibitively high. It was therefore decided that another option should be considered before settling on such an expensive material.

Corrugated Cardboard

The last core material option we considered was corrugated cardboard. Widely used in packaging, it is proven as a lightweight structural material. Whether or not its mechanical properties are adequate for our purpose is difficult to determine since information on its properties are not readily available in technical literature. Regardless of its obvious downfalls with respect to moisture absorption and uncertainty over strength, it is a very interesting option for us since it is available for free and means that we would be re-using a waste material. We have therefore decided to complete our design and conduct our analysis based on the use of corrugated cardboard as the core.

The Design

Having chosen corrugated cardboard as the core material, we are required to create an appropriate core design. First, we should further discuss the properties of the material. Corrugated cardboard is essentially a sandwich structure in itself, with two face sheets covering a layer of fluted corrugation, as can be seen in figure 1.

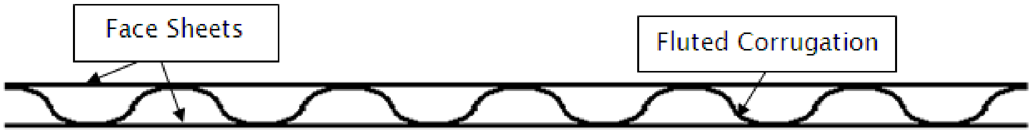


Figure 1: Corrugated Cardboard

In general, loads are applied in the direction of the normal vector of the face planes (vertically in figure 1), leading to stresses on the faces which must resist the bending, while the corrugation offers some resistance to compression. It thus seems that the cardboard should be aligned in such a manner that the faces will resist the bending stresses applied to the surfboard. However, as mentioned before, the core's main purpose is to resist compression of the board rather than bending. We therefore decided to consider in which direction the corrugated cardboard was strongest in compression. Basic observations showed that the highest resistance in compression came from the plane in which the corrugation is visible (into the page in figure 1). From now on this plane will be referred to as the corrugation plane. It was therefore decided that the cardboard should be cut into strips and aligned with the corrugation plane's normal vector in the vertical direction. Furthermore, it was decided that the strips would be aligned along the board's long axis. Carpenter's glue was chosen as the only suitable method of bonding the strips together.

The next aspect of the design that needs to be considered is shape. While the shape of a surfboard is critical to its performance, we will not be considering it in terms of optimal performance, but rather as a proof concept. We will simply be choosing a generic surfboard shape in order to demonstrate that cardboard can in fact be used in our chosen configuration and be tailored to a desired shape. This issue will be addressed further in the construction methods section.

Once shaped, the core will be covered with a single layer of flax/Ecopoxy™ laminate. An appropriate method of application will be required in order to ensure proper wetting of the fibres and lamination to the core. The laminate application method will be addressed in the construction methods section. This is a critical aspect of the design since we are unsure of how it will affect the structural integrity of the corrugated cardboard.

Materials Testing

Before conducting a structural analysis, we need to have proper knowledge of the properties of the materials being considered. Since the materials we have chosen have not yet been used together in structural applications, we are required to perform appropriate testing in order to determine the properties of interest for our design. Since we are considering the board as a sandwich structure, the two parts that need to be tested are the laminate and the core.

Materials and Methods

Flax/Ecopoxy® Laminate

The materials being considered are the flax mat and Ecopoxy® epoxy resin and hardener. The flax mat is the CIC10-F500 non-woven mat obtained from the

Composites Innovation Center (CIC). Specific information regarding the mat can be obtained directly from the CIC. The epoxy system used is Ecopoxy® resin and medium hardener. Any information on the product can be obtained from www.ecopoxysystems.com.

Comment [GC1]: Cite this institution.

The most important properties of the laminate are its tensile strength and modulus of elasticity. It was therefore decided that a tensile test would be necessary in order to perform the structural analysis. Furthermore, since other design options might be considered in the future, any other properties could be valuable. It was therefore decided to perform a three-point bending test on laminate specimens.

Tensile Test

The Instron Universal Testing Machine (IUTS) model no. 4502 was used to perform tensile tests on three different samples of laminate. The samples were made by fully wetting three small sample of fiber mat and compressing them under vacuum. Each sample of fiber mat was initially cut to approximately 10cm by 2.5cm. Once laminated, the samples were bottlenecked using a dremel to a width of approximately 1cm and a bottleneck length of approximately 5cm. Each individual sample was precisely measured and the average values for each dimension recorded. Dimensions are presented in Table 1.

Three-Point Bending Test

The IUTS was once again used to perform a three-point bending test on three laminate specimens. Samples 1 and 2 were as in the tensile test, whereas sample 3 was created using 2 layers of flax fiber. This would allow us to see if the properties of the laminate changed substantially with increased thickness. There was no need to create a bottleneck in the samples. Average dimensions (width and thickness) of each sample were measured and are presented in Table 1.

Table 1: Laminate sample dimensions

Laminate	Tensile Test			Three-Point Bending Test	
Sample	Width	Thickness	Bottleneck length	Width	Thickness
1	12.7	2.2	23.5	14.9	2.1
2	13.6	2.39	24.3	14.6	1.9
3	11.5	2.43	24.9	14.8	3.8
				All dimensions in mm	

Corrugated Cardboard

The corrugated cardboard was procured from a local bike shop. It has a thickness of 5mm and approximately 100 flutes per meter. The properties that must be determined for the cardboard are its compression strength and its flexural strength. Both a compression test and three-point bending test were performed.

Compression Test

Using the IUTS, compression tests were performed on two samples of corrugated cardboard. The samples were produced in the same fashion as the core of the board. For each sample, three small strips of cardboard were cut and glued together using carpenter’s glue. The samples were of approximately 15cm length, 1.5cm width and 1.0cm thickness. Dimensions for the samples are presented in Table 2. The compression test was performed by applying the load normal to the corrugation plane (as described in The Design) using a 15mm diameter platen.

Three-Point Bending Test

The three-point bending test for cardboard was performed in exactly the same manner as the test on the laminate. The samples were made as in the compression test. Dimensions are once again presented in Table 2. The load was applied normal to the corrugation plane.

Table 2: Cardboard sample dimensions

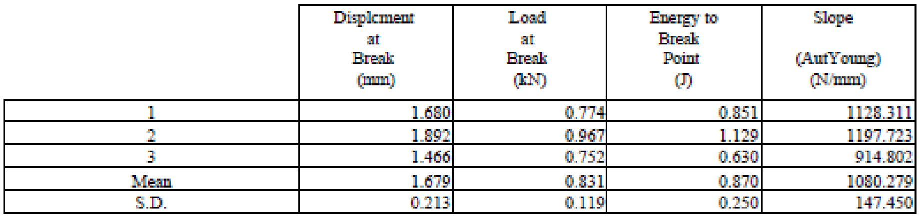
Corrugated Cardboard	Compression Test		Three-Point Bending Test	
Sample	Width	Thickness	Width	Thickness
1	15.1	10.1	15.0	9.9
2	15.0	10.3	15.1	10.0
			All dimensions in mm	

Results and Discussion

Laminate Tensile Strength

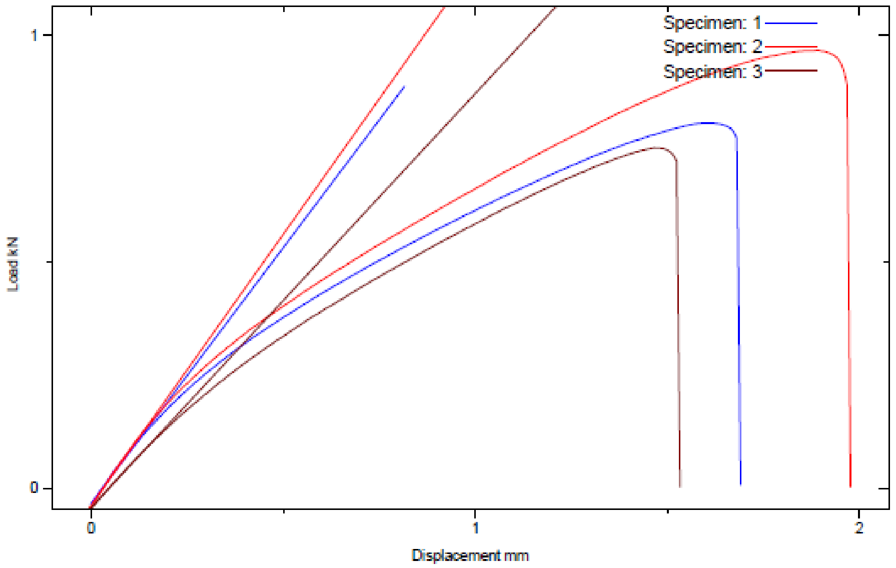
The results of the tensile test on the laminate are presented in Table 3 and Figure 1.

Table 3: Laminate tensile test results



	Displcment at Break (mm)	Load at Break (kN)	Energy to Break Point (J)	Slope (AutYoung) (N/mm)
1	1.680	0.774	0.851	1128.311
2	1.892	0.967	1.129	1197.723
3	1.466	0.752	0.630	914.802
Mean	1.679	0.831	0.870	1080.279
S.D.	0.213	0.119	0.250	147.450

Figure 2: Laminate tensile test



In order for these results to be useful to us, we need to convert the break loads to stresses and convert the slope to the modulus of elasticity. A sample calculation for specimen 1is as follows:

$$Tensile\ Strength = (Load\ at\ Break)/(Cross\text{-}sectional\ Area)$$
$$Tensile\ Strength\ =\ 0.774\ kN/(12.7mm * 2.2mm)$$
$$Tensile\ Strength =\ 27.7\ MPa$$

Complications arise when we consider the modulus of elasticity. It was apparent during the experiment that a certain amount of slip occurred at the beginning as the clamps dug into the sample. This slip would thus be recorded as a displacement or elongation of the sample and lead to a shallower slope than would otherwise be produced. Keeping this in mind, the modulus of elasticity is calculated as follows:

$$\boldsymbol{Modulus\ of\ Elasticity\ =\ Stress/Strain}$$
$$E\ =\ Slope(N/mm)\ *\ Initial\ Gage\ Length/Cross-sectional\ Area$$
$$E\ =\ 1128.3\ N/mm\ *\ 23.5mm/(12.7mm*2.2mm)$$
$$E = 0.949\ GPa$$

The calculated values are presented below:

Table 4: Laminate tensile properties

	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
1	27.70	0.949
2	29.75	0.895
3	26.91	0.815
Mean	28.12	0.887

The values for tensile strength are very close to those assumed in our previous work and will likely be sufficient for withstanding the applied stresses. As for the modulus of elasticity, the values are smaller than expected. However, this is likely due to the slip that was observed during the experiment. The actual modulus of elasticity is no doubt much higher than our experimental values. Finally, it is important to note that we have only considered the ultimate strength of the laminate and not the yield strength. Because of the shape of the plot produced during our experiment it is difficult to determine the yield strength. This will be taken into account during the structural analysis.

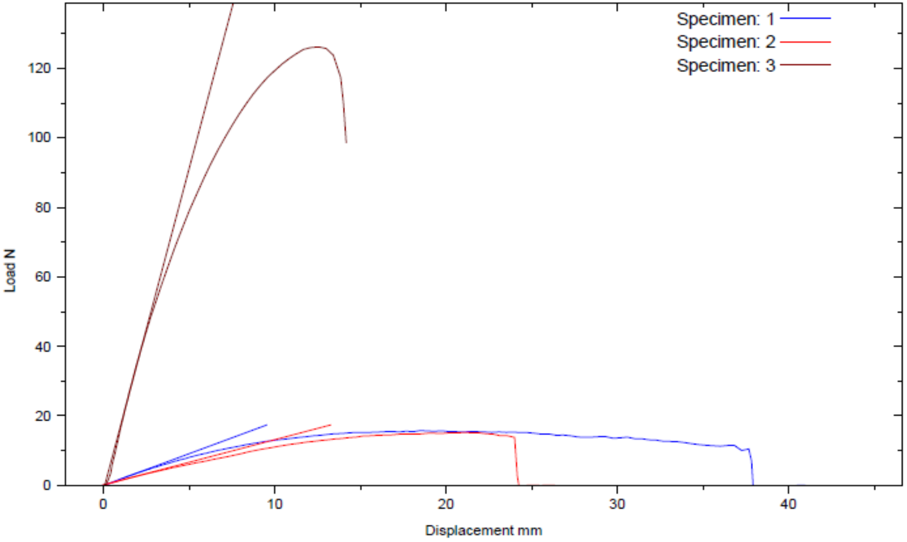
Laminate Flexure

The results of the three-point bending test on the laminate are presented in Table 5 and Figure 2.

Table 5: Laminate flexural test results

	Displcment at Max.Load (mm)	Load at Max.Load (N)	Slope (AutYoung) (N/mm)	Energy to Break Point (J)
1	18.510	15.810	1.824	0.468
2	21.100	15.270	1.300	0.257
3	12.490	126.200	18.482	1.041
Mean	17.367	52.427	7.202	0.589
S.D.	4.417	63.890	9.772	0.406

Figure 3: Laminate flexural test



It is important to note that the laminates never failed during the experiment. After a substantial deflection, the samples began to slip between the supports. The flexural strength of the laminate has therefore not been calculated. The flexural modulus is calculated as follows:

$$Ef = \frac{L^3 * m}{4bd^3}$$ [1]

Comment [GC2]: Complete, formal citation please.

Where,

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[1] Equations used for determining material properties were obtained from W. Callister's "Materials science and engineering: an introduction"

- L is the length between supports (70.0mm)
- m is the initial slope of the load-displacement curve (N/mm)
- b is the width (mm)
- d is the thickness (mm)

This gives us the following flexural modulus values (Figure 3):

Comment [GC3]: Shouldn't this be Table 6?

Figure 4: Laminate flexural modulus

	Flexural Modulus (GPa)
1	1.133
2	1.113
3	1.952
Mean	1.399

We see that the flexural modulus for specimen 3 is much larger than the other two samples. We believe that specimen 3 offered a more realistic measurement of the modulus since it experienced less slip. The measured deflection in specimen 3 was therefore due more to actual bending of the sample rather than slip. It is likely however that the true modulus is higher than this measured value. Since flexural modulus and the modulus of elasticity are usually very similar, it is apparent that the values obtained during the tensile test are much too small [3].

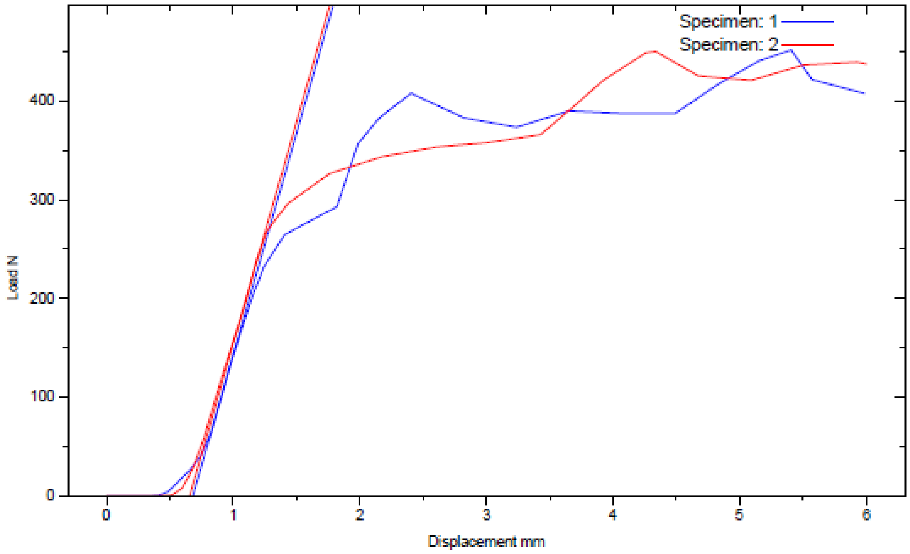
Cardboard Compression Strength

Results of the cardboard compression test are as follows:

Table 6: Cardboard compression test results

	Displcment at Max.Load (mm)	Load at Max.Load (N)	Slope (AutYoung) (N/mm)	Energy to Break Point (J)
1	5.375	452.300	448.679	1.711
2	4.325	450.100	448.940	1.700
Mean	4.850	451.200	448.809	1.706
S.D.	0.742	1.556	0.184	0.008

Figure 5: Cardboard compression test



As can be seen from Table 6 and Figure 4, the results were very consistent between the two tests. Considering the experiment was conducted without any obvious error, we believe that the values obtained are accurate. Since yielding occurred long before the maximum load was applied, we must consider the point where the cardboard yielded in order to determine its strength. From Figure 4, it is apparent that the samples yielded at slightly above the 200N load. As a conservative estimate of the cardboard's strength we will assume yield strength at the 200N load. Given the 15mm diameter platen, we find the yield strength as follows:

$$\boldsymbol{Sy = Load\ at\ yield / Area\ of\ load\ application}$$

$$Sy = \frac{200N}{\frac{\pi * D^2}{4}}$$

$$Sy = 1.13\ MPa$$

Along with a suitable safety factor, this yield strength will be necessary to determine whether or not the proposed design will be able to withstand the compression forces applied.

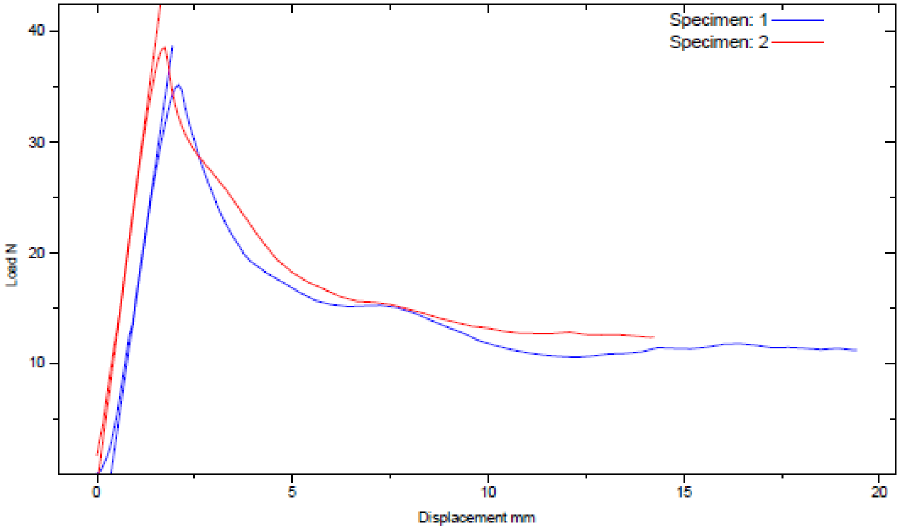
Cardboard flexure

The flexural tests on the corrugated cardboard samples gave the following results (Table 7 and Figure 5):

Table 7: Cardboard flexural test results

	Displcment at Max.Load (mm)	Load at Max.Load (N)	Slope (AutYoung) (N/mm)	Energy to Break Point (J)
1	2.073	35.210	24.564	0.247
2	1.743	38.580	26.923	0.197
Mean	1.908	36.895	25.744	0.222
S.D.	0.233	2.383	1.668	0.035

Figure 6: Cardboard flexural test



As opposed to the three-point bending tests performed on the laminate, the flexural tests on the cardboard did not encounter the issue of slipping between the supports. Furthermore, the samples did indeed fail in bending and thus the maximum load is indicative of the ultimate strength of the cardboard in bending. Again, the results are relatively consistent between the sample specimens. Given the similar dimensions of the specimens, it seems likely that the flexural strength and modulus will be relatively accurate. The flexural strength and modulus are calculated using the following equations:

$$Sf = \frac{3FL}{2bd^2} \qquad Ef = \frac{L^3 * m}{4bd^3}$$

Where,

- F is the load at failure
- m is the slope of the load-deflection curve (mm)
- L is the length between supports (70.0mm)
- b is the width (mm)
- d is the thickness (mm)

We thus find the following properties for cardboard:

Table 8: Cardboard flexural properties

	Flexural Strength (MPa)	Flexural Modulus (GPa)
1	2.51	0.145
2	2.68	0.153
Mean	2.60	0.149

Since flexural modulus and modulus of elasticity are generally very similar, we will be using the mean value from Table 8 as our modulus of elasticity for cardboard in the structural analysis [3]. Ideally we would perform tensile tests on cardboard specimens, but because of the corrugated cardboard's structure, such a test would be difficult to perform since the cardboard would shear at the clamping interface. Since actual tensile strength for the cardboard is thus unknown, appropriate assumptions will have to be made during the structural analysis.

Structural Analysis

A structural analysis for the surfboard is aimed at determining whether or not the board will be able to withstand the various loads applied to it throughout its lifetime. Handling, transportation and surfing all lead to different stresses on the board. Of course, the most significant loads that must be considered are attributed with the surfing itself. It is difficult to analyze the dynamic forces involved with surfing. The effects due to breaking waves and carving cannot be easily determined. We will therefore have to perform a static analysis and make appropriate assumptions to account for the dynamic forces. On the other hand, the most important loads we attribute to handling and transportation will be random impacts.

That being said, we must now create a model which we will be able to use in order to properly analyze the board. The mechanical properties of a sandwich structure can be difficult to accurately determine theoretically since they not only depend on the individual properties of the core and face sheets but also on the interaction between the two. As mentioned above, the face sheets take most of the load to prevent bending, while the core resists shear forces and compression. The laminate will also help protect the core from impact loads and helps disperse point loads over a larger area. The difficulties arise when one considers the strength of the bond between the face sheets and the core. If this bond is not strong enough, the structure risks delaminating, ultimately leading to failure. Regardless, we will be conducting an analysis which assumes ideal lamination in order to determine if the individual materials are appropriate. The use of conservative assumptions would account for weaknesses in the lamination. It will however be necessary to conduct appropriate testing of the prototype in order to confirm or reject our results.

Compression

The first load that we will consider in this analysis is compression. The board must be able to withstand the load of its user without compressing beyond the elastic range. Resistance to compression comes mainly from the core, which has the largest potential for substantial deflection. However, the interaction between the laminate and the board would mean that the load applied to the laminate will be spread over a larger area when applied to the core. Furthermore, since the laminate provides a certain amount of flexural resistance, it will aid the core in resisting compression.

Methods, Results and Discussion

We will assume that the design stress on the core will be the weight of the user divided by the area of his/her feet in contact with the board. While this does not explicitly include any safety factors, we believe it is safe to assume that this stress is suitable given the reasons stated above. Assuming a user weight of 1000N (~100kg) and area of application of 120cm^2 (assumed area of heal and toe box in contact with board), we find a compressive stress of:

$$\sigma_C = 1000N/120cm^2 = 0.083\ MPa$$

Comparing this value with the compressive yield strength of 1.13 MPa gives us a safety factor of 13. Considering the other factors mentioned above that will aid in resisting compression, it becomes clear that compression of the board will not be a problem. This will also allow for more leeway in instances where impact loads are applied.

Bending

Bending in the board must be limited in order to maintain proper lamination and avoid failure. As mentioned earlier, most of the load in bending must be absorbed by the laminate since the core is relatively much weaker. As a simplification for the board's structure, let's consider a sandwich beam and the stresses applied to the laminate and core. The maximum stresses experienced in bending are as follows:

$$\text{For the laminate, } \sigma = \pm\frac{M\left(\frac{h}{2}\right)(E_1)}{(E_1I_1+E_2I_2)}$$ [2]

Comment [GC4]: Proper citation

$$\text{For the Core, } \sigma = \pm\frac{M\left(\frac{h(core)}{2}\right)(E_2)}{(E_1I_1+E_2I_2)}$$

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[2] All equations used in the structural analysis were taken or derived from James M Gere's "Mechanics of Materials"

Where,

-M is the bending moment,
-h is the thickness of the surfboard,
-h(core) is the thickness of the core,
-E_1 is the modulus of elasticity of the laminate,
-E_2 is the modulus of elasticity of the core,
-I_1 is the moment on inertia of the laminate and
-I_2 is the moment of inertia of the core.

If we consider the two equations, we see that the only differences between the stress on the laminate and the stress on the core are due to the differences in height and modulus of elasticity. It is evident from these equations that the stress on the core will be minimized if the ratio of E_1:E_2 is high. Since there were errors in the experimentation while performing the tensile test on the laminate, there is a lack of concrete knowledge of its modulus of elasticity. The mean value of 0.9GPa is much lower than expected, and values for the flexural modulus show that the actual modulus of elasticity must be larger than measured. For the purpose of our calculations, we believe it safe to assume a modulus of elasticity of 3 GPa, which is still much lower than the value assumed in our previous work (6.4 GPa), which had been measured using a combination of flax fiber and synthetic epoxy[4]. The flexural modulus of cardboard, which we are assuming to be the same as the modulus of elasticity, is 0.15 GPa, which gives a very large ratio, E_1:E_2, of 20. This will likely allow for the laminate to absorb most of the load in bending.

Methods, Results and Discussion

We now must consider the loads that the board will need to withstand. First, we must consider the weight of the user. The surfer either is lying on the board to paddle away from shore or catch a wave, in the process of standing up, or erect on the board with only the feet in contact. The maximum stresses will occur when the user is standing because the loads are more localized, causing larger bending moments. Next we need to consider the force exerted on the board by the water. Simplified, this force can be seen as an evenly distributed load over the bottom of the board. However, there are instances when the board will only be partially in contact with water. The uncertainties over where loads will be applied and in what combinations make it difficult to analyze this situation without making improper assumptions and either over-designing or under-designing. Previously, we had considered the board being supported at both ends with the entire weight of the user in the center. It is our belief that designing for such a scenario leads to unnecessarily large required strengths. Instead, we will consider the following schematic which we believe is more indicative of the maximum applied stresses.

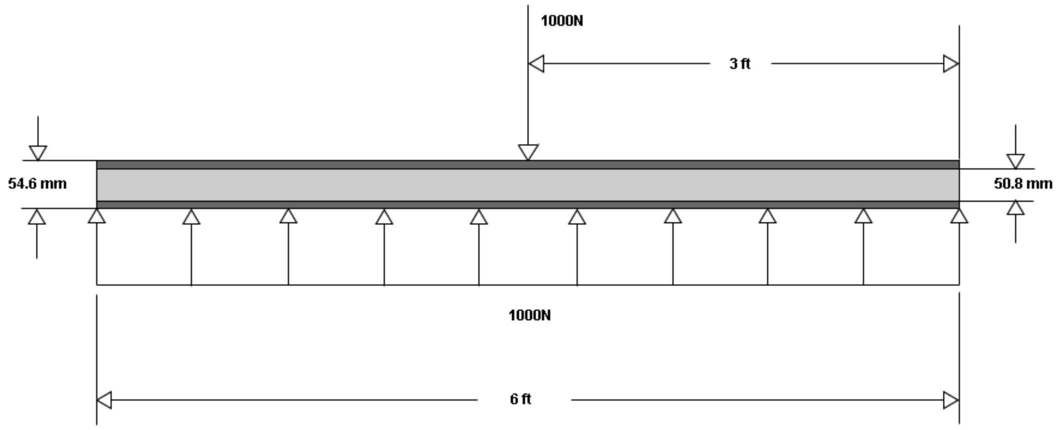

Figure 7: Beam schematic

The schematic shows a concentrated load at the center of the beam, supported by a uniformly distributed load across the bottom. Because the curvature of the board is minimal and the load is concentrated in the center, the board can be approximated as a rectangular prism, or a simple beam. The design strength of the materials will be based on the maximum bending moment in the beam and an appropriate safety factor.

We therefore need to determine the maximum bending moment in the beam. In order to perform the analysis more easily, we will flip the figure upside down and only consider one half of the beam. We now have a cantilever beam with a uniformly distributed load, $\omega = 500N/3ft$ (Figure 7).

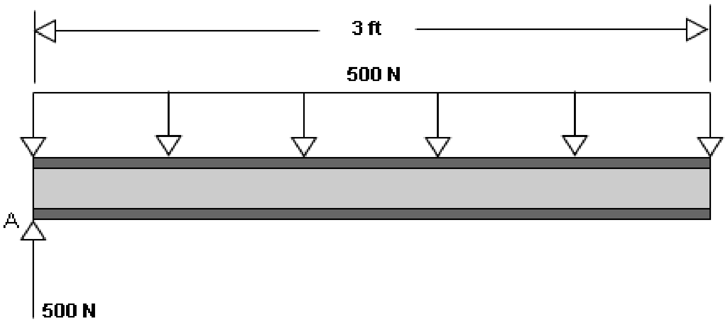

Figure 8: Cantilever beam loading

The internal moment, M_i, in the beam caused by ω can be calculated using the sum of the moments around point A. Since the board is in static equilibrium with no rotational movement, $\Sigma M_A = 0$. Taking the convention of counter-clockwise positive moments, we find:

$$\sum M_A = M_i - \omega(L/2) * (L/2)/2 = 0 \ , \qquad L = 6\text{ft}$$

$$M_i = \omega * L^2/8$$

$$M_i = (500\text{N}/3\text{ft}) * (3\text{ft})^2/8$$

$$M_i = 228.6 \text{ N*m}$$

Since we have only considered one half of the beam, we must multiply M_i by two in order to find the maximum internal moment on the beam.

$$M_{max} = 457.2 \text{ N*m}$$

Using this maximum moment value we can now determine the stresses on the laminate and core. However, we must first calculate the moments of inertia for both components.

$$I_1 = \frac{b}{12}\left(h^3 - h^3(\text{core})\right) \quad [2]$$

$$I_2 = \frac{b}{12}(h^3)(\text{core})$$

b is the length of the beam (6ft = 1830 mm)

- h is the thickness of the beam (54.6 mm) [3]
- h(core) is the thickness of the core (50.8 mm)

$$I_1 = 5.28 * 10^6 \text{ mm}^4$$

$$I_2 = 21.85 * 10^6 \text{ mm}^4$$

We now find the maximum stress in the laminate and core using the following equations:

$$\sigma(\text{laminate}) = \pm \frac{M\left(\frac{h}{2}\right)(E_1)}{(E_1 I_1 + E_2 I_2)}$$

$$\sigma(\text{core}) = \pm \frac{M\left(\frac{h(\text{core})}{2}\right)(E_2)}{(E_1 I_1 + E_2 I_2)}$$

- E_1 is assumed to be 3 GPa
- E_2 is assumed to be 0.15 GPa

$$\sigma(\text{laminate}) = \pm 1.96 \text{ MPa}$$

$$\sigma(\text{core}) = \pm 0.091 \text{ MPa}$$

Given the scenario we have chosen to analyze, these are the maximum stresses that will be applied to the laminate and core. We must reiterate that the uncertainties regarding the loads applied during surfing make the significance of these values difficult to assess. We do not know with certainty that these stresses offer close approximations to the real

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[3] Beam thickness of 54.6mm is based on 2 inch (50.8mm) core thickness and 1.9mm laminate thickness as produced during testing.

situation. For this reason, it is necessary to include large safety factors. Especially considering the low cost of our materials, which will be addressed later, the issue of over-designing becomes relatively void.

Let’s compare the calculated stresses with the material properties. First looking at the laminate, we had measured an ultimate tensile strength of 28 MPa. Comparing to the maximum stress of 1.96 MPa gives a safety factor of ~14. Ideally we would compare the stress to the material’s yield strength, but that value could not be calculated. It can be assumed that the yield strength is no smaller than half the ultimate strength, which would give a safety factor of 7. This seems like a suitable factor for this application given the number of unknowns. As for the cardboard, we do not have a value for the tensile strength. However, the maximum stress of 0.091 MPa is very small and will likely not be enough to cause the core to fail. It is not possible at this time to determine with certainty how this core will perform under the conditions to which it will be exposed. Testing of a prototype will lead to the most significant conclusions.

Impacts

The impacts due to handling and transportation must be considered in order to substantiate the claims we have made with respect to the use of our materials in the application to a surfboard. We cannot quantify such loads since they are entirely user-dependent. It is however necessary for the board to be able to withstand moderately large impacts without causing laminate failure or core compression. As mentioned in our analysis of core compression, we have seen that the corrugated cardboard is able to withstand substantial compressive stress. Impact loads would be much larger than the loads considered in our compressive analysis, but given the computed safety factor of 13, which we believed to be conservative, it does not seem as though normal use[4] impacts would have detrimental effects on the core. As for the effects to the laminate, it may have been useful to perform an impact hardness test, but since we do not have specific load values with which to compare, it was deemed unnecessary. Rather, it was decided that a simple qualitative assessment of the board's resistance to impacts would be performed. Using the prototype, an array of normal use impacts were simulated, from dropping on the floor to hitting a wall. Observations showed no visible damage to the laminate or board's structure. It is possible that microscopic damage may have occurred, but it is not within our means to analyze this possibility more thoroughly. Based on our observations, it is our firm belief that the materials would perform as necessary under normal use conditions. More pronounced impacts should be avoided in order to preserve the integrity of the board and need not be fully accounted for in the design.

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[4] By 'normal use', we mean the board being carried and handled with relative care avoiding large impacts.

Construction Methods

In order to legitimize the design proposed, it is necessary to address the issue of construction. While we have shown that the materials are suitable for use based on our theoretical design, such a design is void unless it can be shown that its construction is both possible and feasible. The construction process outlined below is divided into two parts: the core and the lamination.

Core Construction and Shaping

The cardboard used came from a local bike shop in the form of large boxes. The following steps were followed in the construction of the board.

1. A first strip of cardboard was cut according to the desired curvature of the board. The strip was approximately 1.5 inch wide at the ends and 2.5 inches wide at the center, and just over 6 ft long (Figure 6). This first section of cardboard was then used as a template for the rest of the core. The dimensions were slightly larger than needed for the actual core to account for sanding.

Figure 9: Cardboard template

2. Further strips of cardboard were cut to the shape of the template until there were enough for the entire board.

Figure 10: Finished cardboard blank

3. Strips were glued together using carpenter's glue, giving rise to a rough blank of the board.
4. Once the glue was properly dried, the blank was shaped using a power planer and random orbital sander. This produced the finished blank core, ready to be laminated (Figure 7).

Lamination

Figure 11: Flax fiber mat

Applying the laminate to the board is the aspect of the construction process which worried us most from the beginning. After first seeing the flax fiber mat, it became evident that typical hand lay-up would not be possible because of the thickness of the mat (Figure 8). We required a method to ensure full and uniform wetting of the fibers while compressing the laminate to an appropriate thickness. After researching various laminate construction processes, it was decided that hand lay-up, followed by vacuum-assisted compression (also called vacuum-bagging) would be most suitable for this application. In vacuum-bagging, the laminate is placed inside a sealed plastic bag in which a vacuum is created. Under vacuum, the negative pressure produced within the bag causes its contents to be compressed by the atmosphere. The maximum pressure that can be applied to the contents of the bag is thus 1 atm. [5]. Since we had determined that the compression strength of the core is 1.13 MPa, it was assumed that it would be able to withstand the applied pressure of 1 atm. (101.3 KPa). In order for this to be possible, we were required to build our own vacuum-bagging set-up by purchasing an appropriate pump, tubing and vacuum bag. The system as pictured below consisted of a vacuum pump, a differential pressure switch, and a reservoir(Figure 11): Vacuum bag system. The 120V pump, typically used for refrigeration maintenance had the capacity to pull near full vacuum. The differential pressure switch was built using a syringe, spring and a doorbell button. The syringe is attached to the vacuum system and the plunger could be extended using a certain amount of spring preload. The spring preload was set to meet a certain plunger position and thus a certain pressure. As the negative pressure dropped off, the plunger would extend further outwards, triggering the button which would restart the pump. The reservoir was simply to provide a greater buffer between pump run times. The system also contained a VOC filter, which was not necessary due to Ecopoxy®'s non VOC cure. However, when filled with activated charcoal, the filter would strip the air of VOC's which is critical to ensuring the longevity of the pump.

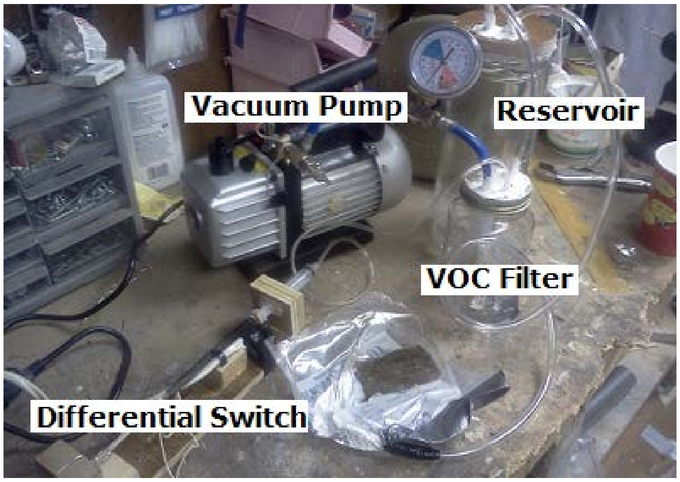

Figure 12: Vacuum bag system

Once the system was built and tested on small laminate samples, the following procedure was followed for laminating the board:

1. The vacuum film was spread out such that when the core was placed on it, the film could be folded over and sealed with sealant.
2. The flax cloth was then cut to the shape of the board and wetted out in epoxy.
3. The wet laminate was then placed on top of the core, carefully ensuring its proper alignment.
4. The vacuum film was then folded over, sealed, and the vacuum line was attached.
5. The pump was then started and pulled the desired pressure. With a proper seal, the pump would only have to run for thirty seconds or so every five

minutes. The process took approximately 2 hours until the epoxy was cured enough to remove it from the vacuum bag.

6. The process was repeated for the bottom laminate.

Figure 13: Board under vacuum

Other steps required to complete the board where:

1. Laminate 2 layers of flax, for the fin[5]. Shape the fin and attach it to the board.
2. Sand and fair the entire board.
3. Coat the board in epoxy as a sealer coat.

Discussion

The construction process outlined above proved to be less than ideal. This is mostly due to the use of cardboard as the core material. The cutting of multiple strips of cardboard and subsequent gluing was extremely time-consuming and inefficient. Such a method would not be practical on a larger scale. Furthermore, the shaping of

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[5] The fin was not considered within the report, but was included in the prototype as a necessary part of the surfboard.

cardboard was difficult because of the way it would quickly deteriorate while using the power planer. Creating a blank with an appropriate uniform shape was not easily achievable using our methods. Using the same procedure is thus discouraged in future projects. More precise methods of creating surfboard cores out of cardboard should be explored. Some extremely complex cardboard core configurations are already being produced using computer software [6].

The complications in the construction process also apply to the lamination methods. While vacuum-bagging was an appropriate method of creating a uniform laminate of suitable thickness, an unexpected drawback occurred while applying the process to the board itself. Since the vacuum is produced everywhere within the bag, the sides of the core were also subject to the atmospheric pressure applied, causing it to slightly cave in along the edges and compromise the board’s core structure. This issue was avoided by initially laminating the edges by simple hand lay-up and only applying a partial vacuum within the bag, thus applying less pressure. This is however not ideal since it does not optimize the thickness of the laminate. Also, rather than removing excess resin from the structure, the vacuum-bagging simply made the resin flow into the cardboard, making it heavier and potentially weakening it. It thus seems evident that while both corrugated cardboard and the flax/Ecopoxy™ laminate can be used for the respective, they are not ideal in combination with each other for construction purposes. Other options should be explored and are discussed below.

Further Considerations

Cost

The cost of producing the surfboard is not easily addressed. The current design must be revised and thus the costs of a final, more appropriate design cannot be determined at this time. Since we acquired the flax mat for free and have no knowledge of the price of such a product on the current market, we are not able to determine the cost associated with that aspect of our design. Cardboard can generally be obtained for free as a waste material and thus has no effect on the overall cost of the surfboard. Approximately 100$ worth of Ecopoxy® was used to produce the prototype, an amount that could potentially be reduced with an optimized process. The rest of material cost is attributed to the vacuum-bagging system. The cost of the pump was 75$ and the rest of the materials added up to approximately 25$. This gave us a total monetary cost of 200$. Since the pump can continue to be used, the actual cost of the prototype was actually only 125$. Finally, we must consider the labor required to produce the board, which was a large downfall of our design. The core construction methods previously outlined required many hours to produce and were inefficient. A new design and complementary construction process should be considered in order to create a more labor-effective product.

Biodegradability

One of the important aspects of our concept was initially to create a product which can be readily degraded in the environment. It is apparent that the soy-based epoxy, once hardened, would be quite resilient to degradation. Appropriate biodegradation tests should be performed on test samples in order to determine the potential for natural degradation. At this time we have no basis upon which to validate any claims of biodegradability. As for the cardboard, studies have shown that paper based products, including cardboard, can biodegrade at a relatively good rate[7]. This depends on the treatments applied to the material. Since we used basic cardboard that was not plasticized, we can assume that it is biodegradable.

Environmental Impact

While a full life cycle assessment is not within the scope of this report, we believe it important to note the potential for reduced environmental impacts using the materials applied in our design. The production of flax fiber can be less energy intensive and more sustainable that the production of its synthetic counterparts. Furthermore, the use of a renewable resource rather than a largely contested resource such as oil is inherently beneficial, and is a large focus of our concept. The same can be said of the use of Ecopoxy® rather than synthetic epoxies. The handling of Ecopoxy® also has beneficial aspects health-wise due to the reduced exposure to known carcinogens and volatile organic compounds. Lastly, the use of cardboard is ideal in terms of environmental impact since we are re-using a waste material that would otherwise be meant for the recycling system or the dump. Direct re-use of waste materials is much more energy efficient than recycling and should be sought out wherever possible.

Prototype Testing

A most unfortunate event occurred soon after the completion of the prototype. A miscommunication involving one the team member's siblings led to the disposal of the prototype (it was thrown away). It is not possible at this time to produce a second prototype since we do not have the materials at hand and lack time. Physical testing of the prototype has thus been put on hold. For reasons outline within this report, a second prototype would be built following a more refined design using different material combinations. For interest's sake, the pursuit of such an option may become a reality if the opportunity arises.

Conclusion and Recommendations

The goal set-out through this design was first and foremost to explore the potential for the use of naturally-derived materials for the creation of laminates. Based on the performance of the flax fiber mat and Ecopoxy® laminate in testing and through its application to our proposed design, we believe that such materials can in fact be very useful. While the application to our specific design was not ideal, mainly due to the use of cardboard as core material, it seems possible that such a laminate could perform if applied to a more suitable design. It will be interesting to keep in touch with the producers of the EcoCradle™ mushroom foam as their product would likely cover all of our needs for appropriate strength, weight, environmental impacts and compatibility with the vacuum-bagging process.

It is not recommended to use such a laminate in applications where extreme high strength and light weight are necessary. The strength of the laminate was shown to be reasonably high, but does not compare to high-performance products using carbon fibers. Although the density of the laminate is not very large, its inherent thickness due to the flax mat limits weight reduction and thus cannot be made as light as its synthetic counterparts. Such issues can in part be addressed with increased research and technology.

Pre-preg flax mats, consisting of a thin layer of woven flax fibers impregnated with epoxy and kept at a cold temperature to stop the epoxy from hardening, are already being produced and are available on the market for uses such as the design we have proposed[8]. This technology allows for the use of flax fiber to produce very thin laminates which are more suitable to a wider array of applications. In the case of our design, pre-preg would allow for simple hand lay-up to be performed without need for vacuum bagging, thus making it possible to use cardboard without worrying about effects on the core. However, as mentioned previously, more precise methods of creating surfboard blanks out of cardboard would have to be explored in order to validate its use. The cost associated with such technologies is however quite high. Furthermore, since they are not currently being produced using naturally-derived epoxies, pre-preg flax mats do not meet our needs in developing entirely organic laminates.

After having worked with the materials ourselves and conducting further research into the use of naturally derived laminates, we believe that the potential for their application is considerable and should be exploited. The environmental benefits in themselves build a strong argument for the use of such materials, especially given the widespread issues related to the production and disposal of synthetic materials.

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References

[1] M. Brodeur*, et al.*, "Design of a novel, all-natural composite surfboard," Report submitted for the course BREE 490 Engineering Design II. Bioresource Engineering Department of McGill University, Ste-Anne de Bellevue, Qc. 2010.

[2] J. Gere, *Mechanics of Materials*. Toronto: Thomson, 2006.

[3] J. Ilic, "Relationship among the dynamic and static elastic properties of air-dry Eucalyptus delegatensis R. Baker," *European Journal of Wood and Wood Products,* vol. 59, pp. 169-175, 2001.

[4] M. Alcock and S. Boyko, "Flax Fiber Mat Assessment " Composites Innovation Center. 2007.

[5] B. Alcock*, et al.*, "The mechanical properties of woven tape all-polypropylene composites," *Composites Part A: Applied Science and Manufacturing,* vol. 38, pp. 147-161, 2007.

[6] M. Sheldrake. April 5th, 2011). *Cardboard Surfboards*. Available: http://www.sheldrake.net/cardboards/

[7] A. Yabannavar and R. Bartha, "Biodegradability of some food packaging materials in soil," *Soil Biology and Biochemistry,* vol. 25, pp. 1469-1475, 1993.

[8] B. van Voorn*, et al.*, "Natural fibre reinforced sheet moulding compound," *Composites Part A: Applied Science and Manufacturing,* vol. 32, pp. 1271-1279, 2001.