Fibrous Boundaries: 'Green' Composites in Architectural Applications

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Figure 1. Green composite FiberWall made from sisal / linen fiber and soy resin

INTRODUCTION

Fiber-Reinforced Composites

Fiber reinforced plastics or composites have been commonly used for a variety of structural applications because of their high specific strength and modulus compared to conventional metals. Initially developed for aerospace structures, these high performance 'advanced' composites are now found in applications from automotive parts to circuit boards and from specialty sporting goods to appliances. While composites have excellent mechanical properties they suffer from two distinct disadvantages. First, most composites currently available in the market made using polymers or resins such as epoxies, polyimides, and polyurethanes and high strength fibers such as graphite, aramids and glass, are designed with long term durability in mind. Most of these polymers and fibers are derived from petroleum, a non-sustainable commodity. By some estimates current petroleum reserves are expected to last only 50-60 years at most. While we are consuming petroleum at the rate of 100,000 times the earth can create it, roughly 1 million barrels per day are used for making composites. Second, most of these fibers and resins do not degrade for several decades under normal environmental conditions.[1] Composites are made using two dissimilar materials and are difficult to reshape or recycle. This is particularly true for the most common composites that use thermoset resins such as epoxies. Hence they can rarely be reused. Currently there is an effort to grind them into powder and use as filler or to incinerate the resin to obtain the fibers. A small fraction of composites are also incenerated fully to obtain energy in the form of heat. However, most of them (over 94%) end up in landfills at the end of their life, along with other plastics.[2] In 2003, 27 million metric tons of plastic waste including composites was dumped into U.S. landfills. In the anaerobic conditions of the landfills these composites may not degrade for several decades or even centuries, making that land unavailable for any other use. On other hand, incineration produces toxic gases and requires expensive scrubbers to contain pollution. Both incineration and landfilling are not environment-friendly. Further, these methods are expected to get expensive as the pollution laws all over the world get stricter and the number of landfills decline.

The push now is to use composites for applications in civil and architectural structures. Although it has been a slow process, fiber reinforced polymeric composites are increasingly being preferred for structural applications by designers, architects and engineers because of their combination of high strength and low weight which increases the design capabilities and aesthetics. Further, their use reduces material consumption, structural weight, transportation costs, insulation requirements while increasing the energy efficiency. Some buildings already use composites bars in place of conventional steel rebars to make the structures more earthquake resistant. Many old bridges are also being retrofitted with carbon fiber/epoxy resin composites to strengthen them and extend their life. Current technology also allows building all-composite bridges that could be installed in very short time. Such applications are bound to increase the use of composites significantly in terms of the tonnage used and will make their disposal even more difficult, exacerbating the existing ecological and environmental problems.

To alleviate these problems created by plastics and composites, governments in many countries have established laws to encourage the use of recycled and/or bio-based 'green' products.[3] Some governments have enforced strict 'take back' laws where the manufacturers must take their packaging and products back when discarded after their intended use. The growing global environmental awareness, societal concerns, high rate of depletion of petroleum resources, concept of sustainability and new environmental regulations have triggered the search for new products and processes that are compatible with environment. Sustainability, 'cradle-to-cradle' design, industrial ecology, eco-efficiency and 'green' chemistry are not just the newly coined buzz words but form the new principles that guide the development of new generation of 'Green' materials.[2] Composite materials are no exception to this new paradigm. In fact, most major manufacturers have plans to make their products 'green' or recyclable to the maximum extent possible and are working vigorously toward that goal. Undoubtedly, environment-friendly, fully biodegradable reinforced plastics or 'green' composite materials will play a major role in greening of the products in the future.

'Greener' Composites

Use of biodegradable, environment-friendly and yearly renewable plant-based wood and 'cellulosic' fibers have been a natural choice for reinforcing (or filling) polymers (plastics) to make them 'greener'. Availability of wood waste and inexpensive plant-based fibers in every part of the world has, in part, fueled their use in the past few years. While the wood powder (saw dust) is an inexpensive waste product, the fibers offer several advantages as well. They are non-abrasive to processing equipment, can be incinerated, CO2 neutral (when burned) and because of their hollow and cellular nature perform well as acoustic and thermal insulators.[4] The hollow tubular structure also reduces their bulk density making them light weight.

Plenty of examples can be found where plant-based fibers are used for reinforcing non-degradable thermoplastic polymers such as polypropylene (PP), high, medium and low density polyethylenes (HDPE, MDPE, LDPE), nylons, polyvinylchloride (PVC) and polyesters to produce what may be termed 'greener' composites.[5-10] Bulk of the plant-based fiber composites, however, are made using wood flour, a waste from saw mills, or wood fiber, obtained from waste wood products such as packaging pallets, old furniture and construction wood scraps, as an inexpensive filler for PP and PVC.[11] Commonly used engineered wood products such as particle board, plywood, medium density fiber board (MDF) contain formaldehyde (an EPA named probable carcinogen) based resin. Since these so called 'greener' composites combine non-degradable resins with degradable fibers, at the end of life they can neither return to an industrial metabolism nor to a natural metabolism. They only get downcycled because of the property degradation in reprocessing.

Longer plant-based fibers such as abaca, bamboo, banana, flax, henquen, hemp, jute, kenaf, pineapple, ramie, sisal etc. with good mechanical properties are being used as low cost alternative reinforcements to commonly used glass fibers, to make composites. These fibers, obtained from the plant stems or leaves, are yearly renewable as compared to wood, which takes 20-25 years to grow before it can be cut and used (e.g. housing studs). As a result, the supply of these fibers could be virtually endless. While these fibers may not be as strong or stiff as graphite or Kevlar® fibers used in advanced composites, on 'per weight' basis flax, jute, bamboo and hemp fibers have higher modulus (stiffness) than E-glass fibers and ramie fibers have excellent stiffness. The hollow tubular (cellular) structure of these cellulosic fibers also provides better insulation against noise and heat in applications such as automotive door/ceiling panels and panel separating the engine and the passenger compartments, compared to glass. They may be easily used as panels in housing construction replacing particle board, plywood, MDF, etc.

Fully Green Composites

Significant research efforts are currently being spent in developing a new class of fully biodegradable 'Green' composites by combining natural fibers with biodegradable resins including those based on soy protein.[11-24] Being in its infancy, most of the current technology is still in the research and development stage. However, some products have trickled down, and a few companies have begun producing them on a commercial scale. These composites are environment-friendly, fully degradable and sustainable, i.e. they are truly 'green' in every way. At the end of their life they can be easily disposed of or composted without harming the environment, completing the nature's intended carbon cycle. While most of these green composites may be effectively used in many applications such as mass produced consumer products with short life cycles of 1-2 years (non-durable), many of them may also be used in indoor applications, with long life of many years, just as wood. For example, they may be used in housing as replacement for wood, plywood, particle boards, MDF or even gypsum boards, for walls, ceiling. Further, the properties of these composites can be engineered to requirements.

Since these composites may be made using conventional molding technique, walls, ceilings, etc. may be hot pressed to desired shape. Further, their properties in different directions can be engineered by using fibers in various forms (woven fabrics, knitted fabrics, nonwovens and yarns) and creating a layered structure. Where needed, they can also have corrugated structure with noise and heat insulating foams incorporated within the corrugations. Thus, prefabricated buildings can be constructed using light weight panels and erected in very short times and hold great promise for mass customization. Finally, fully green composites show great potential to create buildings that are inexpensive, healthy and less strenuous on the environment.

Several green composites have been made using soy protein based resins and a variety of natural fibers[12-20] with properties comparable to wood or better. While wood properties cannot be changed, green composite properties could be engineered depending on the application. These can be used to make any articles including furniture, sporting goods that currently use plywood, particle board, MDF or wood. Panels made of these composites can also be used in architectural applications as discussed later.

Advanced Green Composites

While most of the research up to date has been based on using plant based fibers because of their ready availability, there are significant opportunities to produce high strength green composites or 'Advanced Green Composites'. In fact, such advanced green composites have already been achieved using liquid crystalline (LC) cellulose fibers and soy protein based resins.[25] The LC cellulose fibers used in this study had strength of about 1700 MPa. The advanced green composites which contained only 44% fibers by wt. had strength of over 600 MPa compared to just over 1100 MPa for Kevlar® fiber based composites. The estimated strength of advanced green composites with fiber volume of 65%, most common in composites, was estimated to be over 900 MPa, close to high strength steel. However, the high strength steel has a density of about 9 g/cc whereas the advanced green composites have a density of about 1.4 g/cc. This makes the advanced green composites about 6 times as strong as the high strength steel on per wt basis. The toughness of the advanced green composites was, in fact, about 30% higher than the Kevlar® based composites.

The advanced green composites have significant potential for use in housing construction; particularly in green building construction. Significant opportunities exist to build composites with even better properties using multi-axis CNC fiber placement robot as shown in the image in Figure 2. Precise fiber placement, where needed, and tubular construction would reduce the composite weight significantly while obtaining the desired properties. In addition, the laser and/or infrared curing could be employed during fabrication, reducing the manufacturing time and cost. This fabrication technique also allows to incorporating wired or wireless sensors including strain gauges, piezoelectric transducers, fiber optic sensors, and micro-fiber composite actuators in the composites to detect damage, monitor structural integrity and obtain advanced warning in case of catastrophic failures, making the structures smart.

Figure 2. Fiber placement robot for airplane

Green FiberCabin Design

As the buildings go 'green' and LEED certified, architects, designers and engineers will turn more and more towards greener materials for secondary and even primary structural components. At present there are many things happening in research and in the future, as novel technologies emerge architects, designers and engineers to take note.

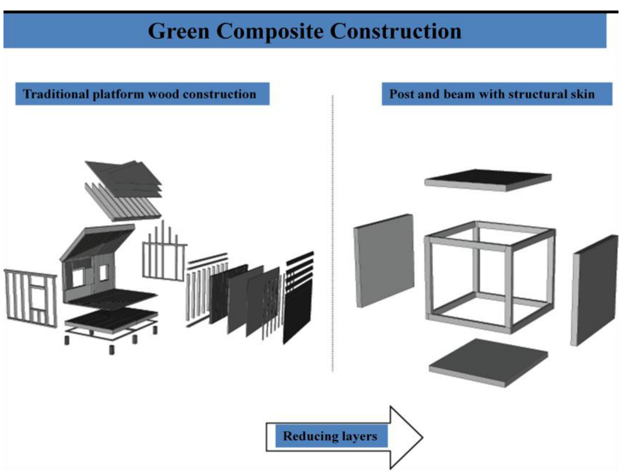


Figure 3. Traditional and new construction technique

This paper discusses a green FiberCabin construction that incorporates medium strength molded green composites for walls and roofing and advanced green composites for structural elements. We also introduce a new concept termed 'Fiber Wall' which is an indoor self-standing wall that uses membrane like composite panels put together in 3-D arrangement that not only can control light, sound and wind but also provide the opportunity for the designers to create surface expressions. As designed the use of green composites can reduce the layers of traditional building assembly. Figure 3 presents a comparison of traditional and the new ways of construction using composites. In the case of traditional wood construction, there are up to 7 layers of material, all having their own functions. They are assembled chronologically, on site and require a costly and time consuming assembly. The green composite cabin, on the other hand, can be built using only three layers. The cabin frame shown in Figure 3 is constructed using the advanced green composites. Whereas the walls are molded to desired shape using green composites made using natural fibers/fabrics. The composite fabrication process using soy protein based resin, and natural fiber mats and hot pressing using molds to obtain desired shape is shown in Figure 4. The top left is the fiber (sisal, kenaf, jute, hemp, etc.) mat, the center is soy protein and the right is the resin being poured onto the mat. Once the mat is fully impregnated with the resin it can be semi dried, put in between the mold (center left) and hot pressed (center) for the required length of time to obtain molded part (center left). The bottom three pictures show the digital mold (left), CNC milling (center) and the final mold (right).

The structural system of panels is now a sandwich panel with two flanges and a core. The flanges can be made with desired 3-D pattern as shown in Figure 5 a. The middle structural core is manipulated to have added surfaces so that interfacial bonding is possible between the core and the flanges. This core may also be made using advanced green composite to improve structural integrity and provide damage-resistant stiff and strong element. Typical structural combinations are shown in Figure 5 b. The sandwich elements are part of a system of panels that can be bonded or bolted together in a variation of combinations. The undulating 3-D pattern gives a myriad of surfaces of different angles that serves as bonding surfaces with the middle core, thus creating a very stiff and strong element. The elements can be folded around its perimeter to enclose its cavities. The sandwich elements function at the same time as insulators and structur-

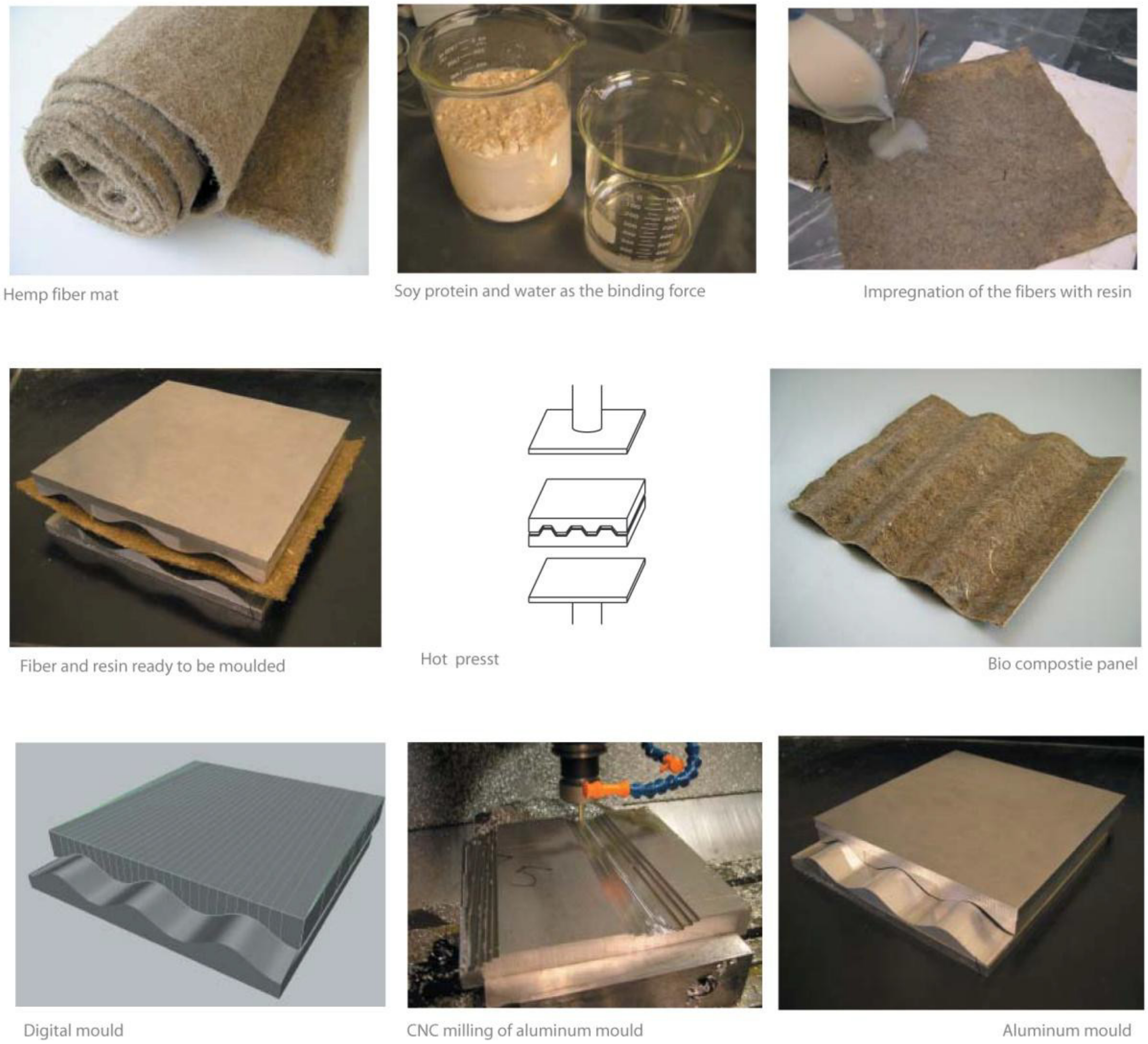
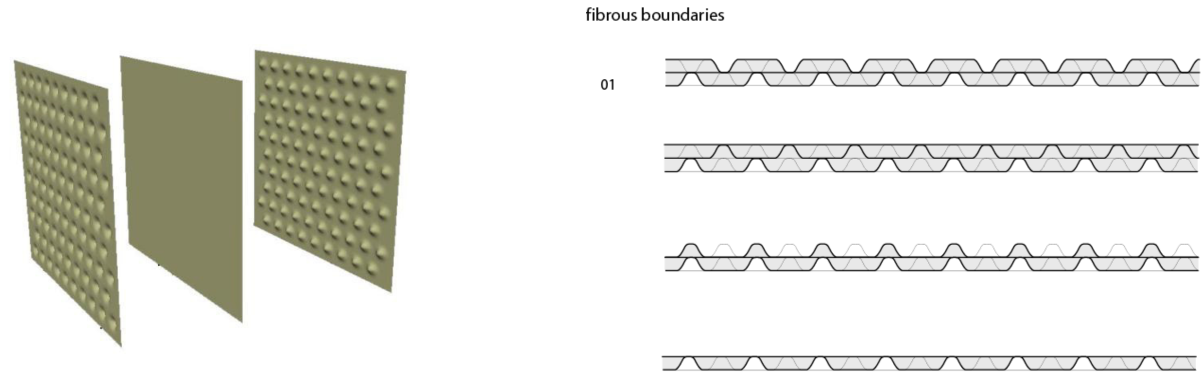


Figure 4. Composite fabrication process using soy protein based resin, and natural fiber

al skin. The walls and the frame bear the load of the ceiling. When having the role as a ceiling the element needs structural support and layers of a planar water repellent roofing material. Some elements are bulging out to create openings for light and access possibilities for people.

A typical FiberCabin molded wall is shown in Figure 6. They may be designed with a variety of shapes and sizes. The only negative aspect is that each shape requires a different mold. However, a set consisting of several molds can allow mass customization of structures where many variations are possible. Figure 7 shows walls made using same mold mounted in different configurations. The variation possibilities are the sum of combinations created by different panels and their role as either wall or ceiling. The slices created by the bulging elements are supported with studs (advanced green composites) and either doors or windows.

An inside view of a fully constructed FiberCabin is shown in Figure 8. The wall (open structure on the left termed 'FiberWall' is constructed of thin sisal fiber based panels or 'elements' that are joined together to form a 3-D panel. Sisal fibers, 40 to 60 cm



(a) (b)

Figure 5. Technique for preparing (a) sandwich structure for insulated walls and (b) typical wall constructions

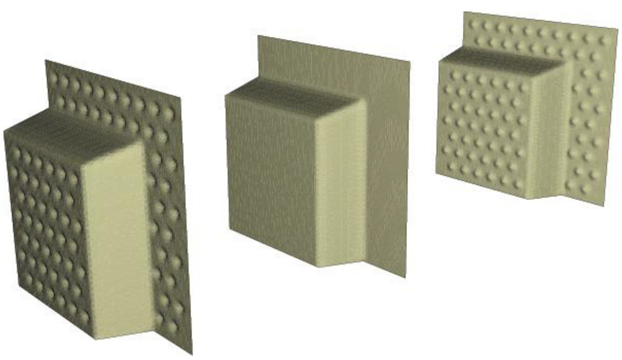


Figure 6. Typical molded walls

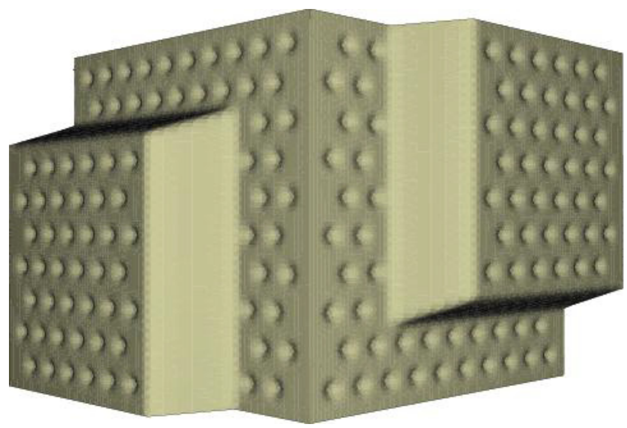


Figure 7. Walls mounted in different configurations

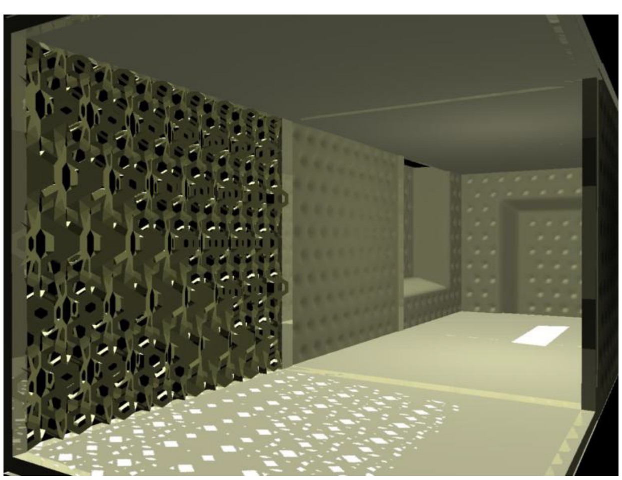


Figure 8. Inside view of a fully constructed FiberCabin

long, were separated into individual fibers and laid down to make into thin mats, impregnated with resin and hot pressed to obtain the desired shape. One such panel is shown in Figure 9 a. Even though there was a certain degree of light transmittance the panels were strong due to the fiber length. While the light transmittance of individual panels could be controlled by mechanically distributing fibers to form patterns with ‘strong’and ‘weak’ areas (Figure 9) the bending stiffness could be controlled by incorporating double curvature. A tetrahedron with three possible connective sides was the most promising unit since it has the potential to grow in many directions and didn’t fold in on itself. The combinatorial logics of six tetrahedrons put together resulted in a geometrical unit that was bent in place and thus had double curved surfaces (Figure 8). Many combinations of panel designs are possible. A typical construction of the FiberWall with circular cut out

(a) (b)

Figure 9. (a) A single panel made using sisal fibers and (b) Typical 3-D FiberWall

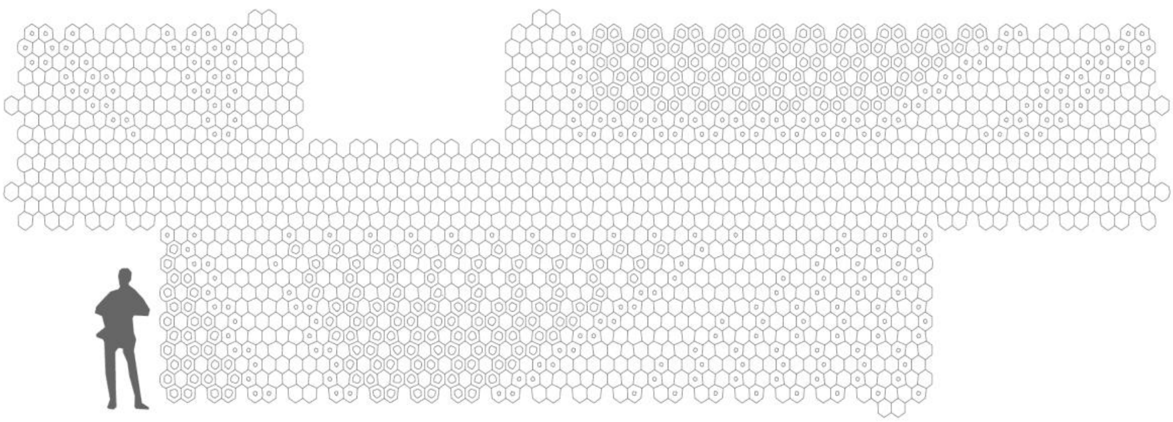


Figure 10. Example of FiberWall with embedded beams and therefore varying light and transparency properties

hole is shown in Figure 9 b. It is possible to add other identical units and make a large porous structure. The system of assembly seemed to have great potential in forming a self bearing wall that could be mass manufactured and yet customizable to control light, design and structure. While these panels were handmade and cut, machine molded panels would create stronger panels thus creating stiffer and stronger structure. An example of the FiberWall with embedded beams is shown in Figure 10. As mentioned earlier many combinations are possible to control the light (transparency), sound and wind yet obtain the desired aesthetics.

CONCLUSIONS

One idea that sticks in the mind in material studies is the notion that materials have certain properties that are inherent to them. When Louis Kahn asks the brick what it wants to be, he is making the point that materials have a certain capacity and 'true nature,' thus the early modern ideal of expressing and searching for the authenticity in materials. Architects have been using materials such as wood, glass, steel and concrete, and wanted to express beauty in the materials themselves, not in ornament. Architects believed, and some still do, that when you know how a material behaves you will find the right answers on how to use it.

Today, it seems like knowledge about materials used in architecture is becoming increasingly complex or how architects relate to materials such as composites require different knowledge and tools. Is it still relevant to talk about a material's true nature when it is made up of two or three different materials as for instance carbon fiber reinforced wood? It is possible to use same materials and manipulate factors such as fiber web production and treatment, resin, mold and hot-pressing is, in order to have any control over the engineering properties of the composite.

This project demonstrates that it is possible to use fully green composites in architectural applications. While the structural elements could be made using high strength "advanced green composites,' walls and ceilings could be made using plant-based fibers. In addition, some of the walls such as 'Fiber-Wall' could be designed to take into consideration light, wind and sound transmittance while maintaining the aesthetics and surface texture desired by the architects and designers. Best of all, at the end of their life all green composites can be composted rather than dumping into the landfills, preserving the nature's intended carbon cycle.

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