# Can We Build with Plants? Cabin Construction Using Green Composites

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**ABSTRACT:** This article discusses the construction (virtual model) of a fully green cabin using two types of green composites: those that use natural plant-based fibers with soy protein-based resin which have mechanical properties comparable to wood and wood products, and those that use liquid crystalline cellulose fibers with soy protein-based resin which have properties comparable to high strength steel. Green composites with moderate strength were used to create molded walls and advanced green composites were used to create the load-bearing framework of the cabin. Construction with molded composites and prefabricated framework can greatly simplify traditional wood construction based on many parts or layers. Since the walls can be molded into different shapes, there are many possibilities for designing cabin shapes. The design is also modular and scalable. The article also describes the building of 3D 'FiberWall' using thin membrane-like green composites, providing fibrous texture. FiberWall design can provide not only light-filtering capabilities but also visibility control, and with added sound absorbant layers, it can also regulate sound in a space. This article exemplifies how materials scientists and architects can work collaboratively to reduce the carbon footprint through green construction.

**KEYWORDS:** Soy protein, green composites, advanced green composites, green tactility and esthetics, renewable resource, design your own material

## 1 INTRODUCTION

Advanced polymeric composites, those that use high strength fibers such as graphite, aramids, glass, etc., as reinforcement, have been used in a variety of structural applications. Advanced composites have high specific mechanical properties by virtue of their low density compared to metals. As a result, they have been steadily replacing metals in many applications over the past three to four decades. Initially developed for the aerospace industry, these high-performance composites can now be found in a wide variety of applications, including automotive parts and sporting goods. Due to ever increasing applications, composites have experienced double-digit growth over the past few decades. The current trend is to use them in civil structures, such as buildings and bridges, for new construction as well as for repairing old and damaged structures. Using the latest technologies, such as CNC fiber placement and 3D printing, can provide even more innovative ways of manufacturing composites and their assemblies as structural components, and also allows for the mass customization of unique parts and designs at a lower cost.

Most of the high strength fibers and resins used in advanced composites, at present, are derived from petroleum. One of the major advantages of these fibers and resins is their nondegradability, which provides long-term durability and safe operation during use. While the nondegradability and high mechanical properties are critical for constructing structures with long life, there are a couple of major problems associated with the use of advanced composites. The first problem is the sustainability of the petroleum itself. As everyone is aware, petroleum is not a replenishable commodity, and at the current rate of consumption it is expected to last only for the next 50 to 60 years [1]. This makes it critical and urgent to develop sustainable replacement materials before the petroleum stocks are fully depleted. The second problem is the disposal of waste created during manufacturing as well as at the end of their useful life. Since civil structures can be expected to use large amounts of composites, they would also generate large amounts of composite waste compared to any of their current applications. Even the current use of composites in the transportation

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industry is generating a significant amount of waste and is expected to see double-digit growth in the coming decades. At present, about 95% of the composites, at the end of their life, are discarded in landfills, while very small fractions are either ground to powder and used as filler or burnt to realize the heat (energy) value [2]. Both landfilling and burning are not only expensive but are environmentally undesirable, as they result in land, air and/or water pollution.

While large multistoried structures or bridges require the high strength and stiffness of advanced composites to be used as structural elements, smaller structures such as single room cabins, temporary housings or shelters, etc., may not need composites with such high strength. For such structures composites with moderate mechanical properties, comparable to wood, would work well. Further, non-load-bearing components such as walls, ceilings, etc., may also use composites with moderate mechanical properties. Some of the structural elements of single houses/cabins would still need somewhat higher strength, particularly if lightweighting of the structure (e.g., for transportation ease) is desired. A point to be noted is that for structures such as single houses/cabins, the most common material used at present is wood. While wood is considered as sustainable, one of its biggest disadvantages is that it can only be harvested after the trees are grown to their maturity, which, depending on the variety, can take 20 to 30 years. However, plant-derived fibers (e.g., jute, hemp, sisal, ramie, banana, pineapple, henequen, flax, kenaf, etc.), which can be used as reinforcement, as well as resins (e.g., plant-based proteins and starches) are yearly renewable. Composites made using plant-derived fibers and resins can be engineered to obtain properties better than those of wood and would be excellent for smaller structures. Furthermore, if high strength fibers are used along with the same resins, advanced green composites having high mechanical properties may be fabricated. These advanced green composites can be used as primary structural elements for construction.

In addition to their good mechanical properties, the rich variety of sensorial properties possible in green composites due to the natural fibers, gives this material family a great advantage in comparison to its oil-based predecessors and many other panelized materials on the market, such as fiber cement and aluminum. The tactility of green composites is warm to touch, combines a fibrous texture and aesthetic with a curved geometry and ages as beautifully as wood.

This article summarizes the fabrication of two different types of green composites having different mechanical properties, and the construction of a fully green cabin built using the two green composites: advanced green composites with properties and toughness comparable to those made with aramid fibers for the main cabin structure (framework), and composites with properties comparable to wood for the molded walls. The article also explores a novel concept of a 'FiberWall,' which is a self-bearing structure of thin membrane-like green composites that can enhance the aesthetics, as well as functionality, of the cabin [3].

## 2 GREEN COMPOSITES

Fully green composites can be constructed using both fibers and resins that are fully derived from sustainable sources such as plants, particularly those that are yearly renewable [4–25]. Since both fibers and resins in this case can be biodegradable, the composites are expected to be biodegradable. At the end of their life they can be easily composted. A wide variety of plant-derived fibers, with different tensile properties, are available around the world. Depending on the mechanical properties of the fiber used, the composite properties can be manipulated. These fibers are also commercially available in many forms, such as loose fibers, yarns, woven and knitted fabrics or nonwoven mats, making it possible to combine them in different layers to engineer the desired properties for the application. Furthermore, high strength cellulose fibers have been developed which can be used as the reinforcing element to obtain composites with excellent mechanical properties [26,27].

### 2.1 Green Composites with Moderate Strength

As mentioned earlier, green composites with moderate properties, comparable to wood, can be easily used to construct smaller structures such as cabins. Since green composites can be protected using the same methods used for wood (e.g., varnish or waterproof paint), exterior use is not an obstacle. While most green composites combine natural, plant-derived fibers that have moderate strength with plant-derived resins such as soy protein and starches, research on other sustainable resins, such as poly(hydroxyalkanoates) (PHAs), and their copolymers, such as poly(hydroxybuterate-co-valerate) (PHBV), poly(lactic acid) (PLA), polylactides, etc., has also shown green composites with properties useful for construction [28–40]. Such green composites can be molded and used for walls, ceilings, doors, floors, etc., replacing wood, plywood, particle boards and gypsum boards. On the other hand, advanced green composites with excellent strength and toughness made using high strength liquid crystalline

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cellulose (LCC) fibers can be used for structural elements or the framework [26,27]. There are several benefits of using plant-based green composites for construction. First, the plant-derived fibers and resins are fully sustainable and yearly renewable. Second, many fibers have good strength and stiffness and are plentifully available around the world. Third, the fibers are inexpensive and commercially available. Fourth, the fibers are available in many forms such as fibers, yarns, woven or knitted fabrics and nonwovens. This makes it possible to fabricate layered composites that combine different fibers and fiber forms, having different properties, to engineer the composites with desired properties. Fifth, many fibers are hollow, which can provide both sound and heat insulation. Finally, because both fibers and resins are biodegradable, the composites can be easily composted or discarded without harming the environment at the end of their life. Thus, the green composite construction practice can reduce the carbon footprint and reduce energy consumption, while also reducing the cost. Furthermore, unlike wood, these composites can be molded into desired shapes.

Many researchers have developed green composites based on plant-derived fibers and resins which tend to be the least expensive, such as soy protein [2–22]. Nam and Netravali studied unmodified soy protein concentrate (SPC)-based resin-based composites reinforced with ramie fibers [8,9]. They fabricated unidirectional composites with 65% fiber volume fraction. Their properties are compared with three commonly used wood varieties in Table 1. It is clear from the data presented in Table 1 that the green composites have better properties in tension as well as flexural mode in both longitudinal and transverse directions corresponding to the grain and perpendicular to grain directions for wood. As a result, they are well suited to replace wood. One of the advantages of using composites is their ability to be molded into desired shapes, which is not possible with wood. In addition, it is possible to construct corrugated composites with much lighter weight, while retaining the stiffness, and also to incorporate insulation during molding. Also, by changing fibers, their volume content, configuration and form, it is possible to obtain composites with different properties in X, Y and Z directions. This option is not available for woods, as their properties are controlled by nature.

Chabba and Netravali made unidirectional composites using (thermoset) SPC-based resin crosslinked with glutaraldehyde and reinforced with flax yarns [6,7]. These composites exhibited a tensile strength and Young's modulus of 126 MPa and 2.24 GPa, respectively, in the longitudinal direction, with just 45% fiber weight fraction. With higher fiber content of 65%, which is normal for conventional composites, the strength and modulus would be over 180 MPa and 3.25 GPa. Once again, these properties are comparable or better than basswood, cherry wood or walnut wood properties. Lodha and Netravali used soy protein isolate (SPI)-based resin with ramie fibers [5]. The tensile stress and Young's modulus of these composites were over 180 MPa and 3.4 GPa. However, when SPI-based resin was modified with stearic acid (MSPI), the composite tensile stress and modulus values were significantly higher at over 267 MPa and 5.8 GPa. At the same time, the moisture absorption of the composites was significantly lower, which allowed less plasticization, thus retaining their properties in humid conditions. The lower moisture absorption was due to resin crosslinking as well as the hydrophobic nature of the stearic acid resulting from its hydrocarbon tail. Again, the fiber weight fraction in these composites was around 45%. With higher fiber volume of 65% the

**Table 1** Tensile and flexural properties of green composite and three different wood varieties [9].

| | | Strength (MPa) | | Modulus (GPa) | | Strain (%) | |
|---|---|---|---|---|---|---|---|
| **Materials** | **Direction** | **Tensile** | **Flexural** | **Young's** | **Flexural** | **Tensile** | **Flexural** |
| Green composite* | Longitudinal | 271(8.6)** | 234(6.4) | 4.9(17.3) | 12.4(9.3) | 9.2(18.3) | 3.1(6.3) |
| | Transverse | 7.4(27.5) | 18(18.9) | 0.9(30.3) | 0.85(9.4) | 5.3(22.5) | 2.8(19.3) |
| Basswood | Grain | 117(20.1) | 93(7.7) | 4.8(24.8) | 8.9(9.6) | 3.2(25.3) | 1.5(7.2) |
| | Perpendicular to grain | 4.8(45.7) | 9.2(26) | 0.34(29.1) | 0.29(17.1) | 1.9(52.1) | 4.3(15.2) |
| Cherry wood | Grain | 124(55.6) | 143(13.9) | 3.5(19.1) | 9.1(23.2) | 3.6(39.7) | 2.2(10.5) |
| | Perpendicular to grain | 9.5(23.1) | 18.7(27.3) | 0.64(14.1) | 0.88(33.9) | 1.9(18.8) | 2.5(19.6) |
| Walnut wood | Grain | 139(18.2) | 133(8.4) | 2.9(6.9) | 6.9(6.2) | 5.5(27.6) | 2.8(16.9) |
| | Perpendicular to grain | 9.4(40.5) | 18.9(23.8) | 0.96(14.5) | 1.2(9.7) | 1.1(17.9) | 1.7(29.6) |

* 65% fiber volume fraction
** Numbers in parentheses show the percent coefficient of variation

tensile strength and modulus values would be much higher, 260 MPa and 4.7 GPA for SPI resin and 385 MPa and 8.4 GPa for MSPI resin. These properties are significantly higher than most wood varieties used for construction and hence can easily be used to replace most wood varieties, particularly composites made with MSPI resin [5]. Lodha and Netravali also modified SPI with Phytagel to form interpenetrating network-like resin and reinforced it with flax yarns [10]. The flax yarn reinforced Phytagel modified composites (45% fiber weight) exhibited strength of over 220 MPa. At 65% fiber volume the properties would be close to 315 MPa. This is not only much higher than most wood varieties, but is comparable to the yield strength of soft and mild steel varieties (A36 steel and 1090 steel) [41]. These composites would be excellent in providing structural support and can be made much thinner than wood, allowing for lighter construction.

There are many other examples of fully green composites that use a variety of plant-derived fibers and soy protein that result in composites with strengths in the range of 250–300 MPa [11–13,15]. One other advantage of using plant-derived fibers is that it is possible to improve properties of some fibers by alkali treatment and, hence, obtain better composite properties [14–16]. One such example involves mercerization of sisal fibers before incorporating them into composites [15]. Mercerization of cotton is a normal procedure where the fibers, or more commonly yarns and fabrics, are treated with NaOH solution in slack condition or under tension. NaOH treatment of natural fibers is also one of the most common chemical treatments to increase the cellulose content by removing the hemicellulose and the lignin [15]. Mercerization performed under stress has been found to decrease the microfibrillar angle in the case of ramie fibers, resulting in improved alignment along the fiber axis and thus higher strength and stiffness [15]. Another reason for the increased tensile properties of fibers is the partial removal of lignin and hemicellulose while not affecting the cellulose fraction. Kim and Netravali mercerized sisal fibers under both slack and stress conditions and found that the fracture stress increased from 283 MPa for control to 339 MPa and 381 MPa after slack and tension mercerization, respectively, and modulus values increased from 5.24 GPa for control to 6.12 and 11.04 GPa, respectively [15]. Mercerization of kenaf fibers was also shown to increase their strength and stiffness [14]. The increased tensile properties of mercerized sisal fibers as well as better bonding due to exposure of hydroxyl groups to polar resins such as soy protein can improve the properties of green composites. Goda *et al.* explored the effect of 15% NaOH solution treatment of ramie fibers and prepared composites using modified starch-based resin [16]. They found that the tensile strength of the fibers increased by up to 18%. They also found that the fracture strains of the fibers increased by 2 or 3 times that of untreated fibers. According to them, all these changes were related to the morphological changes in the fiber. The combined effect of these changes was to increase the composite toughness.

Many researchers have used other resins, such as modified starches, PHAs, PHBV, PLA, PVA, etc., and reinforced them with plant-based fibers to fabricate biodegradable composites [16–40]. These composites have also shown strength in the range of 100 to 200 MPa, comparable to wood. In all cases discussed above, the composite fabrication was done in the lab, without the help of any machines. With the use of machines, it should be possible to improve and optimize the fabrication process and obtain higher fiber content and better fiber orientation to achieve much higher mechanical properties of the composites.

As mentioned earlier, the yield strength of soft steel (A36 and 1090) is in the range of 250–300 MPa and the high strength steel alloy (A514, 4130) is in the range of 690–1290 MPa [41]. However, the steel density is over 7.8 g/cc, whereas the densities of green composites are much lower and can range between 1.3 and 1.5 g/cc. This density difference makes the green composites four to five times stronger than soft steel and comparable to high strength steel on a per weight basis. These composites would be suitable for many indoor applications, including housing panels such as walls, flooring and ceilings.

## 2.2 'Advanced' Green Composites with High Mechanical Properties

Advanced green composites (unidirectional) with excellent mechanical properties have also been fabricated using soy protein-based resins reinforced with high strength liquid crystalline cellulose (LCC) fibers [26,27]. Netravali and coworkers used experimental LCC fibers provided by Dr. H. Boerstoel that had strength in the range of 1600–1700 MPa [42–44]. In the research by Netravali *et al.*, soy protein was modified by blending with polycarboxylic acid (gellan). Gellan forms a crosslinked system and when blended with soy protein results in an interpenetrating network (IPN)-like formulation with strength of over 50 MPa [26]. They further improved the resin properties by adding micro- and nanofibrillated cellulose (MFC/NFC) to it [26]. Finally they fabricated unidirectional advanced green composites that had tensile strength of over 635 MPa and Young's modulus of over 13 GPa with just 40% fibers by volume. With 65% fiber volume the strength and Young's modulus could be expected to be 1035 MPa and 21 GPa, respectively, much stronger than most varieties of steel and comparable to high strength steel. Furthermore, these advanced green composites showed flexural strength in the range of 240 MPa and flexural modulus of around 25 GPa. They also compared the toughness of these composites with those of Kevlar/soy resin composites. Their results, based on static tensile tests, indicated that the LCC/soy resin-based advanced green composites had more than 25% higher toughness than Kevlar/soy resin composites. In addition, the flexural toughness of these advanced green composites was almost twice that of Kevlar/soy resin composites. One of the reasons for the excellent mechanical properties, besides the LCC fibers, was good fiber/resin bond resulting from polar groups present on both protein and cellulose [26]. Further, these composites had a density of only 1.35 g/cc compared to about 8 g/cc for high strength steel. This makes the advanced green composites about five times stronger than high strength steel on a per weight basis.

Kim and Netravali also fabricated advanced green composites using LCC fibers and soy protein isolate (SPI) resin [27]. In this case, however, the LCC fibers were alkali treated using KOH solution, which is much milder than NaOH solution. Another reason for using milder KOH was that the LCC fibers are pure cellulose and contain no lignin or hemicellulose. The fibers were treated under both slack and tension conditions. While the X-ray diffraction studies indicated increased crystallinity for both treatment conditions, fibers treated under tension showed much higher crystallinity. Higher crystallinity also resulted in higher Young's modulus and tensile fracture stress values for the fibers. However, the fracture strain values were lower for all treatment conditions. The higher strength of fibers, as expected, was reflected in the composite properties. The tensile fracture stress values of composites were 540 MPa, 583 MPa and 652 MPa and Young's modulus values were 18.7 GPa, 20.1 GPa and 24.1 GPa for the control (untreated), slack treated and tension treated fibers, respectively. All composites had about 42% fibers by weight. With 65% fiber volume fraction in the composite the fracture stress would be 1020 MPa and Young's modulus would be 37 GPa for fibers treated under tension with KOH. These values, again, are much higher than most varieties of steel and comparable to high strength steel. On a per weight basis, the strength of advanced green composites is over 5 times that of high strength steel. With such high properties, these advanced green composites could be easily used in primary structural applications. In the present research, the structural frame of the cabin was designed with advanced green composites.

# 3 GREEN CONSTRUCTION

As discussed above, two types of green composites can be fabricated: 1) those that use natural plant-based fibers and have mechanical properties comparable or better than wood and wood products (normal green composites) and 2) those that use LCC fibers and have properties comparable to high strength steel (advanced green composites). In this study the natural fiber-based green composites were used to create molded walls (structural skin) and the LCC fiber-based advanced green composites were used to create the load-bearing framework (post and beam). Figure 1 shows a comparison of traditional wood construction of a stud frame house (left), showing its layers of studs, insulation, membranes and cladding, and the possible design of the same size cabin constructed with advanced and moderate strength composites (right), that uses significantly reduced layers. As a result, the construction can be simplified to a great extent. Since the walls can be molded into different shapes, there are many possibilities for designing the compounds of the Cabin. In addition, a 3D 'FiberWall' was built using thin membrane-like green composites showcasing the sensorial properties of the material [3]. The FiberWall can be assembled in various 3D configurations with fibrous texture and desired translucency. A detailed description of the construction is provided in Section 3.2.

## 3.1 Membrane Composites – FiberWall

The biobased green composites with excellent mechanical properties as discussed above have, no doubt, great potential for being used as building elements. This article describes the research investigating the sensorial properties of biocomposites such as translucency, surface texture and aesthetics.

The structure of bilayer membrane composite panels, referred to as FiberWall, were made using sisal fiber, linen textile (fabric) and soy protein resin put together in a 3D configuration to form a self-bearing wall. As mentioned earlier, FiberWall can control incoming light and regulate both visibility and sound.

### *3.1.1 Fiber Aesthetics and Composite Design*

In the past, the green composite samples made in labs were rarely made with aesthetics or architecture in mind and many had a surface expression resembling asbestos, with very little aesthetic appeal. However, some recent fiber / soy protein composite specimens made at Cornell´s lab and discarded due to lack of homogeneity (fiber orientation) stood out as very

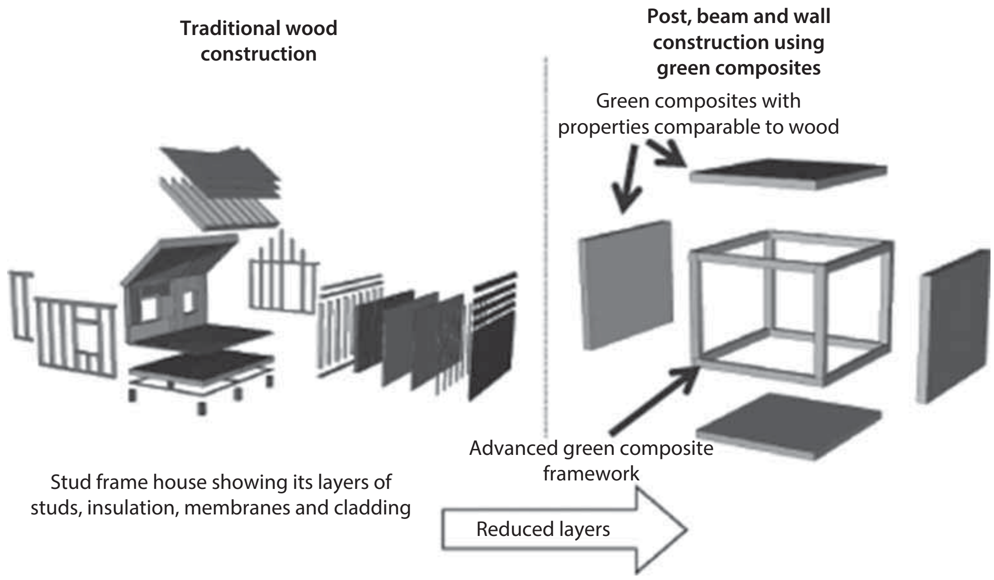



**Figure 1** Comparison of traditional wood construction (left) and composite construction (right) of a simple cabin.

intriguing from an architects point of view. Hence, the birth of the following project. Sisal fibers are light brown like birch, and the long length of the fibers can be easily used to create fascinating patterns visible at the surface, much like the grain in wood.

The sisal fibers used for developing the FiberWall were obtained from a plantation in Yucatan, Mexico. The thin bilayer panels were made by hand laying fibers dipped in soy protein resin (forming the outer layer) on white linen fabric (forming the inner layer), and hot pressed at 120°C for 10 mins in a flat aluminum mold. The shape of the panels was derived from a hexagon with 3 sides slightly bent to ease connection, as shown in Figure 2. Three views of the bilayer panel are presented in Figure 2. Each panel was approximately 8" × 8" in size. The panels transmit light when held up against a light source (Figure 2b) and show some structural stiffness when bending.

When developing FiberWall, one avenue of testing was the fiber reinforcement in the composite panel itself; another was to develop a system of assembling the panels. The sisal fibers used were from 40 to 60 cm long, and came in the form of bundles. They were separated individually and distributed by hand after being soaked in the resin. An apparent challenge, therefore, was to create evenly distributed mats of fibers so that the panels would be strong enough. On the other hand, panels with 'strong' (fiber-rich) and 'weak' (resin-rich) areas, i.e., their inhomogeneity, would get different degrees of light transmittance and allow the creation of interesting patterns. The introduction of linen textile, as inner lining, opened up more experimentation with fiber layup, since the linen provided the sisal fibers with a much needed uniform structural backing and also allowed more opportunities for variation in fiber layup to improve both aesthetics and functionality. As additional design possibilities, one could make a hole in the sisal fiber layer with a linen textile backing or cut out a hole in the linen and expose the sisal, as shown in Figure 3. This could also be a way to optimize use of materials, so that the panel would have the required strength only where needed.

Furthermore, combination of a sisal fiber mat on a linen textile backing created a stronger and stiffer panel, while still transmitting the desired amount of light and giving an almost membrane-like expression. The amount of fibers in the outer layer can be adjusted depending on the amount of light to be filtered. The inner layer fabric thickness and color can also be varied as per the design need. Instead of hand layup used in the present research, it is possible to use nonwovens made using fibers (used for making molded chair) or bark, as shown in Figure 4. Much experimentation and testing was then done to get the right fiber-resin ratio, to obtain the right surface expression and the right heat and pressure in the hot press. The resin to sisal fiber + linen fabric ratio was 50/50, which was found to be sufficient to bind them together.

Fully machine-made textiles designed for this specific project would enhance the composite quality, thus making it easier to achieve the needed stiffness, translucency and surface expression. Additional stiffness could also be achieved through crosslinking of the resin. Also, if working with sisal fibers spun into thread the properties of the composite would be enhanced. When working in a larger scale multi-axis CNC fiber placement robots or tailored fiber placement, one could

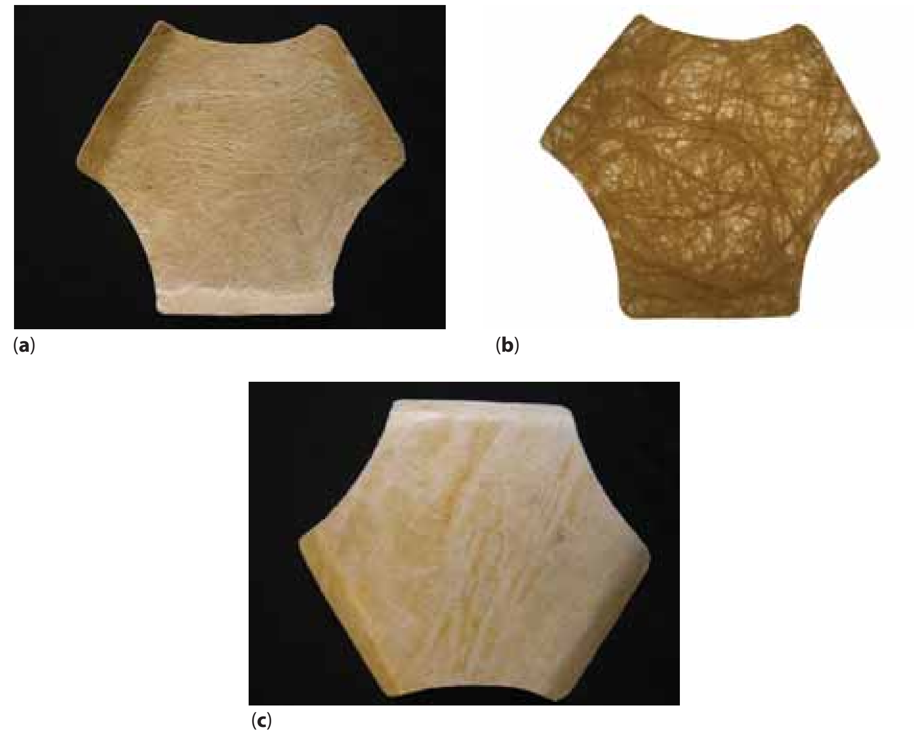


**Figure 2** (**a**) Outer layer: sisal nonwoven fibers. (**b**) Translucent panel held against light, showing fiber pattern. (**c**) Inner layer: linen textile. Note: Each panel was about 8" × 8" in size.

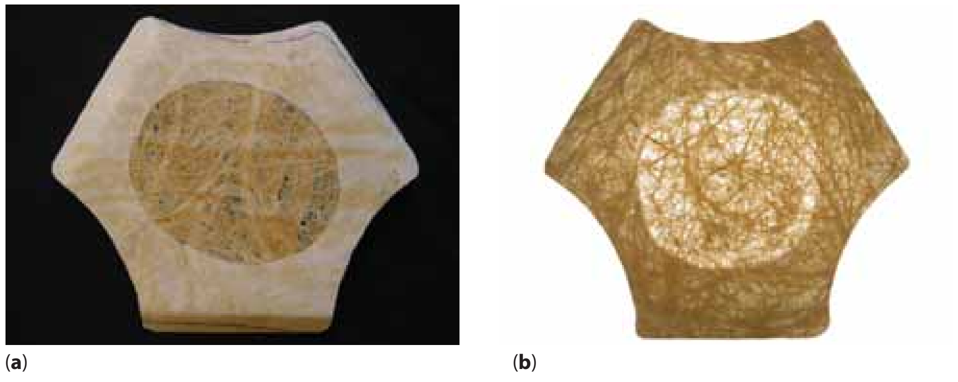


**Figure 3** (**a**) The inner layer of linen fabric with cut out. (**b**) The outer layer of sisal revealing its inner layer due to light transmittance. Note: Each panel was about 8" × 8" in size.

control the mechanical properties and the composites' appearance to a greater extent.

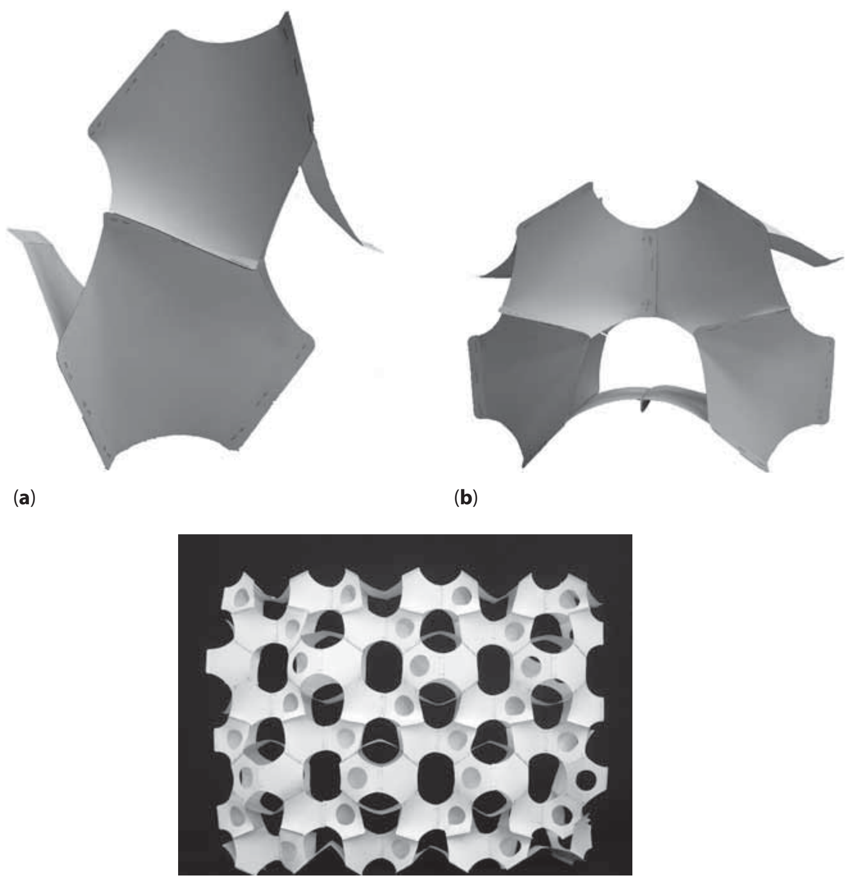
### 3.1.2 *System of Assembly*

Thick paper was laser cut to make individual panels and create quick sketching models of different increments for a system of assembly. A system consisting of three curved hexagonal increments, each with three connective sides, showed great potential when forming an open tetrahedron (a pyramid-like geometrical figure). When several of these tetrahedrons were connected to each other, they seemed to have a 'growing' potential in many directions, even if consisting of only three different single curved shapes. The way Fiber-Wall can connect and grow is shown in Figure 5. When assembled as a vertical wall it could easily be self-supporting. The tetrahedrons were connected at the edges and connective ears were added.

Since molding of green composite panels in their correct curved shape was not economically feasible, the composite panels were made flat, then scissor-cut in the triangular shape and bent into place in the structure. Rivets were chosen as means of connection to create a strong and quick joint. The panels were not made in their actual curved shape, so their structural

**Figure 4** Industrially produced nonwoven mats from cellulose and bark (left) used for the Imprint chair (right) by Johannes Foersom, Peter Hiort-Lorenzen launched in 2005. The mats were designed carefully for desired surface properties.



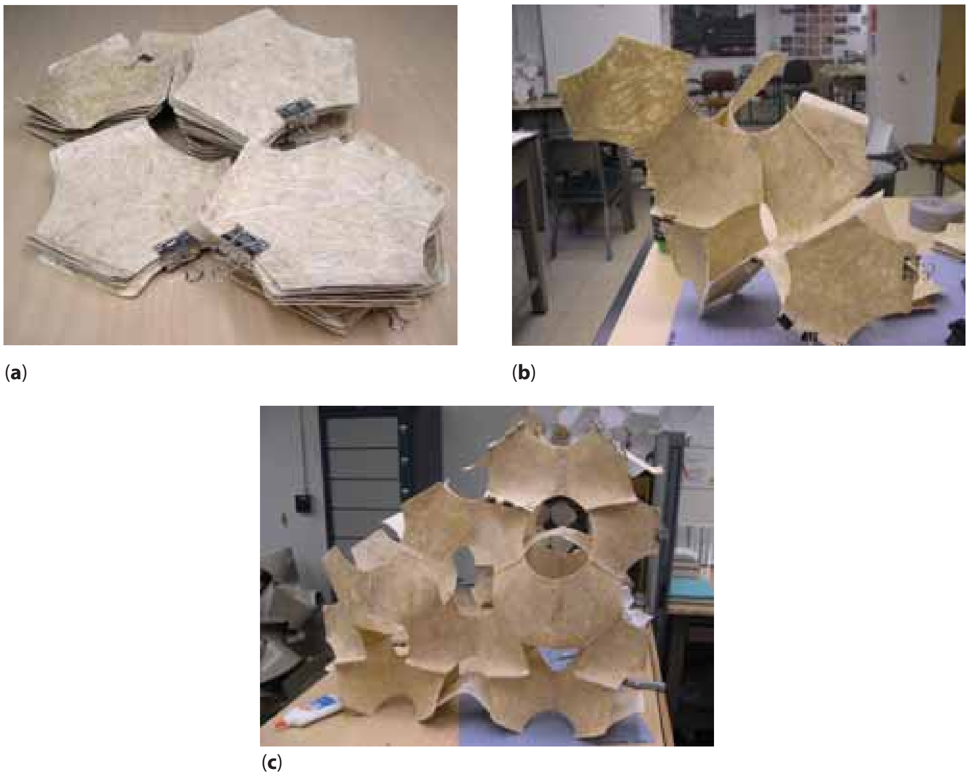
(**a**) (**b**) (**c**)

**Figure 5** (**a**) One unit formed by six panels, (**b**) two units connected and (**c**) several units connected together to form the FiberWall.

capacity in the mockup was not the same as it would be when pressed in a 3D mold, which would create stiffer and stronger panels. Figure 6 shows the sisal fiber/soy protein resin panels and the building steps of FiberWall and Figure 7 shows FiberWall in a geometrical system with inherent 'beams' or areas of rigidity (left) and paper model (right).

FiberWall can not only filter light, control visibility and control wind flow, but with added sound absorbant layers, it can also regulate sound in a space. FiberWall was designed to test several properties such as stiffness, light transmittance and natural fiber aesthetics, and, most importantly, shows the potential of using biocomposites as a self-bearing wall. The green composite specific to FiberWall has a long way to go before becoming a commercially viable product. The surface expression, strength and scale are a result of a handmade process and available tools. By combining



(a) (b) (c)

**Figure 6** (**a**) Bundles of cut fiber composites ready for assembling, (**b**) assembling with rivets and glue and (**c**) FiberWall nearly finished.

current textile and web making technology, better properties should be possible in the future. Figure 8 shows a) FiberWall as an indoor screen in the cabin, filtering light and indoor/outdoor relationships and b) FiberWall model with translucent sisal/soy resin membrane composites.

To summarize, based on the work done with FiberWall, the following points can be made:

- The curvature is restricted to one mold fitting into the other so the pressure is evenly distributed in the hot press: the angle of < 87° worked well.
- The panel size is limited to the size of the hot-press technology.
- The fiber/resin ratio affects the glossiness and translucency.
- Curvature can create desired stiffness.
- The amount of molds/shapes should be minimized to reduce the cost.
- Variations can be achieved by designing the logic of assembly or subdividing molds using different areas for different panels.
- Using different layers of fibers, fiber morphologies (layup) creates different mechanical and sensorial properties.

## 3.2 Framework and Molded Walls – Cabin Construction

Promising results from research in advanced green composites, discussed earlier, suggest that development of load-bearing building elements is possible [26,27]. By combining green composites as surface layers (shear walls) and advanced green composites for structural strength (posts/beams/columns), one could achieve prefabricated semi-monocoque building elements that could make the process of building more efficient. In traditional wood construction (Figure 1, left), there are up to seven layers of material, all with their own functions. They are assembled on site in a costly and time-consuming process.

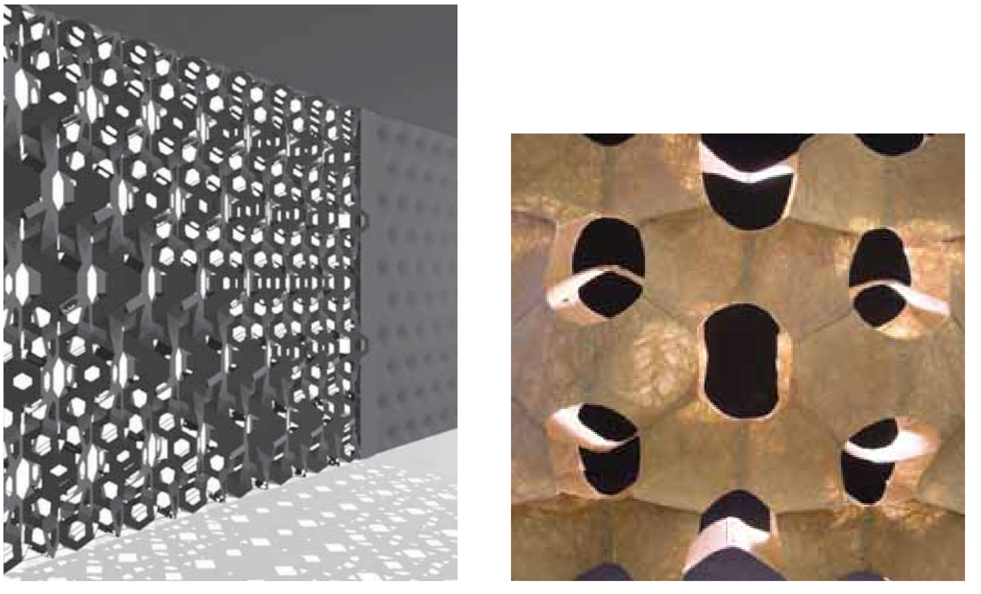
The prefabricated cabin (virtual model) in this study was built with a simple framework made up of advanced green composite beams as the primary structure on which green composite shear walls are fastened as structural skin, as shown in Figure 1 (right). The roof can have flat or folded up variations, but with added gutters inherent in the design of the outer layer and inherent beams for added structural support.

The structural members consist of several laminated layers of advanced green composites. Since the individual panels in the laminated beams/columns can be

(**a**)

(**b**)

**Figure 7** (**a**) FiberWall in a geometrical system with inherent 'beams' or areas of rigidity and (**b**) paper model of a FiberWall testing different sizes of cut-outs in the panel to be able to respond to the site.



(**a**) (**b**)

**Figure 8** (**a**) FiberWall as an indoor screen in the cabin, filtering light and indoor/outdoor relationships and (**b**) FiberWall model with translucent membrane composites.

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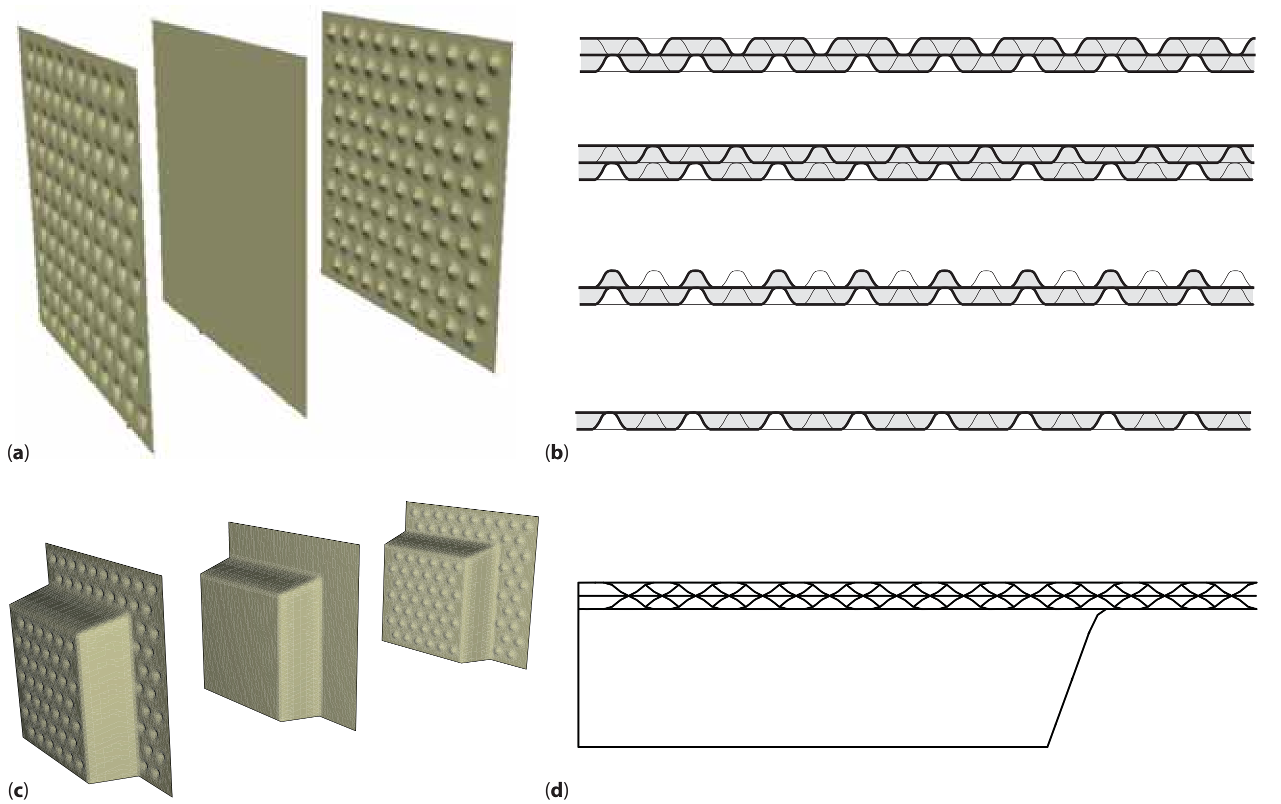

**Figure 9** (**a**) A three-layer sandwich system with two bumpy surfaces and one flat middle layer. The bumps create bonding points between the layers and at the same time continous cavity for air and/or insulation. (**b**) With the moldability of green composites, there is an endless variety in sandwich constructions possible. The sandwich has to avoid cold bridges if used as exterior panels, which is the case for all of the above except the bottom one. Rainscreens and interior cladding could be attached without furring. (**c**) A three-layer sandwich that is folded and (**d**) section of a folded sandwich.

molded in various shapes, the design can vary greatly. An orthogonal system of beams/columns, forming a rectangular plan, was chosen to make additions (scalability) easy and to create a simple framework within which the various walls/roofs can come into play. Longer spans and smaller dimensions than steel and wood are possible, due to the strength of cross-laminated advanced green composites. The concept of I-beams, commonly used with steel construction, can also be used with advanced green composites, making the structure even lighter.

The element consisted of an outer layer of a preferred fiber surface creating the cabin's rainscreen. Polyurethane-based varnishes or paints can make the green composites hydrophobic and protect them from rain. Furthermore, many ultrahydrophobic coatings are available commercially, as well [45,46]. A core of hard rockwool or cellulose fiber mats can be used in between the layers as insulation. The inside layer, exposed to the interior, can be a chosen green composite material as well. Figure 9 shows the molded wall construction possibilities with sandwich structures that can easily incorporate insulation.

The bulges molded into the walls and the way they are distributed depend on the need for structural stiffness, for aesthetic reasons and for interfacial bonding between the layers. The type of green composite panels, the amount of layers and the design of the pattern will give the required property for the sandwich panel. To allow for windows and doors the cabin walls or ceiling are folded out as shown in Figures 10(a) and (b). The moldability of green composites makes it possible to have seamless corners and openings (Figure 10b). This would avoid the complexity of combining several materials in vulnerable areas of the building.

The cabin may be created with repeating (modular) structural framework that can be grown in any direction by simply adding modules (Figure 11). The catalogue of wall and ceiling variations makes customization of cabins depending on the need. The molded walls with folds provide places for doors and windows and others create pockets for sleeping or storage. The glazed walls can use FiberWall as indoor screen, and control light and visibility.

In this study the wall and ceiling shapes were minimized to keep the cost of mold production to a

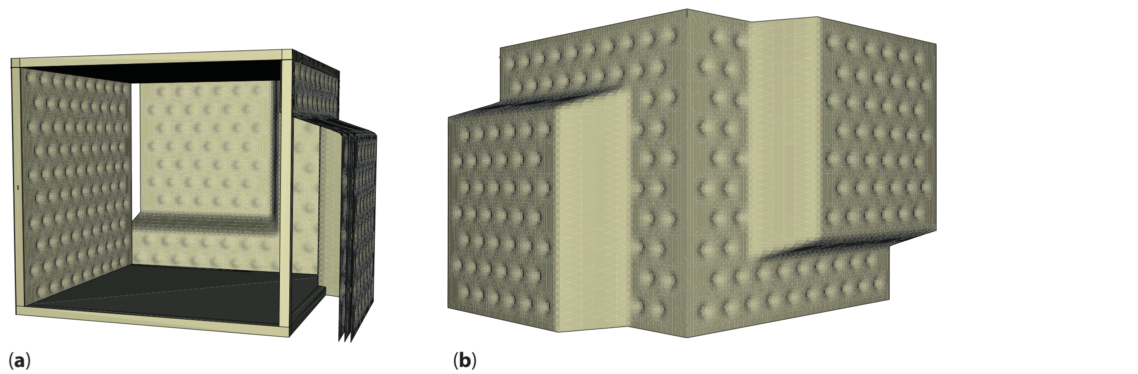


**Figure 10** (**a)** A cabin made from green composites, consisting of sandwich walls molded into two different shapes. By rotating the walls the folds create space for a door when turning down and a window when turning up. (**b**) The exterior of the cabin showing visible bumps and folds. The door and window spaces are hidden in the back.

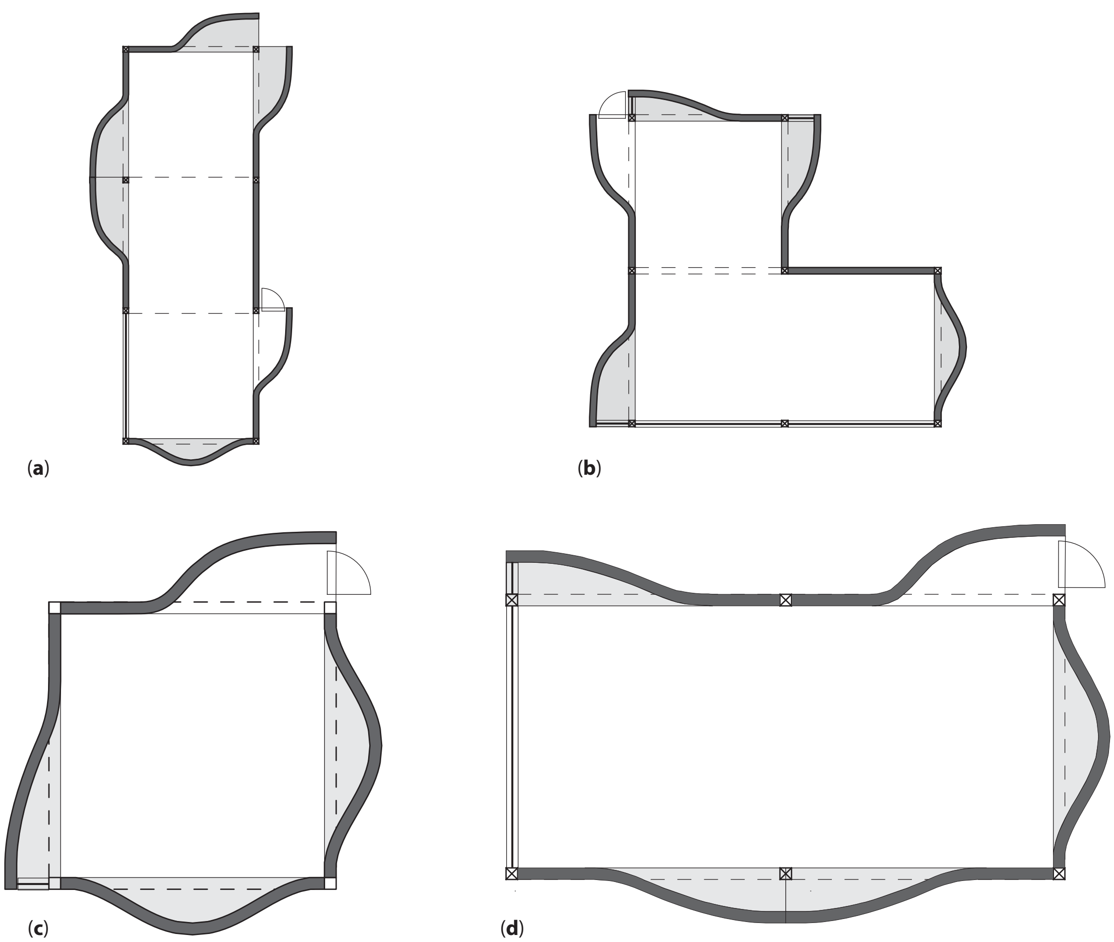


**Figure 11** (**a**) Plan variation; three units in a linear configuration, (**b**) plan variation; three units in an L-configuration, (**c**) one unit plan with one window and one door and (**d**) plan variation; two units with a glazed wall where FiberWall can be added.

minimum. Other ways to reduce mold expenses can be to create large molds that are divided into different sections, each section creating different panel curves, and can even overlap if the panels share curvature.

## 3.3 Manufacturing Developments

Can the manufacturing technology of green composites be capable of larger sizes and more complex panels needed to create houses? The reinforced bioplastic exterior panels of Henry Ford's soybean car, made for a community fair in Michigan in 1941, were an early effort to mass produce cellulose- and soybean-based composites [47]. Currently, there are large-scale mass production facilities for semi-plant-based 'greener' composites in the automotive industry that combine natural fibers and synthetic resin. These composites are used as interior linings or panels in the cars. Even though these composites are made from petroleum-based resins such as polypropylene, polyester, etc., the fibers they use are hemp, jute, kenaf and others, and their production lines are pushing the technology of hot pressing. To optimize production, natural fibers are comingled with synthetic fibers (as resin) and hot pressed in one step into the desired shape. While some of the panels measure roughly 2 m $\times$ 1.5 m, according to the manufacturers, there are no size limitations. A challenge with the hot pressing technology is the high cost of molds, or rather the aluminum metal itself from which the molds are made. However, since curvature is an important way of creating stiffness, looking at ways of making the molds less expensive is a crucial avenue for research. A building component would require a combination of structural strength and precise geometry, which could be achieved using multi-axis CNC fiber placement robots. Precise fiber placement would reduce the composite weight significantly while maintaining the desired aesthetics and functionality. In addition, the laser and/or infrared curing could be employed during fabrication, reducing the manufacturing time and cost. With the current digital manufacturing technology, which combines the low unit costs of mass production with the flexibility of individual customization and an almost endless availability of plant recourses, green composites will potentially allow for affordable custom-made materials and architecture with a much smaller environmental foot print.

In outdoor applications, an obvious challenge with green composites based on plant fibers and resins is how to deal with moisture, since plant fibers are hydrophilic and absorb moisture under normal environmental conditions. Adding a climate protective outer layer of hydrophobic fibers, such as ceramic fibers, could be one way to develop biocomposites that are water resistant. Another technique could be treating the material with clear varnish. Also, as mentioned earlier, several ultrahydrophobic and icephobic coatings are currently available in the market and can be easily applied.

## 3.4 Green Tactility

Many people believe that the current material palette in architecture lacks important tactile and sensorial qualities. The homogeneous and machine-made aesthetics of the modern movement are very much the result of widely used composite claddings such as fiber cement and cellulose laminates that are often preferred by architects today due to their low price, durability and variety of surface expressions. Strict environmental regulations that require low carbon footprint materials, however, are unfortunately not yet fulfilled by these materials or others such as aluminum and steel. Buildings clad with green composites can establish a connection to a place and its fiber resources. The fiber-reinforcement design chosen would give the material a unique tactility and aesthetic that could be made relatively locally or regionally.

## 3.5 Conclusions

This article shows that it is possible to construct fully green structures using two types of green composites. While advanced green composites may be used for the load-bearing framework, those with mechanical properties comparable to wood and wood products may be used for wall, ceiling, etc. Construction with molded composites and prefabricated framework can greatly simplify the traditional wood construction based on many parts or layers. Since the walls can be molded into different shapes, there are many possibilities for designing the cabin compounds. The design can be modular and scalable. Three-dimensional 'FiberWall' using thin membrane-like green composites can be designed to provide light-filtering capabilities along with visibility control, as well as sound regulator. Materials scientists and architects working collaboratively can reduce the carbon footprint through green construction.

As more green composite products enter the market and the knowledge of how to build with green composites becomes part of the building culture, one could also imagine strategies developing which are similar to wood construction using other, more suitable materials in areas of a building that are most exposed to moisture. Use of green composites in civil construction will also solve, to a great extent, the landfilling problem we face today.

In the future, there is a great chance that houses made from plants will become a commercially available option. With an annual production of more than 4 billion tons, plant fibers are one of the largest of the earth's renewable resources. Combined with an increased market demand for sustainable products, green composites could be an affordable choice for architects, allowing the building of carbon-neutral structures without having to compromise on tactile qualities. Since green composites have a moldability similar to plastic, and a natural fiber tactility similar to wood, this material family has a unique combination of properties that might change buildings as we presently know them.

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