# **Bio-Based Composite Materials for Whole House Design: Potential Applications and Research Needs**

Harry W. Shenton III<sup>1</sup> and Richard P. Wool<sup>2</sup>

## **Abstract**

Bio-based composite materials are a new and innovative class of materials being developed today. They consist of environmentally friendly resins and natural fibers. They are made from annually grown renewable resources and therefore, do not deplete petroleum stock or timber reserves. Research is underway to study how these materials can be used to create structural members and systems that would be suitable for use in residential construction. The paper outlines the current state-of-the-art in this newly emerging field and discussed future research needs.

**Keywords:** bio-based, composite material, fiber, housing, resin

## Introduction

Polymer composite materials have found applications in the automotive, aerospace and sports equipment industries. Compared to most metals and unreinforced plastics, they offer a high strength-to-weight ratio, are corrosion resistant, non-conducting, durable and can be fabricated into complex shapes. One major advantage of composite materials is that they can be tailored to meet the specific needs of the structure, by providing reinforcement in areas of high stress and deformation. When performance, and not cost, is the key design objective, FRP composites can be cost competitive and a very attractive alternative to conventional materials.

FRP composites are also being used in repair and construction of civil infrastructure systems; there has been a tremendous push to develop markets for composites in the construction industry. However, high material and fabrication costs relative to traditional construction materials (steel, concrete and wood) have limited the use of polymer composites to very specific applications that take advantage of unique properties of the composite materials. Some of the more successful applications include seismic retrofit of reinforced concrete bridge columns using FRP wraps, strengthening of reinforced concrete slabs and girders with FRP plates and tow sheets, FRP bridge decks, and in the design of marine and coastal structures where composites are immune to corrosion and degradation by marine organisms.

A new and innovative class of fiber reinforced composite materials has recently been developed, which are referred to as bio-based composites (sometimes also referred to as all-natural composites or biocomposites). Bio-based composite materials are a revolutionary idea with many potential benefits to the housing construction industry. Because they are made from renewable agricultural resources like soybeans and corn, and use natural fibers for reinforcement, bio-based composites do not deplete limited timber resources, are not petroleum based like

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<sup>&</sup>lt;sup>1</sup> Associate Professor, Department of Civil and Environmental Engineering, University of Delaware, Newark, DE 19716, Email: shenton@ce.udel.edu

<sup>&</sup>lt;sup>2</sup> Professor, Department of Chemical Engineering, University of Delaware, Newark, DE 19716, Email: wool@ccm.udel.edu

traditional polymer composite materials, and their disposal does not stress the environment. The composites have a high strength-to-weight ratio and therefore, would be easier to transport and install, reducing wear-and-tear on the roads as well as decreasing labor costs. Their lightweight also means that larger housing components can be fabricated in the plant and assembled in the field, with fewer connections and without the need for a heavy crane. As with traditional FRP composites, the myriad of possible fiber-matrix configurations means that composites are highly tailorable to the application.

At a fraction of the cost of petroleum based composites, and with the significant "green" factor, bio-based composites may offer an attractive, cost-competitive alternative to typical wood frame construction. They also open the door to alternative design approaches for panelized construction and whole house design. Researchers, however, are only now beginning to understand and explore the full potential of these innovative materials. Presented in the paper is a brief overview of the current state-of-the-art in bio-based composite materials, as they are used and applied to develop structural components that could be used for housing. This is followed by a discussion of research needs in this area.

## **Current State of the Art**

Professor Richard Wool, head of the ACRES (Affordable Composites from Renewable Sources) research group at the University of Delaware has, for the past several years, been investigating the use of soybean triglycerides as raw materials in the synthesis of new polymers suitable for liquid molding processes. Genetically engineered soybean oil and other plant oils have been made amenable to polymerization using a broad range of chemical routes (Williams and Wool, 2000). The group has already compiled a large database of material properties for various soybased resin/fiber composite materials (O'Donnell, et al, 2003). The natural fibers tested to date include flax, hemp, cellulose, recycled paper, recycled cardboard, newspaper and chicken feathers. Modulii as high as 5 GPa have been achieved, representing a five fold increase over the neat resin. A figure showing the storage modulus of some of the different bio-based composite designs tested thus far is shown below.

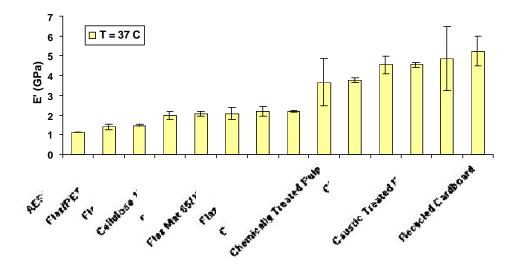


Figure 1. Modulii of different soy-resin and natural fiber composites

Using these resins the authors have designed, fabricated and tested a variety of "unit beams" of different designs (Dweib, et al, 2004). The beams are 42" in length, 4" deep and 8" wide. They are of a sandwich construction, with top and bottom face sheets separated by a foam core and intermittent webs. The beams have been fabricated using Vacuum Assisted Resin Transfer Molding (VARTM), a process that is ideally suited for making very large composite parts, inexpensively. The beams have been tested in three point bending to failure. Strength, stiffness and modes of failure have been characterized. The design that showed the most promise, thus far, consists of the soy-based resin and recycled paper as the reinforcement. Other designs have not achieved the same results in terms of strength and stiffness, but nevertheless could end up being viable configurations because of their ease of fabrication. A photograph of one of the unit beams is shown below.

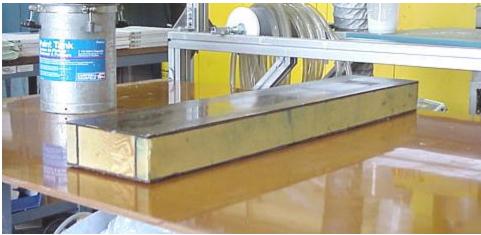


Figure 2. Composite beam made from recycled paper and soy-based resin.

Funded through the NSF/PATH program, the ultimate goal of the project is to develop a monolithic roof system for residential construction using the all-natural composites. The roof will be designed to carry all of the normal dead and live loads a roof must carry, without the need for supporting rafters or trusses. The beam sections are a first step toward achieving this goal. They represent a unit section of the monolithic panel that can be envisioned as a one-way slab for roofs of typical dimension. It should be noted that in this early design the strength and stiffness of the foam core has been neglected in the design of the beam, but would serve a very important purpose in an actual house by providing inherent insulation. Thus, the design will not only be environmentally friendly, but also energy efficient. A prototype design of the roof has been completed based on the mechanical properties obtained to date and the results of the unit beam tests. The full scale roof would be 10" deep, 15' from ridge to eave and have face sheets 0.35" thick. Scale model test results show that the full scale roof will satisfy the code requirements for strength and serviceability.

The field of bio-based composite materials is just in its infancy; however, there are a few other activities ongoing in this area in the U.S. that the authors are aware of. With funding through the NSF/PATH program, Chandrashekhara and co at the University of Missouri-Rolla are conducting research on the application of soy-based resins and synthetic or natural fibers for

housing applications (NSF Award 0229731). One thrust of the effort is in development of pultruded bio-based composite structural members. Drzal and co at the Michigan State University are exploring the use of surface treated bast fibers and pineapple leaf fibers to achieve the desired mechanical properties of the biocomposite (NSF Award 0122108).

## **Future Research Directions**

Researchers have only just begun to explore the potential for bio-based composite materials. The residential construction industry should be an ideal market for these types of materials, because the high volume of materials used should help to drive down the costs of the composites. Furthermore, the mechanical properties that can be achieved with bio-based composite materials should be adequate for use in the somewhat less demanding environment of low-rise construction. However, a tremendous amount of research remains to be done; presented below are just a few of the areas for research where significant advances can be made.

#### Materials research

Fundamental research on bio-based composite materials should be a top priority. These materials offer numerous advantages over conventional construction materials and also traditional petroleum based composite materials, as mentioned earlier. Any work conducted in this area will benefit not only the housing industry, but also other industries where the biocomposites could be used. With regard to structural performance the goal of course is to develop the best possible material, at the least possible cost. Specific research needs in this are include:

- ?? Developing new bio-based resin/fiber composite materials. There is a myriad of natural fibers available and potentially new bio-based resins to be developed that should be investigated. While they would not be a truly all-natural material, hybrid composites that include natural fibers and some synthetic fibers are another design variation that deserves attention.
- ?? Improving the mechanical properties of the materials. Studies and demonstration projects have shown, time and again, that the design of civil structures with composite materials is usually stiffness driven; adequate strength is usually not a concern. This is just the opposite of what you find when designing with traditional civil materials (strength governs and stiffness is not a concern). Increasing the modulus of the bio-based composite materials, without using expensive synthetic fibers, is the most critical need.
- ?? Most composite materials are brittle and exhibit very little ductility. Alas, civil structures are not built with cast iron, and reinforced concrete design is based on ductile yielding of the reinforcing steel. There will always be tremendous resistance and reluctance from the construction industry to use brittle materials. Research must focus on how to provide at least a limited amount of ductility to these new and innovative materials/systems.
- ?? As with any new material there are always concerns with durability and long-term performance. Civil structures are usually designed to last 50 to 75 years, and at least until more recently, preventative maintenance of civil structures has been severely lacking; therefore, durability is a primary concern. Research needs to be conducted to study the durability of these materials and to develop improved materials that can withstand the

effects of the environment. Degradation due to environmental effects such as moisture, freeze/thaw, abrasion, UV exposure are of concern. The effect of these factors on the mechanical properties is an important area for further research.

## Large panel systems

Large, monolithic panels are in principal relatively easy to design and fabricate out of composite materials. Using a sandwich structure design, the panel would consist of outer face sheets, separated by a foam core. The sandwich may or may not include web cores. Structural Insulated Panels (SIPs), a type of sandwich panel made from oriented strand board and foam, are already in use in residential construction in the U.S., but only to a limited degree. SIP's typically come in 4 ft widths and must be placed side-by-side and anchored to create an entire wall. The size of composite material structures, on the other hand, are usually only limited by the space available to fabricate the part. In fact, very large and complex composite parts have been fabricated using VARTM, including for example, boat hulls and railcars. Therefore, one can imagine fabricating entire walls, floors, roofs and foundation systems as one piece using composite materials. Very large monolithic bridge decks have been fabricated using the same approach, so the foundation for this type of construction has already been laid. Cut-outs for windows and doors could be blocked out in the forming process, or cut into the panel after fabrication. The benefits of this type of construction are numerous and include: large, monolithic components mean fewer "parts" and therefore faster construction at the field site; increased strength and stiffness due to the monolithic construction which leads to improved hurricane and seismic resistance; reduced weight for improved seismic performance and lower shipping costs; more energy efficient due to the inherent insulation of the panel construction; higher quality control with factory built panels; integral interior and exterior finishes which can be applied using gel coats; and design flexibility since the panels can be modified and altered (i.e., cut, sawn, drilled, bolted to, even nailed to).

Research needs to be conducted on designing and fabricating large monolithic panel components for houses. Numerous issues need to be addressed, including:

- ?? Tailoring the composite material and panel system to meet the design requirements; developing optimal material designs.
- ?? Characterizing the structural performance of the panels for all possible load combinations: normal, in-plane tension and compression, in-plane shear, and combined loads. Research to develop generic panels that could be used as floors, walls or roofs is also an important topic.
- ?? Integrating electrical, HVAC and plumbing into the panel system. This may involve innovative approaches to providing these services (embedded wiring harness; integral piping and duct systems), or conventional chase systems in the panel. A systems approach should be taken so that all of the functionality of the panel and manufacturing issues are considered when the panel is designed.
- ?? A major challenge with any type of panelized construction is connections. Connection of the floor to the foundation, walls to the floor and roof to the walls. Research needs to be conducted to find cost-effective, robust methods for connecting the monolithic composite panels together. This could include bonded, bolted or press fit connections.
- ?? Damage to a panel is unavoidable. Research needs to be conducted on methods for repairing panels, both in factory repair and after the house is built.

## Whole house designs

Extending the concept from panels to the whole house is natural. As mentioned previously, boat hulls and railcars, both complex 3D structures have been fabricated using composites: one can imagine an entire house fabricated as a unit, or in very large parts. In the simplest of designs, this entails moving from fabrication of 2D flat panels, to a 3D box. A tremendous advantage of composites is the freedom of form they provide; therefore, composite houses could be designed with very different and innovative shapes and profiles, both inside and out. Specific research issues in this area include:

- ?? Developing alternative shapes and configurations of the whole house.
- ?? Characterization of the structural performance; optimized shapes for improved structural performance.
- ?? Integrated electrical, HVAC, plumbing and security systems into the whole house.
- ?? Research into manufacturing of large, complex components made from bio-based composites.
- ?? Developing methods for providing flexibility in the architectural design of the house, while maintaining costs.

## Cost effective manufacturing techniques

The cost of fabrication of a composite material part usually represents a major portion of the total cost. For use in housing, the fabrication of panels or whole house systems must be simple and inexpensive for them to be competitive with traditional construction materials. This eliminates some methods for composite manufacturing, such as injection molding and hand-layup. Currently the most viable fabrication technique for very large composite parts is VARTM. VARTM, however, is still fairly labor intensive. Research needs to be conducted to find alternative and inexpensive methods for fabricating very large composite parts. This will require a systems approach, taking into account the structural and functional design requirements and fabrication constraints. Some of the specific research needs in this area include:

- ?? Developing simplified VARTM processes for fabricating very large panels.
- ?? Methods for monitoring and controlling the VARTM process for very large parts. Currently there is no inexpensive method for determining if a part is completely wet-out using the VARTM process. Only after the mold is stripped can one determine the completeness of the infusion. If it isn't this can amount to a significant economic loss. Monitoring and control of the process would lead to better quality control and less waste.
- ?? Alternative fabrication processes must be developed. One alternative may be a casting process, much like concrete casting, only using a composite mixture.
- ?? The current composite materials are cured under ambient conditions. There is no requirement for pressure or heat. There is also no requirement for post curing. However, in some parts of the country normal temperatures and heat may in effect provide an element of post curing that could be beneficial to the material properties. Research needs to be conducted to explore the benefits and potential for natural post curing of very large composites.
- ?? Quality control is always a critical issue and a concern for owners and engineers. Voids, debonds, delaminations and poor infusion are just a few of the defects that can develop.

Research needs to be conducted on ways to improve the quality of the manufactured part, and methods for testing and assessing the quality.

## Conclusion

A new and innovative class of composite materials are being developed that may be particularly attractive for use in the housing industry. Bio-based composites consist of resin and fibers made from annually grown, renewable resources. They are environmentally friendly and do not deplete petroleum or timber reserves. However, additional research and development must be undertaken before their full potential is realized. Some areas where additional research is needed includes basic materials, construction of very large panels, whole house design and cost effective manufacturing processes.

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