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# Newly invented biobased materials from low-carbon, diverted waste fibers: research methods, testing, and full-scale application in a case study structure

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## Abstract

This project demonstrates newly invented, biobased construction materials developed by applying low-carbon, biomass waste sources through the Authors' engineered fiber processes and technology. If manufactured and applied large-scale the project inventions can divert large volumes of cellulose waste into high-performance, low embodied energy, environmental construction alternatives that lessen society's dependence on greenhouse gas emitting products associated with global warming. Biobased materials produced in this work include: 1. High strength-to-weight-ratio "bioboards" as a dense, thin, multi-purpose construction hardboard from 100% waste sources and without resins, binders, or adhesives. Bioboards are used in flat and multidimensional form to create the project inventions. 2. Modular, three-dimensional-core, structural insulated wall, floor, and roof "BioSIPs" panels developed using bioboards as main structural components. BioSIPs received patenting during the project. This publication describes research and computational methodologies, testing of project materials, and their full-scale application as the exterior and interior materials and construction system for a solar-powered case-study building. The authors are currently advancing project inventions for commercialization.

*Keywords:* biobased construction materials; low-carbon construction materials; biobased materials testing; mechanical properties of low-carbon building materials; computational methods for developing low-carbon materials

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## 1 INTRODUCTION

The focus of this project is application of biomass waste fibers as source material for the invention, development and fabrication of new low-carbon, biobased construction products. These new products are shown in the present work to compete with and, in specific applications, outperform their carbon-intensive competitors while offering lower embodied-energy, more environmentally sound construction options.

Cellulose waste used in the work includes: post-consumer wastepaper, recycled cardboard, industry scrap, agricultural residues, anaerobically digested bovine waste, forest residues, construction wood cutoffs, hemp, flowers and aromatic plants. These wastes are optimized using the Authors' engineered fiber technology, computational software advancements, research and prototyping methodologies, and they are demonstrated as resources for new biobased materials that are applied in construction of a solar-powered case-study building (Figure 1).

## 2 OVERVIEW

### 2.1 Buildings as global warming contributors

Buildings—as one of the world's largest consumers of natural resources—rely significantly on nonrenewable fossil fuels,

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**Figure 1.** *(**A**) and (**B**). 100% Biomass waste in all forms is processed using biobased technology to produce superior-strength building products without formaldehyde, glues or toxic, off-gassing chemicals. No trees are cut or harvested. Simply put, tons of low-cost waste are transformed into high-value products using proprietary wet-process techniques. Following are a range of cellulose waste sources used in this work: curbside wastepaper, cardboard and industry paper scraps; agricultural residues and bovine waste; hemp and marijuana from newly developing medicinal, food and fiber economies; wood and forest wastes, and construction leftovers; grasses, flowers, noxious weeds and other fast-growing and aromatic plants such as cedar, eucalyptus and herbs.*

especially petroleum, as content for construction materials and building operation. Statistics indicate that the world's building stock consumes approximately 40% of global energy while contributing at least 30% of annual, global greenhouse gas emissions due to nonrenewable resource use. This positions buildings as significant contributors to global warming and the associated environmental upheavals occurring daily worldwide.

It is therefore imperative and urgent that more aggressive and expeditious solutions be developed to reduce environmental damage caused by existing and future buildings. An important opportunity for achieving this goal is through reconsideration of the construction materials we produce and use.

## 2.2 Building life cycle assessment

A construction prerequisite coming into effect worldwide is accountability for a building's resource efficiency, energy use and environmental impact. This is known as a building's 'carbon footprint'.

A commonly used method for analyzing building carbon footprint is 'life cycle assessment' (LCA). LCA helps identify energy and carbon inflows and outputs from beginning to end of a building's life. The lower the inputs and outputs, the lower the building's carbon footprint and predicted negative environmental impact.

LCAs include two major assessment components:

- *Energy consumed as related to Building Envelope and Operation,* and specifically as a function of construction enclosure system efficiencies, and heating-, ventilation- and cooling system efficiencies; and
- *Embodied carbon as related to Materials.* Referred to as the 'cradle-to-gate' measure, this assessment marker indicates energy and resource inputs included in the composition, manufacture and transportation of a material to the consumer.

Referring to the first LCA assessment component above, a high-efficiency construction envelope is critical for reducing a building's energy use and greenhouse gas emissions. However, this assessment measure is flawed in that efficiency gains are *accumulative and are factored across the building's lifetime* which allows for a long, drawn-out, lag time before gains are achieved. Another drawback to this LCA measure is that high-efficiency building envelopes are often fabricated using extractive, petroleum-reliant methods which actually contribute to an increased building-carbon footprint. Rather than waiting years for carbon reduction investments to pay off, more direct and immediate solutions are needed. They are currently available and can be immediately implemented by addressing the second LCA component: *Materials.*

Since building materials *are analyzed and applied early on* in the building planning process, carbon reductions and lower embodied energy gains are immediately available through specification and use of lower-carbon-footprint materials. Examples of such materials include biobased products fabricated from nonextractive waste resources via lower-embodied-energy methods and manufacturing.

Some of the main challenges for mainstream acceptance of biobased materials is their demonstration as products that can compare with, and/or outperform, petroleum-based counterparts in all areas, including structural performance, ease of use, versatility and cost.

This project focuses on the presentation of a new range of biobased material inventions and low-carbon methods that can compete with and in specific instances outperform, petroleum-based construction materials and methods.

# 3 VALIDATION OF BIOBASED CONSTRUCTION

Two full-scale biobased case studies by Julee Herdt provide design and scientific groundwork for validating the project premise.



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**Figure 2.** *(**A**) and (**B**). Farmhouse model, positioned inside the constructed Farmhouse residence and surrounded by a range of biobased materials used in the home's construction. First-place trophies for CU's back-to-back wins in first-ever and second international Solar Decathlon competitions. Biobased construction materials and methods were cited as significant contributors to the wins of the CU teams.*

### 3.1 Case study 1: farmhouse

The Farmhouse residence was designed and constructed by Julee Herdt as a petroleum-alternative environmental archetype for suburban living. It was constructed using off-the-shelf biosource products such as boards, planks and masonry modules combined in a highly detailed, thermally sound and durable design. The Farmhouse is powered by photovoltaics and a grid-tied electric backup. Heating and cooling are provided via a vertical-loop ground-source system. Scientific evaluation of the project's carbon footprint by Julee Herdt in collaboration with architect Dr Victor Olgay, and which was peer-reviewed and published by the International Solar Energy Society and the American Solar Energy Society, shows that the biobased Farmhouse exhibits the following in comparison to an equivalently sized, standard wood-frame residence:

- 40% less embodied energy in materials
- 70% higher energy efficiency based on a one-year 'energy in operation analysis'

### 3.2 Case study 2: international-competition-winning solar decathlon projects

To validate biobased construction as a modular concept, Julee Herdt tested her early theories and material developments through two separate competition-winning solar home designs constructed along with University of Colorado (CU) student teams. The CU homes were prefabricated as biobased kits-of-parts, transported and then tested on a world stage in the first-two-ever international Solar Decathlon competitions at the National Mall, Washington, D.C. In back-to-back first-place wins in both the competitions, the CU biobased homes out-performed all other methods, e.g. wood-frame systems, structural insulated panel (SIP) systems and various hybrid systems in aspects such as energy use in operation, building thermal control and user comfort. These wins provided critical support and scientific credentials for continued advancement of Julee Herdt's biobased building material developments and applied research (Figure 2).

## 4 BIOBASED MATERIAL CHALLENGES

### 4.1 Overcoming hurdles for biobased building products and methods

Over the years, biobased product offerings have been limited mainly to low-density, interior-use flat boards and heavy, fibercement, masonry-type products. Product designers and manufacturers have struggled to develop versatile biobased materials and systems for various construction categories with difficulties related to the following factors:

- Technological inabilities to convert biomass into structurally predictable products
- Generally low product strength-to-weight-ratio
- High cost of product shipment due to weight
- Inability to overcome biofibers' hygroscopic nature and tendency to swell, shrink and lose strength following prolonged moisture exposure. Advancements have been made in developing natural plant-based, nonpetroleum, water-resistant additives. However, most of these additives contribute additional weight to already weighty biobased products, especially in particle-type boards. Such additives have also exhibited molecular bonding difficulties during processing with biofibers, resulting in unreliable water-resistant performance of the final building products.

In considering engineered wood fiber materials as biobased options, the most commonly used products include medium-

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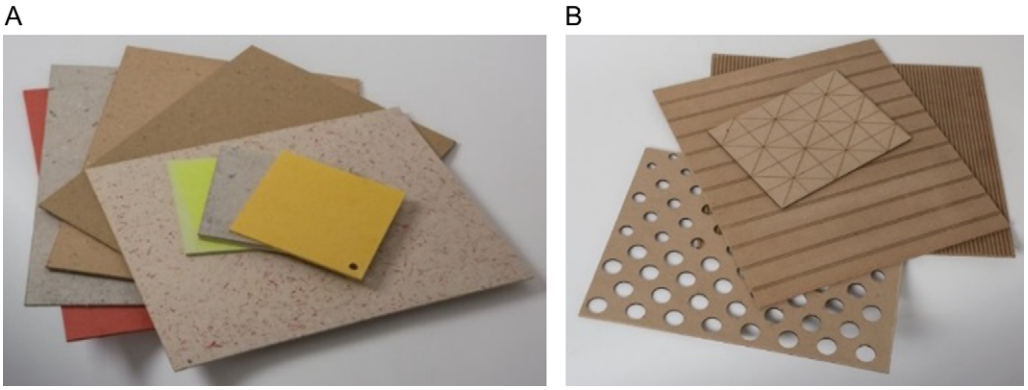


**Figure 3.** *(**A**) and (**B**). Example range of bioboards produced from waste fiber mixes such as plants, grasses, recycled boxes, curbside waste and industry scraps. Bioboards with engineered, lasered cuts, ready for folding into 3D structural building materials.*

density fiberboard (MDF), particleboard and oriented strandboard (OSB). Though these products are touted as sustainable, they are generally fabricated using petroleum-based preservatives and binding resins that have been linked to environmental damage, greenhouse gas contribution and human health risks from usage. Commonly used in their manufacture are energy-intensive petrochemicals such as phenol formaldehyde (PF) and/or diphenylmethane diisocyanate (MDI). This makes these products questionable as environmental options for reducing building carbon footprints. Their promotion as such is misleading for conscientious consumers working diligently to establish greener buildings.

# 5 NEW BIOBASED SOLUTIONS DEVELOPED THROUGH THIS PROJECT

Successful low-carbon-footprint, biobased product options developed through this project include the following:

## 5.1 Bioboards

These are flat fiberboards produced from 100% waste cellulose. They are versatile, have strengths suitable for multipurpose construction applications and are a high-performance alternative to standard hardboards made from hardwood fibers. Bioboards function as higher-strength-to-weight-ratio, higher-density replacements to heavier particleboard, MDF and OSB in specific applications such as construction panels, furniture substrates, interior walls and ceiling boards, in addition to having other uses. Bioboard is also the main design and structural material for fabricating high-strength-to-weight 'BioSIPs' building panels produced through the work. In this paper, bioboard is alternately referred to as 'substrate.'

Bioboard was initially developed in flat, planar form. The team advanced their processes so that thin, dense bioboard can be manipulated into strong three-dimensional (3D) shapes through prescribed, engineered cutting and folding of the material into compound curves, trapezoids and computer-generated forms exhibiting capacity to support structural building loads (Figure 3).

Bioboard is produced in the following thicknesses:

- 1.59 mm (1/16 in)
- 2.54 mm (0.10 in)
- 3.18 mm (1/8 in)
- 4.76 mm (3/16 in)
- 6.35 mm (¼ in)

## 5.2 BioSIPs

BioSIPs—as the project's modular, biobased building enclosure invention—are a new type of SIP (structural insulated panel) with improved performance over standard SIPs.

SIPs are defined in the construction industry as 'sandwich panels' in which opposing OSB sheets are glued to insulation slabs to make them function as stressed-skin structural building panels. SIPs are factory-produced and shipped to construction sites for rapid assembly of buildings.

The key advantages of SIPs over wood-frame and other systems include quicker onsite construction and project time-savings, higher resistance to moisture and mildew, energy- and cost efficiency, and improved structural performance for supporting monolithic building loads.

Standard OSB SIPs suffer from several drawbacks such as the following:

- The panel faces are manufactured from petroleum-based chemicals and resins, which bind their wood strands.
- These chemicals are known to off-gas into interior environments, thereby posing risks to human health.
- OSB should always be covered or encapsulated in environments, thus generating a need for additional material use.
- Panel insulation is generally glued to OSB surfaces, creating a potential for structural failure if the OSB shears away.
- Given the nature of OSB, i.e. its inability to be flexed into complex, multidimensional architectural forms, standard SIPs are limited in their building design potential and application possibilities.
- When post-construction internal integration of components such as conduit, wiring, plumbing and framing is desired,

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OSB must be drilled, cut, or otherwise penetrated with power tools, which is time-consuming and not user-friendly.

### 5.3 BioSIPs as an improved SIP method with lower carbon footprint

BioSIPs are designed to counter these drawbacks as a higher-strength-to-weight-ratio, environmentally friendly, and more flexible SIP for all construction types, including residential, commercial, industrial, transportable and rapid deployment.

Since the main structural components of BioSIPs are fabricated using 3.18-mm-thick (1/8 in) bioboard made from 100% waste fiber, a BioSIPs panel can weigh half as much as its 12.7-mm (1/2 in) OSB-skin counterpart.

The most significant distinguishing aspect of BioSIPs is its unique 3D, load-bearing, bioboard structural core that functions as a columnar, diaphragmatic, lateral support system. No standard SIP has a 3D core. A patent for the BioSIPs invention was acquired during this project. BioSIPs cores can be fabricated with internal channels and perforations for ease of electrical, plumbing or other component installation, either pre- or post-building construction.

BioSIPs are insulated using high-density, high-pressure, non-chlorofluorcabon, non-off-gassing insulation manufactured by US-based NCFI company. Other insulation types can be used in BioSIPs, including batt or loose fill; however, an optimum balance between thermal and structural performance is accomplished using high-density foam. NCFI insulation yields an approximate value of R7 per inch (2.54 cm) of BioSIPs' panel thickness, which represents the highest *R*-value available in a standard SIP. BioSIPs' monolithic insulation prohibits straight paths of thermal transfer and moisture movement across panel thicknesses. Cam locks at panel edges further reinforce BioSIPs' tight thermal control while enabling quick onsite assembly (Figures 4–6).

BioSIPs overall panel depth for this project was established as 16.51 cm (6-1/2 in). The team determined that by varying panel depths to smaller and larger dimensions, i.e. from 2.54 cm (1 in) to 30.48 cm (1 ft), and by eliminating insulation in certain instances, BioSIPs could also function as strong panels for many other applications such as interior partitions, furniture cores, modular and free-standing furniture, shelving, and countertops, in addition to other uses (Figures 7 and 8).

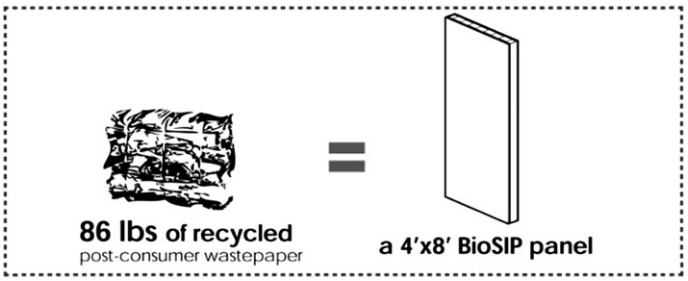


**Figure 4.** *Thirty-nine kilograms of recycled fiber (86 lbs) are diverted into the fabrication of one 2.44 m (height) × 1.22 m (width) × 16.51 cm (thickness) (i.e. 4 ft × 8 ft × 6-1/2 in) BioSIPs building panel.*

## 6 ENGINEERED MOLDED FIBER TECHNOLOGY FOR DEVELOPING PROJECT INVENTIONS

The project inventions were developed using the team's fiber methodologies and technology for optimizing the mechanical properties of cellulose wastes, such as their density, strength-to-weight-ratio, water resistance, ductility and flame retardance. The technology is referred to as 'engineered molded fiber' (EMF) technology, and its basic processes were established by John Hunt in collaboration with researchers at the US Department of Agriculture, Forest Products Laboratory.

In EMF technology, all types of 100% low-to-high-value biomass is applied in closed-loop wet-pulp methods. Fibers are processed, hydro-pulped, then hot-pressed between rigid molds, resulting in engineered fiberboards (bioboards) with high strength, ductility and stiffness using relatively small amounts of material inputs. No supplemental adhesives, binders or resins

**Figure 5.** *(**A**) and (**B**). Full-scale BioSIPs 3D panel core with holes for addition of electrical conduit and wiring. BioSIPs with insulation encapsulating 3D cores, and including panel skins, being stacked by team members for shipment.*

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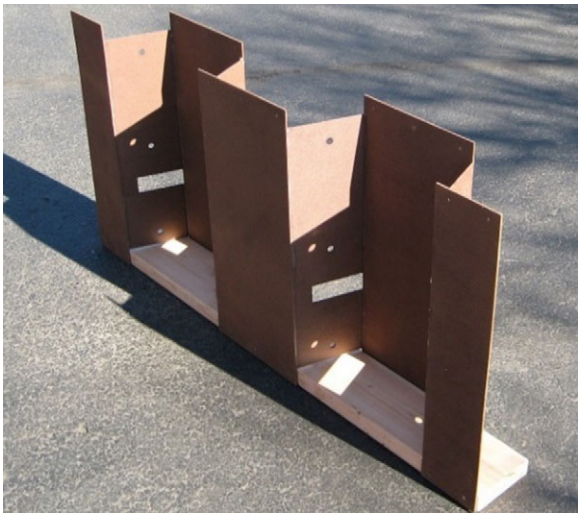

**Figure 6.** *Early BioSIPs 3D core design prototype for testing of compression loading strengths.*

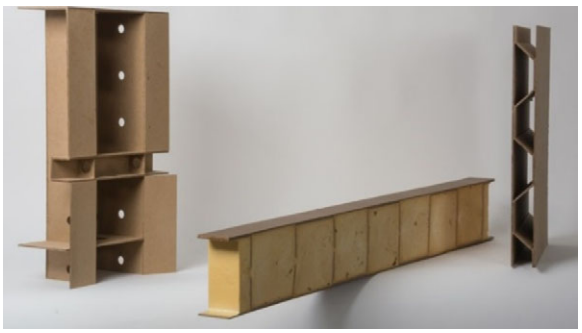

**Figure 7.** *BioSIPs structural panels for wall, floor and roof constructions. Left to right: noninsulated panel core with electrical perforations and conduit channels, and without panel surface skins; insulated panel section with exterior surface skins; panel section with skins and without insulation.*

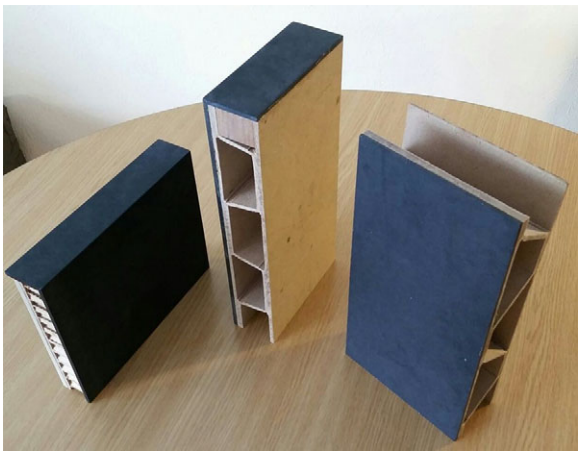

**Figure 8.** *Examples of interior-use BioSIPs panels for furniture, interior walls and sliding doors.*

are needed since environmentally inert, naturally occurring cellulose bonding results in high interfiber strength.

Water left over from EMF processing is recycled and filtered in a closed-loop recovery system. Virtually all fiber inputs result in finished products. Recently developed, natural water-resistant additives can be included in the fiber pulping stages to enhance the hydrophobic properties, hardness and fire retardance of project biobased materials, while keeping their overall weight relatively constant (Figures 9–11).

### 6.1 Fiber sources for project inventions presented in this paper

As the baseline for the bioboard substrate discussed herein, waste feedstocks are assumed to be old corrugated containers (OCCs) sourced from cardboard and boxes. Many other fiber types were also used to produce materials in the overall project.

## 7 PROJECT METHODOLOGIES

### 7.1 Software products advanced for all project phases: ANSYS and geocost

ANSYS is finite element analysis (FEA) computational software used for structural investigations, fluid dynamics modeling, heat transfer modeling and explicit and implicit numerical modeling. ANSYS software was modified by the team and applied for fiber science and product development, and it was integrated with material science software packages developed by John Hunt for assessing proposed biobased product designs prior to actual physical prototyping of the project inventions.

The team's ANSYS developments helped generated information such as mathematical calculations, structural performance predictions, and constitutive property projections for the bioboards to be cut, hinged and flexibly bent into various, desired 3D shapes. They also allowed the team to simultaneously and broadly vary and investigate extensive ranges of fiber mixes for bioboard fabrication in order to predetermine the mechanical and structural capacities of the proposed substrates':

- Internal fiber bonding strengths
- Structural capacities in different physical configurations
- Compressive, tensile and shear strengths
- Thermal conductivity and heat transfer
- Density (pounds per cubic foot) / Specific gravity

Excel spreadsheets integrated with ANSYS generated mathematical instructions describing pluralities of cuts needed to create desired 3D bioboard shapes. The spreadsheets produced specifications for appropriate depths, widths and spacing of the cuts needed for incising then folding each bioboard type into 3D configurations with predicted strengths and structural load-carrying capabilities. ArchiCAD in standard form was integrated with Excel to produce computer numerically controlled

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**Figure 9.** *(**A**) and (**B**). Sorted recycled cardboard ready for hydro-pulping. Post-pulped fibers in bins ready for processing as EMF bioboards.*

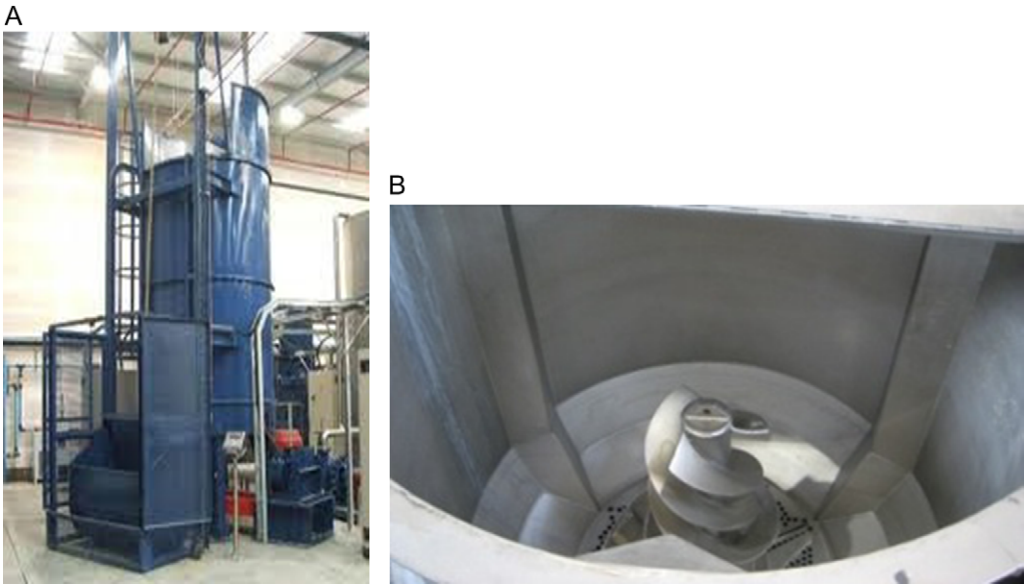


**Figure 10.** *(**A**) and (**B**). Hydro-pulping tank for fiber processing Hydro-pulping blades. Proprietary equipment is not shown.*

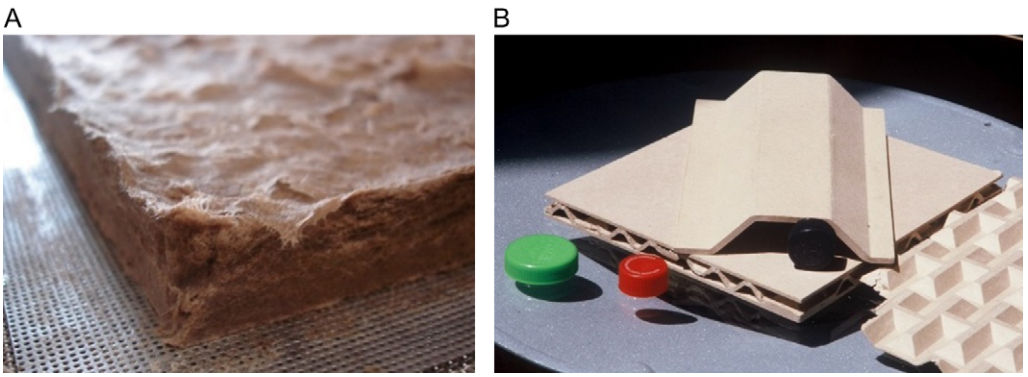


**Figure 11.** *(**A**) and (**B**). Wet fiber mat in expanded form after initial, first-stage pressing of a bioboard Examples of high-density fiberboards fabricated through proprietary project pressing techniques.*

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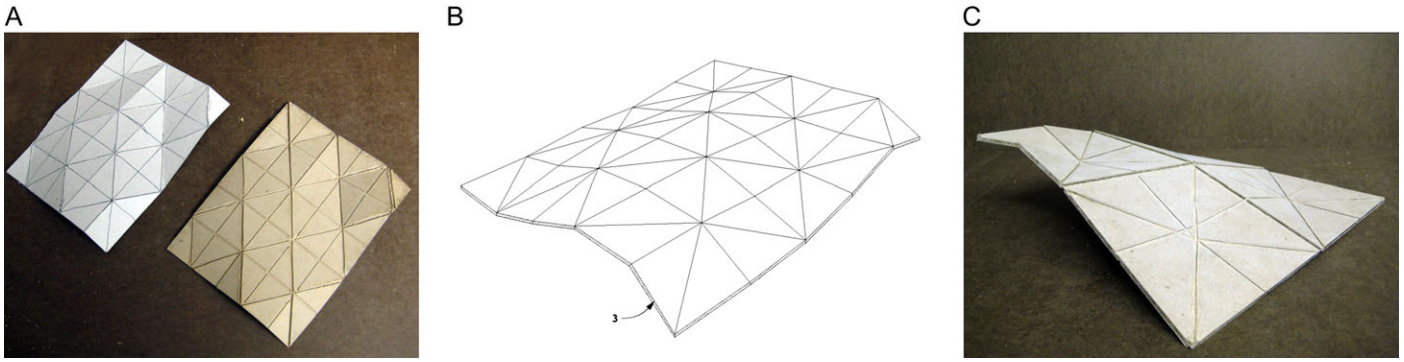


**Figure 12.** *(**A**)–(**C**). Methods of the BioSIPs team: 3D physical modeling (left), computer modeling (center) of corresponding 3D form, and final full-scale prototyping of the form for use as a prototype building panel (right).*

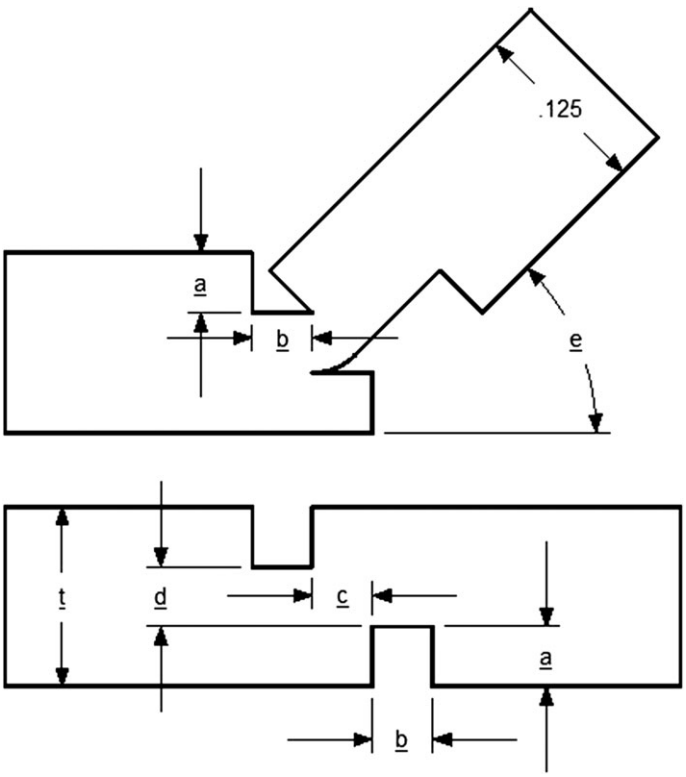


**Figure 13.** *(**A**) and (**B**). Excel example of cut and hinge locations for folding bioboard substrate into a specific 3D board geometry. (A) Depth of cut. (B) Width of cut. (**C**) Spacing between cuts on opposite board sides. (**D**) Depth of board thickness to be left between opposing cuts. (**E**) Desired 3D angle. (t) Overall board thickness. The bottom drawing shows the bioboard after the first cuts are performed. The top drawing shows the board angled into panel position.*

(CNC) drawings for fabricating precise and accurate bioboard prototypes and BioSIPs product ideas (Figures 12–15).

## 7.2 Geocost

Geocost software was enhanced by the team and was integrated with ANSYS to predict the economic and manufacturing impacts of producing bioboards and BioSIPs at a mock manufacturing facility, and to assess predicted material strengths and structural capacities of bioboard and BioSIPs products.

The environmental output capabilities of Geocost were developed to assess the project inventions in such terms as: Volumes of waste diversion achieved through fabricating various product designs using waste feedstocks, and natural resources and energy saved through use of waste fiber feedstocks compared to products using wood or virgin materials in their manufacture.

## 7.3 Standards and metrics

American Hardboard Association (AHA) standards were applied for establishing the fundamental properties of bioboards e.g. its water absorption capacity, thickness swelling behavior, modulus of rupture, tensile strength, dimensional tolerances, moisture content and for evaluating bioboard's use as wall paneling, furniture components and utility boards. For application of bioboards as BioSIPs' stressed-skin surface material and as a replacement to petroleum-based OSB in BioSIPs design, ASTM D 1037 standard was applied. For development of bioboards and BioSIPs to meet requirements as wall, floor and roof enclosures, International Code Council (ICC) and International Building Code (IBC) criteria were applied (Table 1).

# 8 BIOBOARD TESTING

Bioboards were produced, subjected to full-scale testing and compared to hardboard and petroleum-based engineered lumber and standard particleboard products for applications such as building construction, furniture and interior use. Bioboards—as low-carbon-footprint materials without resins and bonding agents—were shown to compare to, or even outperform the petroleum-based counterparts, while providing high-strength-to-weight-ratio, environmental options, whose fabrication as building products actually necessitates consumption of waste stockpiles.

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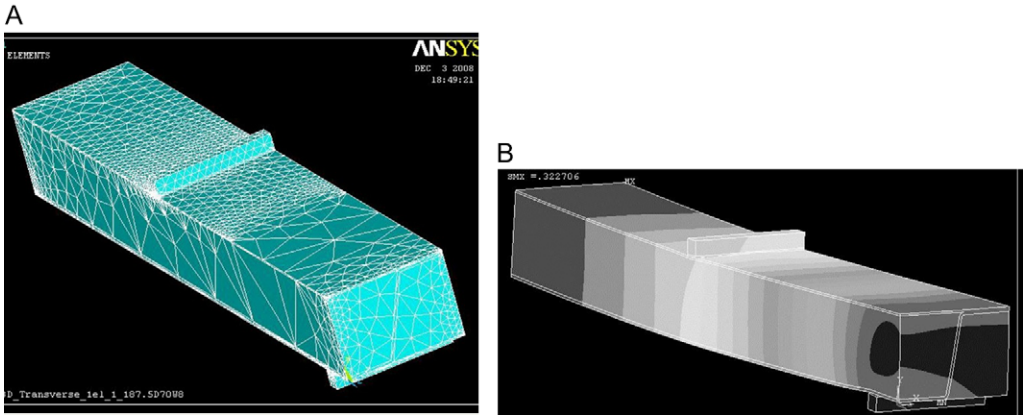


**Figure 14.** *(**A**) and (**B**). ANSYS models showing strength and performance predictions for full-scale transverse load testing. Transverse loads are live and dead building loads applied perpendicularly to a wall, column, floor or roof. A building material's ability to resist these loads and its measured deflection are referred to as its 'transverse loading capacity.' The rectangular shapes above indicate ANSYS isometric renderings of a BioSIPs panel section under simulated load forces applied onto a steel tube bearing against the midpoint of the panel. The wire frame indicates compression of the panel as it resists loads; wire densification indicates major stress points. The gray-shaded section indicates the panel's ability to resist buckling under increased loading with the lighter area indicating the panel's comparatively high resistance measurements. The ANSYS simulations predicted BioSIPs would offer greater resistance to bending loads than would standard SIPs. The results of the actual transverse load testing confirmed this hypothesis. The high transverse loading performance of the BioSIPs panels is attributed to the 3D core serving as an internal stiffening structure for load resistance.*

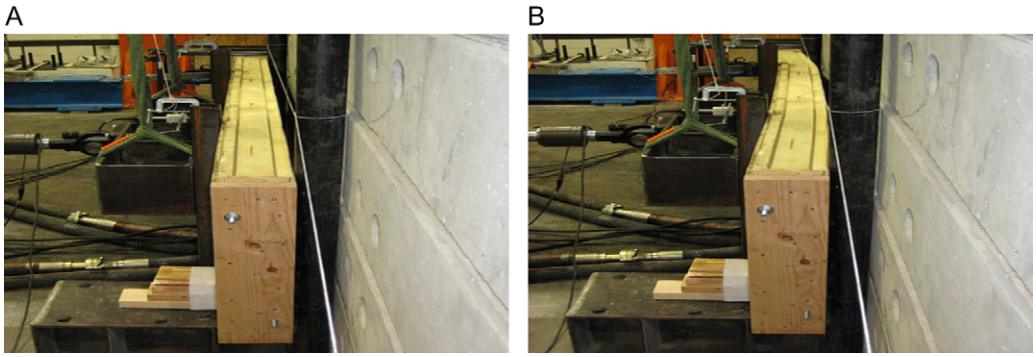


**Figure 15.** *(**A**) and (**B**). Transverse load test being initiated on BioSIPs prototype. Panel shown in bending due to testing-to-failure.*

**Table 1.** *Properties of bioboards compared to those of standard hardboard and a common US particleboard with petroleum-based resins.*

| Property | BioSIPs *untempered* OCC fiberboard | Standard *tempered* fiberboard, average values | 3/8-in particleboard as baseline for average values |
|---|---|---|---|
| Modulus of rupture (MOR), pounds per square inch (psi) | 8600 and higher | 6500 | 1310 |
| Modulus of elasticity (MOE), (psi) | 1 041 400 and higher | 800 000 from 2009 information | 257 000 |
| 24-h thickness increase (TI) | 27% for untempered and with some wet-strength additives in mix | 28% | Not available, but average particleboard values are around 24% |
| Density (lbs/ft^3) | 63 and higher | 65 | 42 |
| Formaldehyde emissions | No formaldehyde, petrochemicals, phthalates, asbestos, or VOCs used in BioSIPs fiberboard manufacture | <0.1 ppm | 0.03 ppm. Contains petroleum-based chemicals and aliphatic aldehydes, rosin acids, terpenes, and polycyclic hydrocarbons |

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# 9 BIOSIPS FULL-SCALE TESTING

BioSIP prototypes were tested at an ASTM-certified materials laboratory to determine whether BioSIPs wall, floor and roof panels meet and can be predicted to function structurally as a more efficient alternative to standard SIPs. The test methodologies were straightforward: Apply a load, measure the displacement at ultimate failure and use the measured data to assess areas for panel design improvement. The following tests were performed:

- Axial compression
- Transverse loading
- Racking shear

*Size of bioboard test prototypes:*

- 3.18 mm (1/8 in) for applications as a flat construction board, and for BioSIPs cores and skins.

*Sizes of BioSIPs full-panel test prototypes:*

- 2.44 m (height) × 0.61 m (width) × 16.51 cm (thickness) (i.e. 8 ft × 2 ft × 6-1/2 in).
- 2.44 m (height) × 1.22 m (width) × 16.51 cm (thickness) (i.e. 8 ft × 4 ft × 6-1/2 in).

## 9.1 Axial loading tests

Axial loading tests were performed based on ASTM E72-05 SIP criteria to determine BioSIPs' ability to withstand loading in downward directions. According to this standard, SIPs' allowable axial loads are to be determined based on the compressive load at which a net axial deformation of 0.125 in occurs, or, from the ultimate load to be borne divided by a safety factor of 4, whichever value is lower.

By protocol, the BioSIPs test prototypes included an integrated wood frame sill and header plate secured with steel nails at the top and bottom of the test panel. The panel was then secured in the testing equipment by means of steel I-beams for uniform load distribution by the load actuator.

### 9.1.1 *Summary and interpretation of axial load testing*

The data in Table 2 show that BioSIPs remained stable under increasing compressive loading over time. Destructive testing resulted in ultimate failure through a combination of cracking and buckling of BioSIPs skins at the top and bottom of the panel near the steel nail connectors.

**Table 2.** *Axial Compressive Loads vs. Deflections for BioSIPs Panels.*

| 2.44 × 0.61 × 16.51 BioSIPs panel | | | | | 2.44 × 1.22 × 16.51 BioSIPs panel | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Time | Load | | Vertical displacement at ends | Horizontal deflection at mid-height | Time | Load | | Vertical displacement at ends | Horizontal deflection at mid-height |
| (min) | (lbs) | (plf) | (in) | (in) | (min) | (lbs) | (Plf) | (in) | (in) |
| 0.0 | 914 | 457 | 0.0000 | 0.0000 | 0.0 | 212 | 53 | 0.0000 | 0.0000 |
| 2.0 | 1763 | 881 | 0.0121 | 0.0050 | 4.0 | 1659 | 415 | 0.0200 | 0.0100 |
| 6.0 | 2831 | 1416 | 0.0270 | 0.0100 | 7.0 | 2825 | 706 | 0.0352 | 0.0150 |
| 10.0 | 3802 | 1901 | 0.0423 | 0.0130 | 10.0 | 4181 | 1045 | 0.0514 | 0.0200 |
| 13.0 | 4919 | 2460 | 0.0574 | 0.0180 | 13.5 | 5896 | 1474 | 0.0720 | 0.0260 |
| 16.0 | 5969 | 2985 | 0.0720 | 0.0200 | 16.5 | 7117 | 1779 | 0.0859 | 0.0300 |
| 19.0 | 7105 | 3553 | 0.0875 | 0.0240 | 19.5 | 8540 | 2135 | 0.1014 | 0.0360 |
| 22.0 | 8070 | 4035 | 0.1024 | 0.0280 | 22.0 | 9474 | 2368 | 0.1104 | 0.0400 |
| 24.5 | 8662 | 4331 | 0.1094 | 0.0300 | 24.5 | 10 194 | 2549 | 0.1182 | 0.0420 |
| 27.5 | 9407 | 4703 | 0.1199 | 0.0320 | 27.0 | 10 921 | 2730 | 0.1271 | 0.0430 |
| 30.5 | 9871 | 4935 | 0.1272 | 0.0340 | 30.0 | 12 569 | 3142 | 0.1425 | 0.0500 |
| 34.5 | 11 550 | 5775 | 0.1469 | 0.0400 | 33.5 | 14 303 | 3576 | 0.1606 | 0.0580 |
| 37.0 | 12 789 | 6395 | 0.1613 | 0.0450 | 36.5 | 15 836 | 3959 | 0.1761 | 0.0620 |
| 40.0 | 14 096 | 7048 | 0.1773 | 0.0500 | 39.5 | 17 136 | 4284 | 0.1910 | 0.0650 |
| 43.0 | 14 950 | 7475 | 0.1926 | 0.0570 | 42.5 | 19 242 | 4811 | 0.2113 | 0.0750 |
| 46.5 | 16 428 | 8214 | 0.2119 | 0.0630 | 45.5 | 20 793 | 5198 | 0.2270 | 0.0820 |
| 50.5 | 17 826 | 8913 | 0.2319 | 0.0710 | 49.0 | 22 973 | 5743 | 0.2501 | 0.0900 |
| 54.0 | 19 377 | 9688 | 0.2518 | 0.0800 | 53.5 | 25 183 | 6296 | 0.2753 | 0.0950 |
| 57.5 | 21 147 | 10 574 | 0.2758 | 0.0930 | 58.0 | 27 155 | 6789 | 0.3000 | 0.1010 |
| 61.5 | 22 960 | 11 480 | 0.2996 | 0.1020 | 62.0 | 29 279 | 7320 | 0.3310 | 0.1100 |
| 66.0 | 25 329 | 12 665 | 0.3319 | 0.1100 | 66.0 | 31 147 | 7787 | 0.3606 | 0.1150 |
| 70.5 | 26 758 | 13 379 | 0.3618 | 0.1210 | 71.0 | 33 278 | 8320 | 0.3915 | 0.1260 |
| 75.0 | 28 223 | 14 111 | 0.3920 | 0.1300 | 75.0 | 36 691 | 9173 | 0.4234 | 0.1260 |
| 78.3 | 28 711 | 14 356 | 0.4133 | 0.1320 | 80.0 | 41 703 | 10 426 | 0.4737 | 0.1430 |



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Using ANSYS predictions prior to testing, the team set an axial capacity loading goal of 3164 pounds per linear foot (plf) for the BioSIPs panels. The panels outperformed this goal with test results showing:

- The 0.61-m-width BioSIPs exhibited a loading capacity of 3589 plf.
- The 1.22-m-width BioSIPs exhibited an allowable load of 2621 plf.

BioSIPs high axial loading performance is attributed to the 3D core acting as a strong columnar structure that yields overall stiffness and internal strength, especially through integration with the bioboard surface skins and insulation.

BioSIPs are expected to be among the strongest SIPs in the marketplace in terms of axial loading capabilities (Figure 16).

Since US testing equipment was used in the experiments, all load values given in the following are expressed in units of kips and feet (Tables 3 and 4).

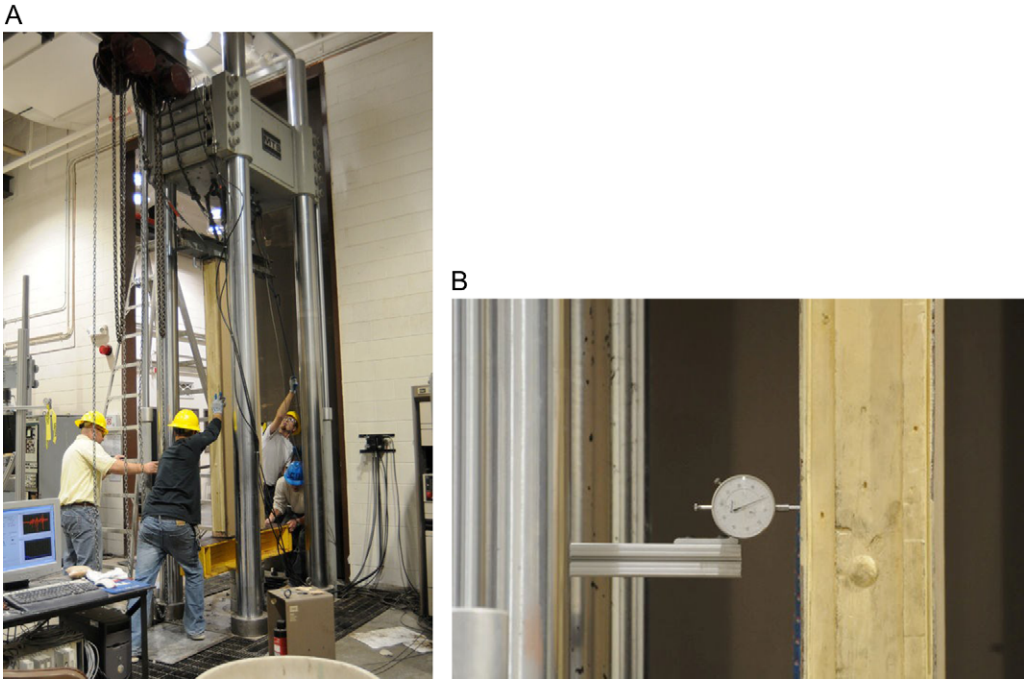


**Figure 16.** *(A) and (B). Axial testing sample of BioSIPs being placed in a 1000-kip MTS actuator (universal testing machine) by team members. Dial micrometer measuring BioSIPs deflection during testing.*

**Table 3.** *Results of axial compression load tests of BioSIPs at key points.*

| Test Standard: ASTM E72, Section 9 – Compressive Load | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Test name | Sample name | Panel properties | | Load at 0.125-in deflection | | Max load | | Deflection at max load | | Failure characteristics |
| | | Size (m and cm) | Weight (lbs) | (lbs) | (plf) | (lbs) | (lbs) | Vertical (in) | Horizontal (in) | |
| Axial 1 | TR2 | 2.44 × 0.6096 | 68.5 | 5823 | 2911 | 17 838 | 8919 | 0.3680 | 0.0790 | Test samples failed by a combination of cracking and buckling of skins near the fasteners at the top and bottom of the panel. |
| Axial 2 | TT1 | 2.44 × 1.22 | 127.5 | 10 884 | 2721 | 41 935 | 10 484 | 0.4761 | 0.1430 | |

**Table 4.** *Axial compression load strains and deflections at allowable loads.*

| 2.44 m × 0.61 m × 16.51 cm BioSIPs Panel | | | | | 2.44 m × 1.22 m × 16.51 cm BioSIPs Panel | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Allowable line Load, $P_a$ Allowable live Load | Vertical deflection | Strain | Lateral deflection | | Allowable line load, $P_a$ | Vertical deflection | Strain | Lateral deflection | |
| (plf) | (in) | (in/in) | (in) | as L/xxxx | (plf) | (in) | (in/in) | (in) | as L/xxxx |

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**Table 5.** *Transverse load results vs. BioSIPs deflection limits.*

| 2.44 m × 0.61 m × 16.51 cm BioSIPs Panel | | | | | 2.44 m × 1.22 m × 16.51 cm BioSIPs Panel | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Initial deflection. | Load | | Deflection | | Initial deflection | Load | | Deflection | |
| (in) | (lbs/sq ft) | | (in) | | (in) | (lbs/sq ft) | | (in) | |
| L/180 | 284 | | 0.51 | | L/180 | 168 | | 0.51 | |
| L/240 | 213 | | 0.38 | | L/240 | 121 | | 0.38 | |
| L/360 | 149 | | 0.26 | | L/360 | 62 | | 0.26 | |
| Allowable load $P_a$ | Failure load, $P_f$ | | Allowable load, $P_a = P_f$ / sq ft | | Allowable load, $P_a$ | Failure load, $P_f$ | | Allowable load, $P_a = P_f$ / sq ft | |
| | (lbs) | (lbs/sq ft) | (lbs) | (lbs/sq ft) | | (lbs) | (lbs/sq ft) | (lbs) | (lbs/sq ft) |
| | 8625 | 563 | 2156 | 141 | | 11 029 | 360 | 2757 | 90 |

**Figure 17.** *BioSIPs prototype undergoing transverse bending test using a 22-kip MTS actuator.*

## 9.2 Transverse bending tests

Transverse bending tests were performed to determine BioSIPs' ability to withstand loads applied perpendicularly to the plane of the panel's longitudinal axis, such as that experienced when live or dead loads act on a building. ASTM E72-05 criteria were applied for these tests. According to this standard, allowable transverse loads of SIPs should be determined based on ultimate load to be applied divided by a safety factor of 4, and at L/180 and L/240.

A two-point quarter-span loading method was applied. BioSIPs prototypes were placed in an elevated position above the laboratory floor, with the top and bottom panel faces bearing against a 3-1/2-in-diameter steel pipe. Transverse loads were applied using a 22-kip MTS actuator in the displacement mode.

### 9.2.1 *Summary and interpretation of transverse load tests*

Results indicate that BioSIPs remained stable under increasing transverse loading over time. Absolute displacement of BioSIPs under transverse loading was recorded at the midpoint deflection. Table 5 presents a summary of test calculations. Ultimate bending and buckling of BioSIPs occurred along the steel members.

**Figure 18.** *BioSIPs prototype secured in racking shear test equipment. Racking shear testing was performed using a 22-kips MTS actuator.*

Using ANSYS modeling simulation prior to transverse testing, the team set an allowable transverse loading goal capacity of 75 lbs/sq ft. The test panels exceeded this goal with following results obtained:

- The 0.61-m-width BioSIPs showed a loading capacity of 141 lbs/sq ft.
- The 1.22-m-width BioSIPs showed a loading capacity of 90 lbs/sq ft.

BioSIPs high transverse loading performance is attributed to the 3D core acting as an internal stiffening structure.

BioSIPs are predicted to perform especially well in terms of their ability to carry transverse loads and are expected to be a superior alternative to standard SIPs (Figure 17).

## 9.3 Racking shear tests

Racking shear tests were performed to determine BioSIPs' ability to withstand asymmetrical forces acting diagonally across panels. ASTM E72-05 criteria were applied for these tests. According to these criteria, the allowable racking capacities of SIPs are determined based on ultimate load required divided by a safety factor of 4, or from the racking load at which a net deflection of 0.125 in occurs, whichever value is lower.

BioSIPs racking shear tests were performed by placing the test prototypes horizontally off the laboratory floor with the



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**Table 6.** *Racking load test results vs. deflection.*

| Test name | Sample name | Panel properties | | Max. load | | Deflection (in) at max. load | | | Net deflection |
|---|---|---|---|---|---|---|---|---|---|
| | | Size (m and cm) | Weight (lbs) | (lbs) | (plf) | Drift (in) | Uplift (in) | Slippage (in) | (in) |
| Racking #1 | TT2 | 2.44 × 0.6096 | 68.5 | 1,699 | 850 | 2.20 | 0.27 | 0.02 | 1.90 |
| Racking #2 | TR1 | 2.44 × 1.22 | 121.0 | 3,665 | 916 | 1.27 | 0.30 | 0.05 | 0.92 |
| Test Standard: ASTM E72, Section 14 - Racking Load | | | | | | | | | |

**Table 7.** *Calculated allowable racking loads of BioSIPs.*

| 2.44 m × 0.61 m BioSIPs Panel | | | | | 2.44 m × 1.22 m BioSIPs Panel | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Failure load $P_f$ | | Allowable load, $P_a = P_f$ / sq ft | | Ultimate load calculation | Failure load, $P_f$ | | Allowable load, $P_a = P_f$ / sq ft | |
| | (lbs) | (plf) | (lbs) | (plf) | | (lbs) | (plf) | (lbs) | (plf) |
| | 1699 | 850 | 425 | 212 | | 3665 | 916 | 916 | 229 |
| Net deflection calculation | Net deflection (in) | | Allowable load (lbs) | (plf) | Net deflection calculation | Net deflection (in) | | Allowable load (lbs) | (plf) |
| | 0.125 | | 158 | 79 | | 0.125 | | 984 | 246 |
| Allowable load = 158 lbs, 79 plf | | | | | Allowable load = 916 lbs, 229 plf | | | | |

panel's long edge rigidly anchored to the test equipment. Lateral forces were applied to the opposite long panel edge using a 22-kip MTS actuator in the displacement mode. Deflection was measured and recorded as 'uplift' at the upper-left face of the BioSIPs prototype for measuring 'slippage'; deflection was also measured at the lower-right corner for measuring the total movement, i.e. 'drift.' The net racking shear displacement of BioSIPs was then calculated as $D_{net}$ = *drift - uplift - slippage*.

Test results indicated BioSIPs to meet required racking shear values. However, in this performance area the panels met code requirements but did not exceed required values. The team interpreted that for BioSIPs to exceed SIP racking shear criteria, an alternate fastening system could be developed for attaching the top and bottom of BioSIPs panels to building substructures. This could enhance BioSIPs' ability to compete with and potentially outperform standard SIPs in racking shear performance.

Ultimate BioSIPs' racking failure occurred through:

- Lifting/tearing of the sill plate from the steel beam
- Tearing of the panel skin around the nail heads at the point of attachment to the sill plates
- Crushing of the BioSIPs panel foam near the load source
- Separation of the foam from the skin and the bioboard panel endplates

### 9.3.1 *Summary and interpretation of racking shear load test*

Using ANSYS modeling simulation prior to testing, the team set a goal of an allowable racking load of 300 plf. The tests revealed the following results, which meet SIP design and performance requirements:

**Figure 19.** *Computer rendering of BioSIPs case study building prior to construction.*

- The 0.61-m-width BioSIPs panels showed a loading capacity of 212 plf.
- The 1.22-m-width panels showed a loading capacity of 229 plf.

BioSIPs racking shear tests indicate that currently designed BioSIPs meet ASTM criteria and will be comparable to other manufacturers' SIPs racking strengths (Figure 18; Table 6, 7).

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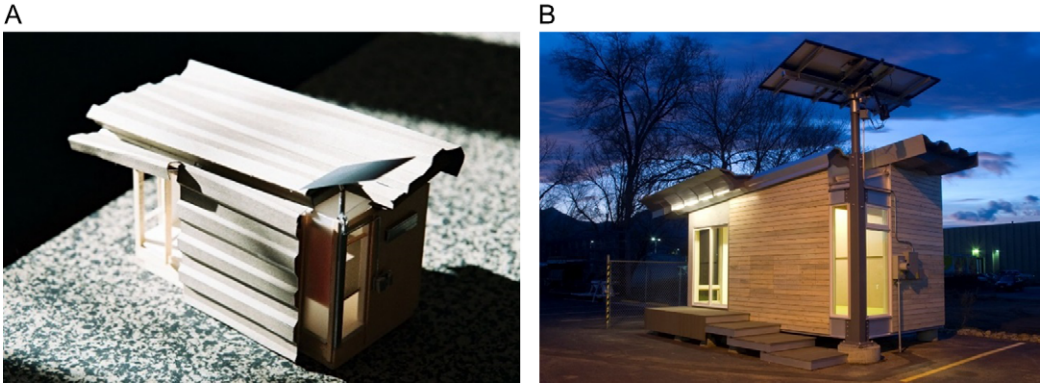


**Figure 20.** *(**A**) and (**B**). Early BioSIPs design concept model. Completed BioSIPs building.*

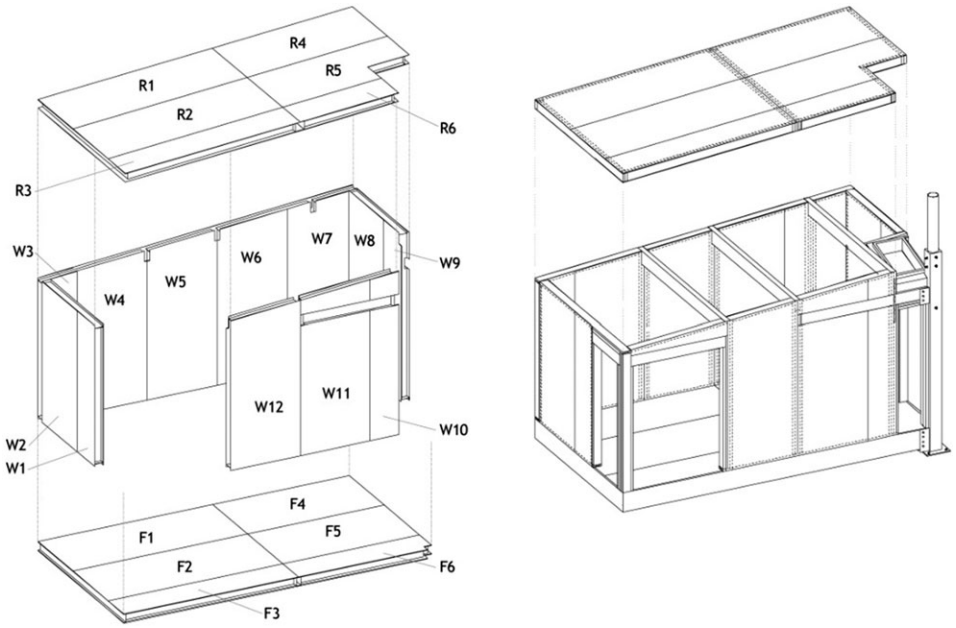


**Figure 21.** *BioSIPs panel layout showing panel sizing, construction sequence, placement, and assembly for the BioSIPs Research Structure.*

**Figure 22.** *State-of-the-art attachment systems joining dense, thin bioboard for the construction of BioSIPs furniture and interior systems.*

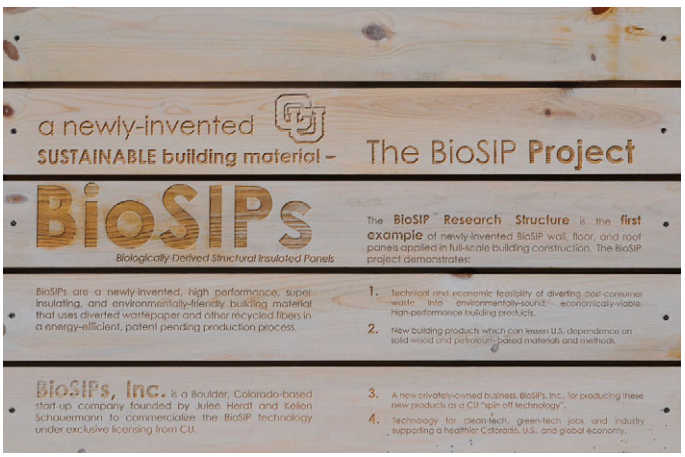


**Figure 23.** *Digital graphics lasered into building walls and surfaces, which relay the project story to visitors while quantifying environmental benefits associated with the biobased inventions created from diverted waste.*



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**Figure 24.** *Student team members installing the dual-axis Sanyo 215 N photovoltaic (PV) solar tracker. The tracker rotates on two axes for maximum energy gains throughout the year and produces 142 kWh of electricity per month while helping power an adjacent commercial building.*

**Table 8.** *Environmental savings achieved through construction of a BioSIPs home.*

A typical US home is 2400 sq ft or approximately 30 ft × 40 ft and two stories tall. Construction of a 'BioSIPs Home' using waste cardboard (OCC) as feedstock to manufacture the required 127.33 BioSIPs wall, floor and roof insulated enclosure panels needed for the home, by using 86 lbs of waste fiber per panel, shows that the following would be diverted:

- 127.33 panels needed × 86 lbs of waste per panel = 10 950 lbs, or 5.48 tons of diverted waste fiber used to manufacture panels for the BioSIPs Home

According to Waste Management, a leading U.S. recycling company, recycling 1 ton of cardboard for new products rather than producing new cardboard saves the following:

- 46 gallons of oil
- 390 kWh of energy
- 6.6 million Btu of energy
- 9 cubic yards of landfill space

Constructing the 'BioSIPs Home' from waste cardboard fibers would save the following:

- 5.48 tons of waste cardboard fibers × 46 gallons of oil saved per ton of recycled cardboard = *252 gallons of oil*
- 5.48 × 390 kw energy saved per ton of recycled cardboard = *2137 kWh of energy*

(*Continued*)

**Table 8.** *(Continued)*

- 5.48 × 6.6 million Btu saved per ton of recycled cardboard = *36 million Btu of energy saved*
- 5.48 × 9 cubic yards saved per ton of recycled cardboard = *49 cubic yards of landfill space*

According to the Idaho Forest Products Commission statistics, the amount of lumber required to be obtained from harvested trees and needed to build the typical 2400 sq ft US home includes approximately the following:

- 16 000 board feet of framing lumber
- 14 000 sq ft of wood products made with petrochemicals, including OSB, glulam beams, wood I-joints, laminated veneer lumber products, hardboard, particleboard and MDF

Use of BioSIPs as reduced-carbon materials would prevent cutting and harvesting of trees required to manufacture these products while reducing petrochemical use in construction

**Table 9.** *Waste and energy savings statistics of BioSIPs research structure.*

Four thousand pounds of recycled post-consumer wastepaper were diverted for construction of the BioSIPs Research Structure. The building even consumed its own cellulose refuse during and for its construction! Some BioSIPs panels were fabricated from the waste generated by the BioSIPs team over the course of the project, such as pizza boxes, job site packaging, architecture drawings and even model building scraps.

- Wall, floor and roof panels = 2285 lbs of post-consumer waste
- Furniture, interior finishes and ceiling materials = 1715 lbs of post-consumer waste

CNC roof trusses construction = 625 lbs of post-consumer wood framing

793 lbs of Colorado beetle kill forest waste from forest floors following a beetle blight = 1510 ft of siding

The BioSIPs Research Structure produces 142 kWh of electricity per month as an alternative to standard grid-tied electrical energy use. This supports a healthier environment, helps to power an adjacent commercial building, and results in the following:

- In annual reduction in $CO_2$ emissions of 3060 lbs per year
- The equivalent of 3808 vehicle driving miles reduced per year in a petroleum-powered car
- The equivalent of planting 134 trees
- An estimated electrical usage savings of $25 per month (at 2016 electricity costs)

## 10 FULL-SCALE BIOBASED INVENTIONS APPLIED IN A CASE STUDY BUILDING

The 'BioSIPs Case Study Building' was designed and constructed using the new biobased inventions to demonstrate their high strength, high thermal performance, energy efficiency and user comfort in a new building typology while diverting 1814 kg (4000 lbs) of biomass into new proof-of-concept biobased

- Modular, structural, wall, floor and roof panels
- Interior wall partitions, ceiling partitions and sliding partitions
- Furniture, cabinets, shelves and interior components

The BioSIPs building is 3.7 m wide, 5.5 m long, and approximately 3.7 m tall (12 ft × 18 ft × 12 ft). It is located in a region

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that experiences extreme heat, cold, wind, rain and snow. The building was exposed to an unexpected 100-year flood, and it withstood the heavy rains, ground water, and moisture without any adverse consequences. For heating, the building relies on a small energy-efficient electric space heater during cold months. It remains comfortable year-round. Passive cooling is achieved through window placement combined with the structure's 'vented' roof, which is an air cavity present between the rippled metal roof sheathing and the underlying BioSIPs roof panels. BioSIP panels for the building's construction were prefabricated at a local SIP factory through minor adjustments to the standard SIP manufacturing methods. They were shipped to the project site for a quick assembly (Figures 19–24).

## 11 CONCLUSION

There are numerous ways to quantify the types of gains that can be achieved through large-scale manufacturing of the biobased waste inventions developed in this project. An individual's perspective drives the choice of metric. To conclude, this paper has provided an overview of the environmental benefits that can be derived through the use of bioboards and BioSIPs panels as the wall, floor and roof enclosure systems in a standard US home via an interpretation of specific natural resources saved, waste diverted and energy conserved (Tables 8, 9).

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