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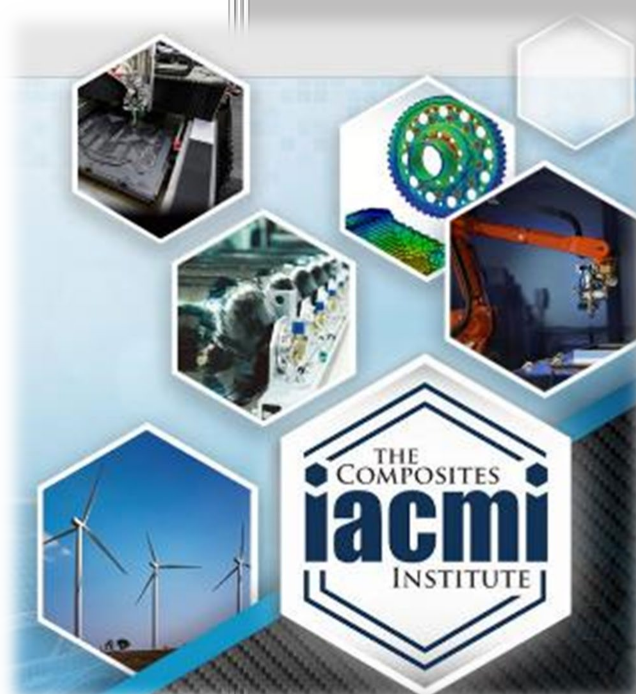
Bamboo Bio-composite Truck/Trailer Decking



Final Technical Report

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ResourceFiber.
BAMBOO FIBER FOR INDUSTRY

U.S. DEPARTMENT OF
ENERGY

Author: Leland Slaven, David Knight

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Bamboo Bio-composite Truck/Trailer Decking

Principal Investigator: David Knight

Organization: Resource Fiber

Address: 1831 29th Avenue, Suite 200, Homewood AL 35209

Phone: 205-747-2832 ext 701

Email: DKnight@Resource-Fiber.com

Co-authors:

- Uday Vaidya, PhD (Chief Technology Officer, IACMI; UT-ORNL Governor's Chair in Advanced Composites Manufacturing
- Lawrence T. Drzal, Professor, Michigan State University, Former Director IACMI Vehicles TA
- John Unser, Technology Impact Manager, IACMI-The Composites Institute
- Soydan Ozcan, Scientist & IACMI Recycling Lead, Oak Ridge National Laboratory
- John Smith, Fontaine Commercial Trailers, Inc.

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1.1 List of Acronyms

AM – additive manufacturing

BF - bamboo fiber

ECM – extrusion-compression molding

FCMF – fibers and composites manufacturing facility

LFT long fiber thermoplastics

MA-PP maleic anhydride

PLA – poly lactic acid

PP – polypropylene

PA6 – polyamide-6 (nylon)

SEM - Scanning Electron Microscopy

SFT short fiber thermoplasticswt% - Weight percent

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N/A

2 EXECUTIVE SUMMARY

Bamboo is one of the fastest growing plants in the world. Massively productive, bamboo will maintain that productivity with limited inputs and minimal management resulting in predictable volume and operating margins and with low overhead. The goal of this project was to develop a bamboo bio-composite trailer decking product that replaces apitong, is lighter weight, stronger and luminescent. The collaboration partners, Fontaine, Resource Fiber and IACMI, worked closely to develop the bamboo bio-composite decking to Fontaine Trailer's (end-user) specifications. The various technological objectives were (a) To conduct a comprehensive Design of Experiments study for bamboo composites to understand the structure-property relationships for different resin composites and bamboo forms (strips, woven, bulk etc); (b) To establish the nail pull out characteristics of trailer deck geometry bamboo composite form. The nail pull out is a critical test in trailer decks; (c) To design, process and prototype select number of trailer decking planks for Fontaine evaluation; and (d) To conduct life cycle analysis to conduct energy calculations from the various conversion steps of the bamboo from crop to product. The project meets DOE/IACMI metrics of reduced embodied energy, lightweighting and lowering the cost of the end product. It also offers a green solution to a value-added application, i.e. trailer decking.

The development goals and benefits of bamboo composite decking included:

A. Decreased weight when compared to Apitong and Gen 1, thereby reducing operating costs and petroleum usage due to increased miles per gallon.
B. Flexibility to allow camber design into trailers.
C. Luminescence to increase safety during low light and dark conditions.
D. Composite material to maximize use of bamboo bio-composites as substitute for petroleum-based composites.
E. Embedded layer(s) of conditioned bamboo for added strength and stability.
F. Improved safety over Apitong by temporary cargo indentation in planks for better stability.
G. Cradle-to-cradle design so end-of-life becomes beginning-of-life for other products.

Resource Fiber's bamboo biocomposite trailer decking passed nail pullout tests as compared to apitong (incumbent), was lighter weight than apitong, and used less embodied energy particularly when bamboo is sourced domestically. The planks were optimized in the lab setting to the extent possible and successfully installed on the trailer at Fontaine for field testing. Despite the process not being fully optimized due to through-heat and tooling limitations within the budget constraints, the prototype decking withstood 400 cycles of reverse fatigue loading of a 107,000 lb Caterpillar 349F which was extreme conditions of field testing by Fontaine Trailer.

Resource Fiber plans to outsource production of a next round of planks with a commercial pultrusion processor, then to do a re-test with Fontaine Trailers. Tooling specific to the part is required. Long-term commercial plans are to continue outsourcing production while supplying bamboo fiber and mats. Commercial markets include heavy haul trailers, military trailers, and decking for marine, industrial and residential use.

3 INTRODUCTION

Bamboo is one of the fastest growing plants in the world. Massively productive, bamboo will maintain that productivity with limited inputs and minimal management resulting in predictable volume and operating margins and with low overhead. It is:

(a) Renewable – Bamboo yields six times more fiber per acre than trees. An *annual harvest* begins after just 5-6 years for biomass bamboo and 10-12 years for timber bamboo;

(b) Sustainable – Bamboo captures five times more carbon than a like-sized wood timber forest and requires little water, fertilizer and no pesticides. Bamboo biochar accelerates plant growth by improving soil function and water retention. Companion planting is used to enrich the soil;

(c) Versatile – Bamboo produces a raw material fiber for a wide variety of uses. It is lightweight and has the tensile strength of steel;

(d) When coupled with additional products that could be manufactured in the U.S. using bamboo fiber, the scale of the industry becomes sizeable and, in time, is projected to be valued in the billions of dollars just in the U.S.

(e) Test results within the scope of the Resource Fiber NFE-16-06296-CRADA Grant indicate that bamboo can replace up to 70% of petroleum used in composite and glass fiber materials.

Partners/Collaborators

Fontaine Commercial Trailer is a Marmon Highway Technologies/Berkshire Hathaway company. Its customers have made it the largest platform trailer manufacturer in the world. More fleets and owner operators are earning their living with Fontaine than ever before. They know that Fontaine offers the best quality, the highest resale value and the most reliable performance in the industry– All backed by the best warranty in the business. Fontaine offers superior technology and consistently leads the industry with innovative new products.

Fontaine Commercial Trailer intends to purchase from Resource Fiber certain bamboo bio-composite trailer decking being developed by Resource Fiber in collaboration with IACMI. The decking must meet performance standards and specifications that meet industry and Fontaine requirements. Fontaine projects annual volume to exceed 600,000 square feet.

The University of Tennessee (UTK) and the Oak Ridge National Laboratory, Manufacturing Demonstration Facility (MDF) has comprehensive assets and skilled personnel in the Fibers and Composites Manufacturing technologies. Technologies of relevance to the IACMI project include processing, characterization, testing and modeling of bamboo-based composites. Several processes including extrusion-compression, pultrusion, compression molding, compounding, additive manufacturing and wet laid processing of bamboo composites apply to trailer decking. Graduate and undergraduate students and technical staff support the collaboration with Resource Fiber and Fontaine.

Michigan State University/Scale-up Facility based in Corktown, Detroit is the IACMI's home to large scale equipment including a 4000 ton Schuler press, a 3500 ton Milicron injection molder, Tencate tape line, double belt press and related equipment for large scale composite molding. The bamboo forms require pressing of trailer deck panels to full scale as the program progresses from the development phase to the large-scale prototyping.

Resource Fiber has acquired and developed proprietary equipment, intellectual property, key personnel, and customer relationships – all related to bamboo industrial products. The company has six issued patents and five U.S. patent applications pending. Resource Fiber also has trade secrets and proprietary technology relevant to the proposed project. New and significant patentable intellectual property has been created within the scope of this project.

4 BACKGROUND

Over the last several decades, the quality of wood fiber used in a wide variety of products, (including industrial uses such as construction materials and paper) has declined due to the substitution of fast growing, less mature trees for the once dominant old growth trees. The highest quality wood fiber originates in old growth trees. Products still made from old growth wood fiber are in short supply or will be within 10 years, depending on species.

The apitong (Dipterocarpus grandiflorus) species of hardwood is historically the most widely used for trailer decking for 18-wheel trucks and shipping container floors, yet resources are becoming scarce. Apitong is old growth and its lumber is cut and imported from Malaysia, Indonesia, and other Asian countries. Supplies are projected to be depleted in about 10 years. One of the largest users of apitong in North America (Fontaine) anticipates apitong price increases as supplies dwindle. The International Union for Conservation of Nature (IUCN) Red List of Threatened Species lists the majority of apitong subspecies as Critically Endangered due to habitat loss (new palm oil plantations) and conversion into lumber.

Certain bamboo species, when engineered and manufactured into products correctly, can replicate the characteristics of old growth wood. This results in higher quality products, greater durability and stability, and a longer product life than many wood products currently on the market.

Resource Fiber LLC is the only vertically integrated bamboo company in the U.S. driving domestic bamboo manufacturing. Operations are in Tennessee and southwestern Alabama, an area selected for its exceptional growing conditions and cost-competitive locale. Bamboo is a rapidly renewable plant that is widely used in the manufacture of hundreds of products - the majority imported from China. Resource Fiber's mission is to generate renewable resources for long-term profit, improve people's lives through U.S. job creation, and bring health to the planet through replenishing soil and air quality.

The goal of this project was to develop a bamboo bio-composite trailer decking product that replaces apitong, is lighter weight, stronger and luminescent. The collaboration partners, Fontaine, Resource Fiber and IACMI, worked closely to develop the bamboo bio-composite decking to Fontaine's specifications as noted in Table 1.

The technical objectives of the project included:

A. To conduct a comprehensive Design of Experiments study for bamboo composites to understand the structure-property relationships for different resin composites and bamboo forms (strips, woven, bulk etc).
B. To conduct adhesion studies on bamboo with thermoplastic resin
C. To establish the nail pull out characteristics of trailer deck geometry bamboo composite form. The nail pull out is a critical test in trailer decks.
D. To design, process and prototype select number of trailer decking for Fontaine evaluation.
E. To conduct a life cycle analysis (LCA) for energy calculations from the various conversion steps of the bamboo from crop to product.

The development goals and benefits of bamboo composite decking included:

A. Decreased weight when compared to apitong and Gen 1, thereby reducing operating costs and petroleum usage due to increased miles per gallon. Gen 1 refers to Generation 1 with conventional Apitong wood deck used in the incumbent solution
B. Flexibility to allow camber design into trailers.
C. Luminescence to increase safety during low light and dark conditions.
D. Composite material to maximize use of bamboo bio-composites as substitute for petroleum based composites.
E. Embedded layer(s) of conditioned bamboo for added strength and stability.
F. Improved safety over Apitong by temporary cargo indentation in planks for better stability.
G. Cradle-to-cradle design so end-of-life becomes beginning-of-life for other products.

Table 1. Summary of the mechanical specifications supplied by Fontaine required to be met for them to purchase trailer decking.

Properties	Apitong	Goal of bio-composite
Density (lb/ft3)	46	≤
% Tangential Shrinkage	10.9	≤
% Radial Shrinkage	5.2	≤
% Volumetric Shrinkage	16.1	≤
Hardness Resistance (Janka*) (psi)	1,520	≥
Modulus of Rupture (Strength) (psi)	19,900	≥
Modulus of Elasticity (Stiffness) (million psi)	2.07	≥

5 RESULTS AND DISCUSSION

5.1 Processing of raw bamboo

Resource Fiber (RF) processed 7.5 tons of bamboo fiber of which about 500 lbs were used for this project. RF receives bamboo from Latin America. The material is conditioned into mats and slats. The full length of ten feet is typically saved for railroad ties. In this work the continuous bamboo would serve as the core of the deck panel. Excess trims and edges are cut to smaller lengths and saved for processing shown in Figure 1, and described later in this report. Hence, all forms of the bamboo are utilized, with a goal of zero waste.

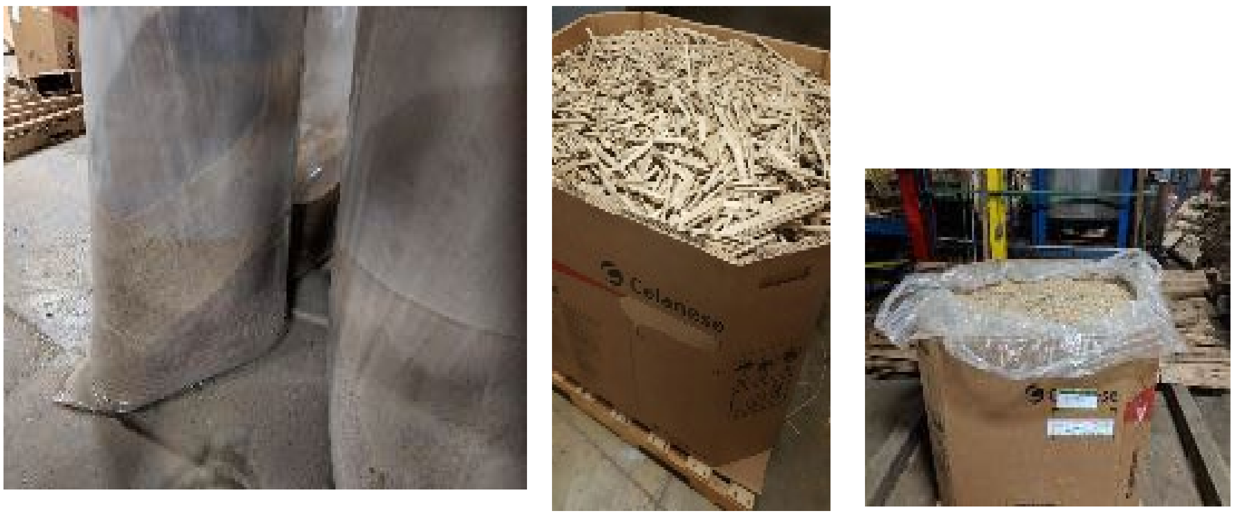

Figure 1, Illustrates off cuts from the processing in the form of solid fiber results in edge cuts, sawdust and short fibers for compounding bamboo bio-composites for decking exterior.

In terms of material make up for the decking skin and core, the core bamboo strips are interlayered with polypropylene (PP) film to wet out the strips. The skin (jacket) would comprise either (a) additive printed compound made of bamboo-polylactic acid (PLA) or extrusion-compression molding bamboo-PP. This report elaborates on the full-scale decking panels as developed and tested.

5.2 Preliminary molding trials with additive printed bamboo PLA and bamboo strips

Since the design concept considers either 3D printed bamboo skins (jacket) or extrusion/pultrusion/extrusion-compression molded skin (jacket) with bamboo strips serving as the core - these were evaluated on a coupon basis. As part of the initial trials with 3D printed bamboo PLA and how they interact with the bamboo strips, a design of experiments was created. For this, bamboo PLA was 3D printed at the Manufacturing Demonstration Facility (MDF), Oak Ridge National Laboratory (ORNL) on the Big Area Additive Manufacturing (BAAM) machine.

Figure 2 illustrates how the BAAM piece and bamboo strips were co-molded. Upon heating during compression molding the coarse bamboo would melt into the continuous bamboo strips to form a homogenous structure, which was validated with initial experiments. Transverse tension and flexural samples from this material were tested.

Figure 2. Sequence of compression molding. A 6"x6" tool is used. Bamboo strips are laid in the tool. The 3D printed bamboo-PLA is placed over the strips. The layup is heated and pressed to produce a laminate.

Differential scanning calorimetry (DSC) was conducted on 3D printed bamboo-PLA to determine its optimal processing conditions. From Figure 3 it can be noted that the melting point determined by DSC is 148°C. Hence all panels were processed in the 170^{0}C range for compression molding.

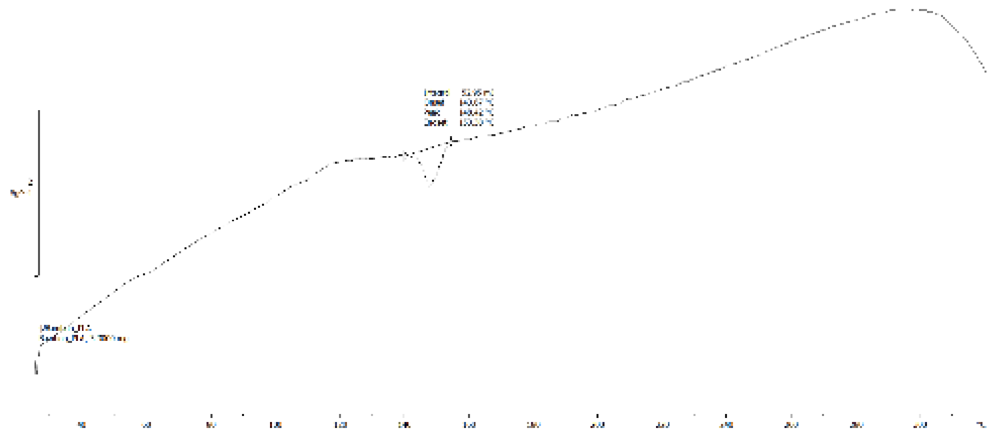

Figure 3. DSC of bamboo-PLA to determine the optimal processing conditions in compression molding. The x-axis is temperature and y-axis is the heat release.

One of the goals of producing the co-molded coupons was to evaluate the interfacial bonding between bamboo and resin in the 3D printed bamboo-PLA. Different processing conditions were used, one at 28 psi,and the other at 111 psi.

The stack was compression molded at 170^{0}C at a pressure 28 psi. The pressure was adjusted to balance flow versus consolidation, hence excess flow would not be encountered. The panel dimensions were 150 mm 150 mm x 22 mm, Figure 4.

Bamboo-PLA

Bamboo strips

Figure 4. Example of strips and consolidated panel

5.3 Transverse tension (TT) testing

ASTM D7291/D7291M-15 Standard test method for through thickness flatwise tensile strength and elastic modulus of a fiber reinforced polymer matrix composite material was used to evaluate the transverse tensile response of the bamboo to bamboo-PLA composite.

Since the skin to core bonding influences the composite performance, it is important to evaluate the separation of these constituents, for which the transverse impact test is ideal. The test involves preparing disk shaped coupons which are bonded to cylindrical flat face metal halves, see Figure 5. A tension load is applied forcing the specimen to witness transverse tension till failure occurs. The integrity of the interface is hence measured quantitatively and qualitatively.

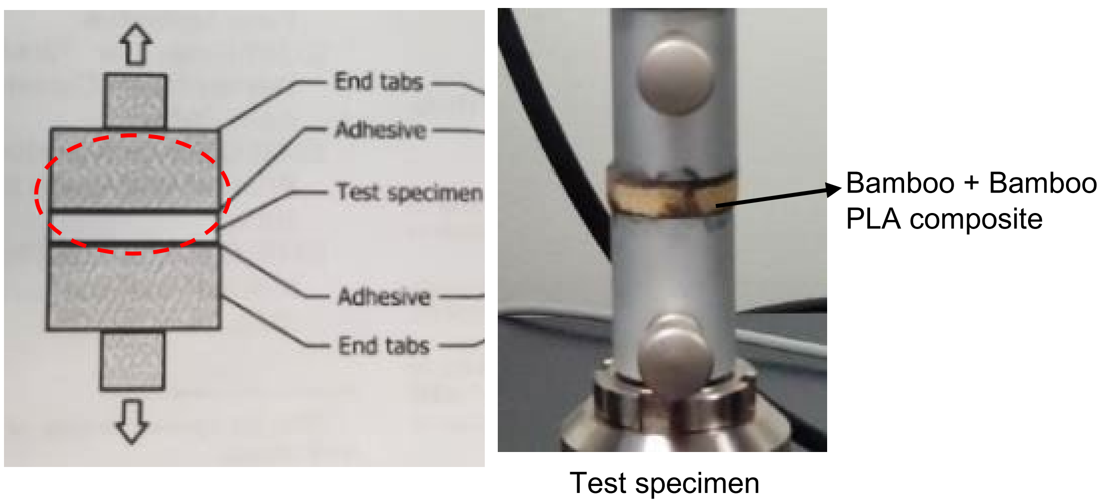

Figure 5. Schematic of the flatwise tension test (Left) schematic and (Right) specimen under transverse tension test

Table 2. Flatwisetensile strength of 20% (bottom) and 40% bamboo-PLA (top).

Specimen	Flatwise tensile strength (MPa)	Flatwise tensile strength (MPa) Average	Std. Dev
1	2.5	2.65	0.2
2	2.8		
3	2.4		
4	2.7		
Specimen	**Flatwise tensile strength (MPa)**	**Flatwise tensile strength (MPa) Average**	**Std. Dev**
1	3.25	4.1	1.2
2	2.84		
3	5.09		
4	5.25		

Figure 5 illustrates the samples that were used per the transverse test protocol. Table 2 illustrates the average of 4 specimens with the bamboo core-bamboo-PLA for the 20% by weight bamboo-PLA indicating 4.1 MPa transverse tension strength. Table 2 provides raw data for two sample types, 40 wt% bamboo-PLA and 20 wt% bamboo-PLA respectively both with bamboo-core. It can be seen that the average transverse strength reduces from 4.1 MPa to 2.65 MPa as the bamboo content increases. This can be explained by less resin content to bond the bamboo, making it easier to microcrack during tension.

5.4 Flexural testing

Flexural testing of the samples was conducted in accordance with ASTM D7264 / D7264M – 15 - Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials. Figure 6 illustrates the panel, samples and testing protocols. An increase in flexural properties was seen with the increase in fiber % in bamboo-PLA part (20 wt % to 40 wt %). 150 % increase in flexural strength and 180% increase in flexural modulus was observed for 40 wt% over 20 wt% respectively. It may be noted that the flexural strength and modulus trends are consistent with fiber dominated properties see Table 3 and Figure 7 While transverse tensile strength was matrix dominated, hence the trends were opposite, i.e. TT for 20% bamboo-PLA was higher than 40% bamboo-PLA.

Bamboo + bamboo PLA panel

Flexural specimens cut from the panel

Flexural testing

Figure 6.   Flexural test (a) Bamboo+Bamboo-PLA panel; (b) flexural test samples cut from the plate; and (c) flexural testing of the beam

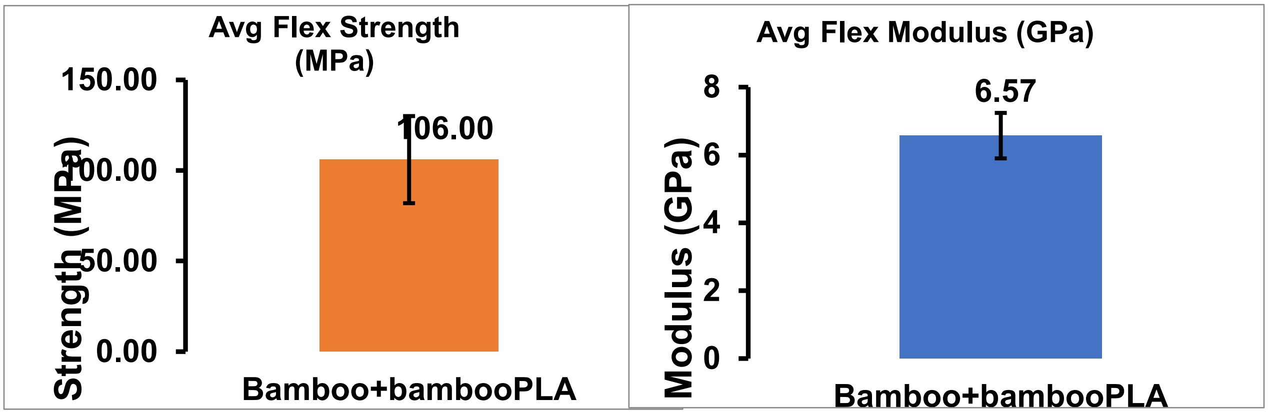

Figure 7. Flexural strength and modulus for 40% bamboo PLA with bamboo core

Figure 8 illustrates representative flexural failure mode for the bamboo core-bamboo/PLA sample. The failure is primarily through tension failure on the underside (opposite to loading direction). The continuous bamboo core strips were on the underside. They underwent fracture leading to onset of delamination initiation. The failure was primarily dominated by fiber fraction, hence the 40wt% fraction exhibited higher properties than the 20% bamboo-PLA.

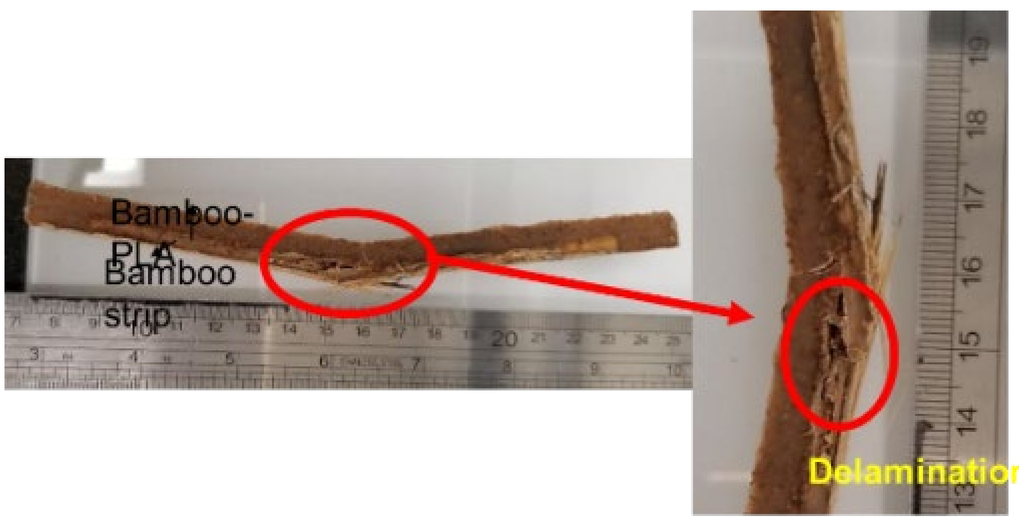

Figure 8. Representative failure modes in flexural loading of bamboo-PLA/bamboo strip

5.5 Extrusion compression molding of bamboo PLA and PP

The goal of this section was to produce and evaluate the bamboo-PLA and bamboo-polypropylene (PP) through an extrusion-compression molding (ECM) process. The resulting material is compression molded into plates. In the actual production these would form the skin (jacket, face) of the decking. But before going to that step, flat plate trials were conducted to evaluate process and properties.

This process is used for manufacturing of materials in pellet form (unreinforced, short fiber thermoplastics (SFTs), long fiber thermoplastics (LFTs)). ECM process is a combination of two basic operations, namely extrusion and compression molding. The pellets are fed into the low shear extruder (plasticator) where the temperature of the plasticator is maintained above the melting point of the polymer, and a 'charge' is produced. The hot, molten charge is then transferred to the mold mounted in a fast-acting compression press. The closing of the press results in the flow of the charge within the mold cavity, to obtain the desired shape. The part is then removed from the mold after the material is subjected to determined 'dwell time' under pressure prior to its removal. Figure 9 and 10 illustrates the ECM process cycle. It is to be noted that the extruder used in this process is a low shear type, which helps to retain maximum fiber length, ultimately resulting in maximum mechanical properties in the finished product.

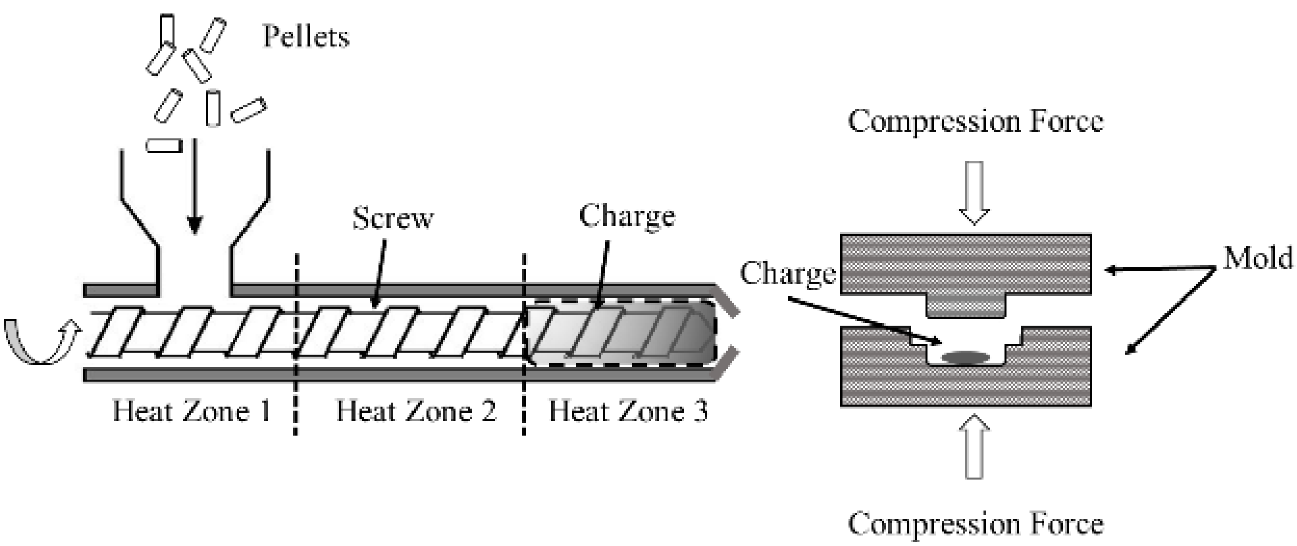

Figure 9. Extrusion-compression molding schematic

Figure 10 illustrate the process flow of compounded bamboo-PP pellets through a B-30 Impco Plasticator. The material is plasticized and then compression molded at high rate of speed 300 inches per minute to press into plates. The charge was consolidated at a pressure of 500 psi with a dwell time of 3 minutes.

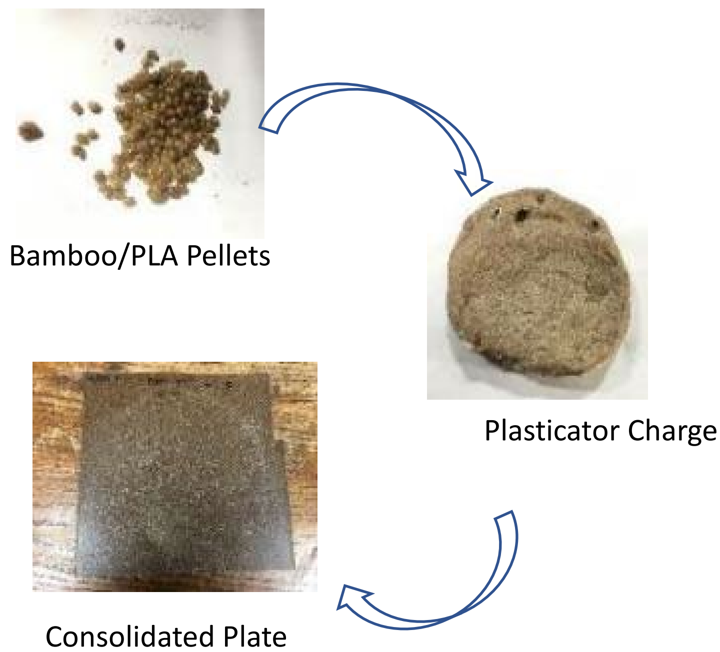

Figure 10. Process flow with bamboo-PP in ECM. Compounded bamboo-PP pellets are fed through the plasticator to produce a charge. The charge is then compression molded into flat plate.

5.6 Flexure and Izod impact testing

The flexural strength for bamboo-PLA and bamboo-PP is shown in Figures 11a and 11b respectively. For PLA systems, the neat PLA provided the highest properties. The flexural strength property decreased with increase in fiber content from 20, 30 to 40 wt% bamboo. However, the flexural modulus increased with adding bamboo to PLA. For bamboo-PP, adding bamboo fibers enhanced both the strength and modulus over neat PP. The highest values were obtained for 5% and 10% respectively, and 15 and 20% were still above that of neat PP. To maximize the use of bamboo in the system and other benefits of its use, the study moving forward used 20 wt% or greater bamboo content.

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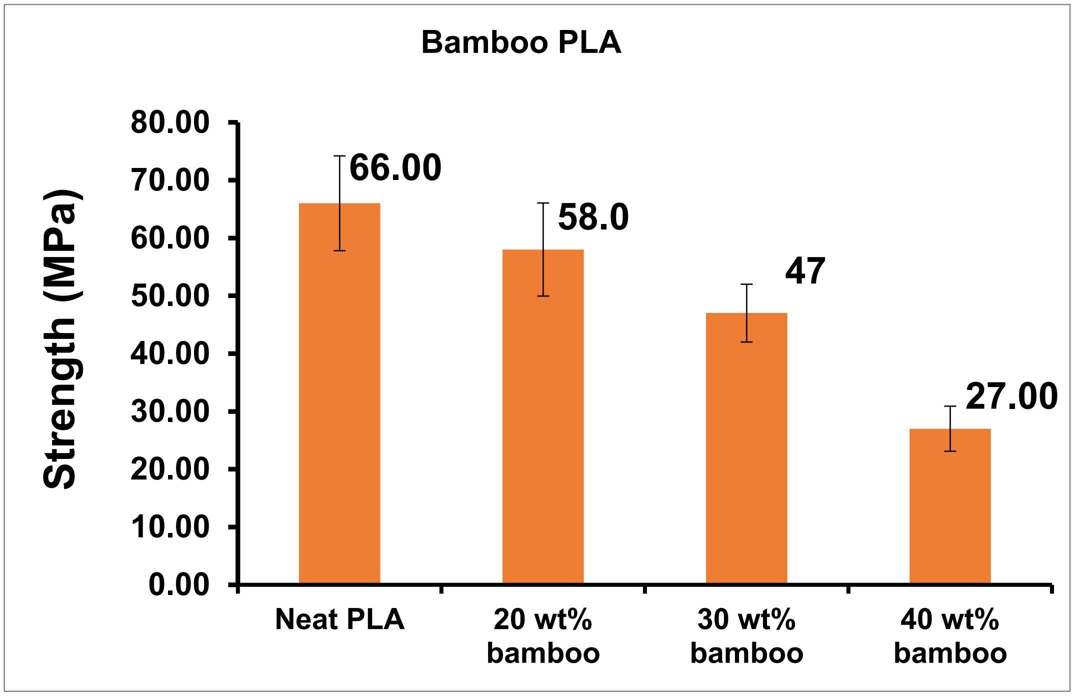


Figure 11a . Flexural strength of bamboo-PLA produced via ECM

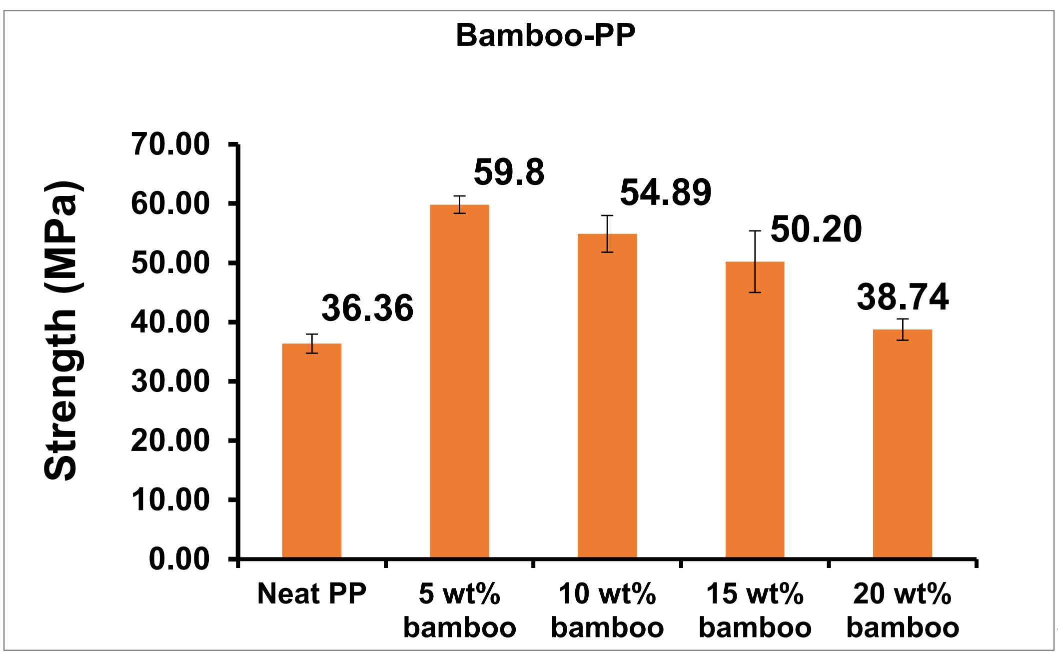
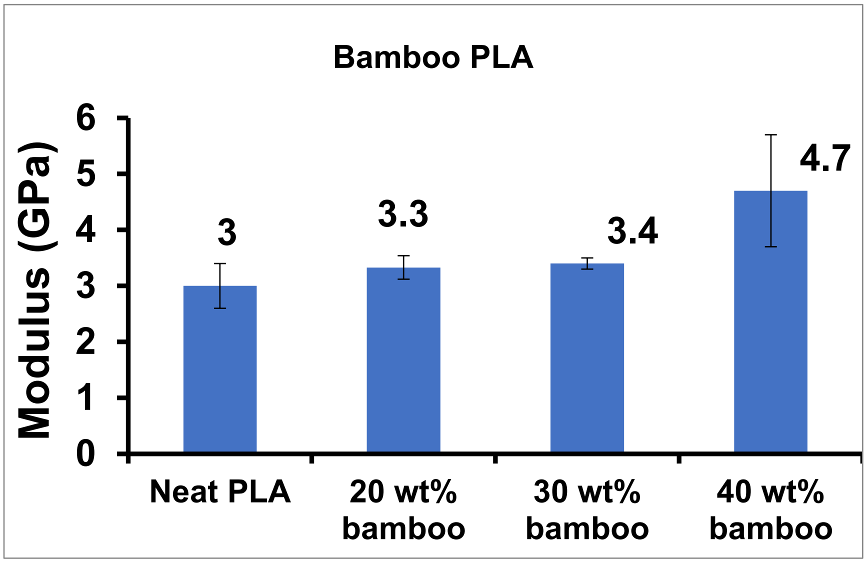


Figure 11b. Flexural strength of bamboo-PP produced via ECM

The failure originated at the tension side and ran through the thickness of the samples. With longer fibers this mode can be curtailed from providing a continuous fracture path. The Izod impact strength trends are illustrated in Figure 13. The bamboo-PLA exhibited the highest Izod strength at 20 wt% loading and this reduced at higher fiber loading. The bamboo-PP had inverse proportionality to fiber loading. The neat PP exhibited the highest Izod resistance which is expected due to the ductile nature of PP and the fibers act as constraints reducing the strain in the sample. There is some compromise between gain in modulus versus reduction in ductility.



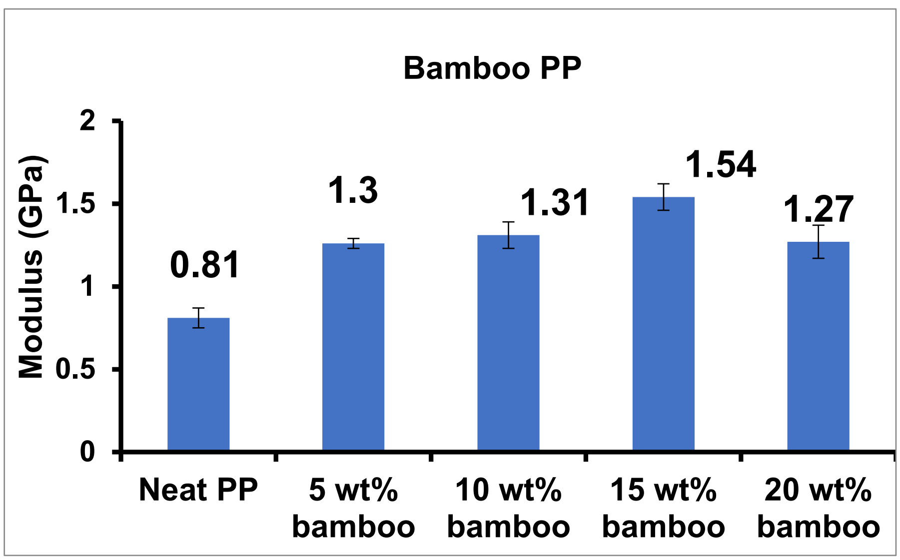
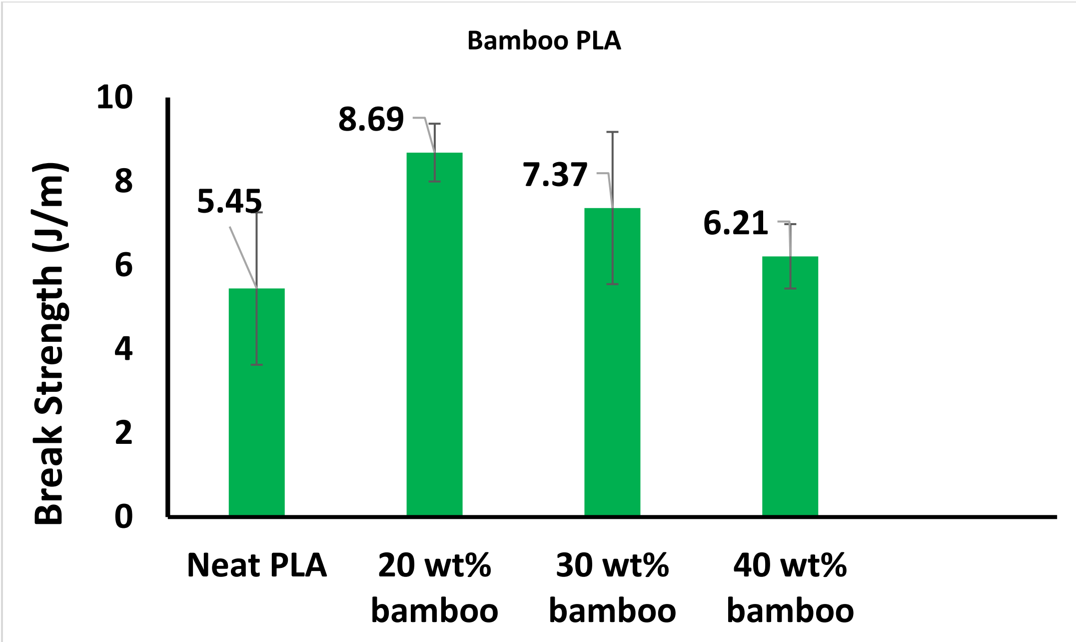


Figure 12. Flexural modulus for bamboo-PLA and bamboo-PP



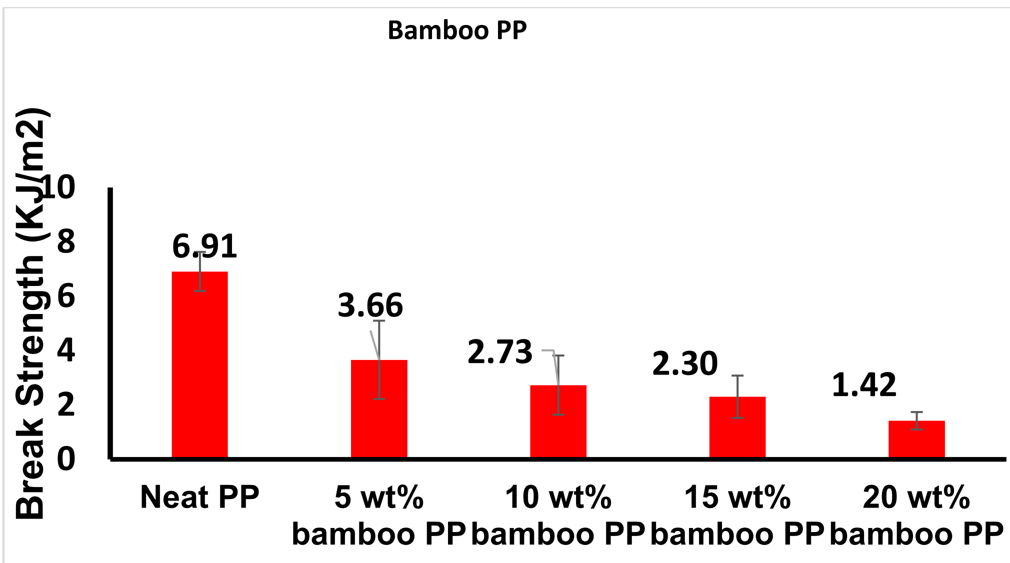


Figure 13. Izod impact data for bamboo/PLA and bamboo/PP

5.7 Summary of preliminary results (Transverse tension and flexure)

- Flexural strength of bamboo-PLA specimens decreases with the increase in fiber wt%, whereas flexural modulus increases with the increase in bamboo wt %
- Poor bonding and irregular shape of bamboo fibers might be responsible for the deterioration of strength properties. However, stiffness increased with increase in fiber content.
- Impact strength of the 20 wt% bamboo-PLA specimens are higher than the neat PLA specimens. However, further increase in fiber wt% decreases the impact strength.

6 Adhesion of Bamboo Fiber to Polypropylene and Phosphorescent PP

Summary. Bamboo has attractive mechanical properties and is a candidate reinforcement for various polymer composite structural applications. However, to obtain optimal mechanical properties and durability, adhesion between the bamboo and a neat or modified polypropylene polymer is necessary. This portion of the project investigated the conditions and surface treatments required to provide acceptable levels of adhesion of polypropylene and phosphorescent modified polypropylene to bamboo. Results indicate that several factors need to be addressed to optimize adhesion: removal of native bamboo surface by mechanical sanding; chemical treatment of the bamboo to chemically activate the surface for adhesion to maleic anhydride functional polypropylene coupling agent; adequate drying conditions to remove absorbed and adsorbed water; and the correct combination of temperature and pressure.

After extraction, bamboo fibers are generally chemically treated to properly bond with polymer matrices in order to exhibit the mechanical properties required for the desired application. Many surface modifications have been reported to improve the interfacial adhesion between the composite constituents[15,17–19], with alkali treatment being one of the simplest and most effective methods [20]. Alkali treatment using sodium hydroxide (NaOH) solutions is one of the most common methods for treating bamboo fiber bundles [21] and can enhance not only the interfacial adhesion between natural fibers and polymeric matrices but also the mechanical, physical and thermal properties of the fibers [22,23]. This treatment promotes solubilization of hemicellulose and lignin [21,24] and separates the fibers into fibrils, which increases the available surface area of the fiber to be 'wet' by the polymer matrix enhancing the interfacial bonding [23]. The treatment is also capable of increasing the chemical reactivity of the fiber by breaking hydrogen bonds and increasing the number of free hydroxyl groups [23,24]. Bonding in the composite interphase can also occur by mechanical anchoring since the treatment increases the roughness of the fiber surface [24].

In this study, bamboo strips were used as-received and were surface treated with NaOH to improve their potential for adhesive bonding. To further improve the performance of the composites, alkali treated bamboo strips were coated with maleic anhydride functionalized polypropylene to enhance their adhesion to the polypropylene matrix, the effects of modifying the bamboo fiber (BF) surface with NaOH and maleic anhydride (MA-PP) on the morphological and flexural properties was investigated in order to optimize the adhesion.

Surface treatment of Bamboo with NaOH. NaOH was purchased from Avantor (Macron Fine Chemicals). The bamboo strips were soaked in a 5 wt.% NaOH solution at room temperature for 5 h. The mass ratio of water to bamboo was 30:1. The treated bamboo was rinsed with deionized water (DI) water several times to obtain a neutral pH in the rinse water. This was followed by drying at room temperature for 20 h, and then oven drying at 60 °C for 3.5 h. These bamboo specimens are referred to as NaOH modified.

Surface treatment of Bamboo with MA-PP emulsion. Maleic anhydride modified polypropylene is a commonly accepted coupling agent to promote adhesion between a hydrophilic surface such as bamboo and a hydrophobic polymer such as polypropylene. Three methods were investigated to apply ma-PP to the bamboo surface. In the first, a thin film of ma-PP was made and applied to the bamboo surface under heat and pressure. This method did not produce acceptable results. A second method consisted of producing a ma-PP powder which was then dispersed in water and sprayed on the surface of the bamboo. This also did not produce acceptable results.

A commercial product, a maleic anhydride modified polypropylene emulsion Michem® Emulsion 91735, was obtained from Michelman and selected as the coupling agent. This liquid water-based emulsion provided ease of application and superior wetting of the bamboo. The NaOH modified bamboo was treated with the ma-PP emulsion with the following procedure: The bamboo was vacuum dried in an air-circulating oven for 15 min at 200 °C. The Bamboo strips were immersed in the ma-PP emulsion for 10 seconds followed by removal of excess ma-PP by repeated brushing with a paintbrush. The ma-PP treated Bamboo was dried under a laboratory exhaust hood overnight at room temperature. This resulted in a thin uniform ma-PP film and this material and procedure was used for the entire project.

6.1 Bamboo Surface Characterization.

Scanning Electron Microscopy (SEM). Bamboo as received, NaOH modified and ma-PP modified were examined with a Carl Zeiss Auriga FIB scanning electron microscope at an accelerating voltage of 5 keV. Fibers were mounted on the SEM sample holder on top of carbon tape. The fracture surface of flexural coupons was also observed. All samples were sputter-coated with tungsten to prevent surface charging.

X-ray photoelectron spectroscopy (XPS). Bamboo as received, NaOH modified and ma-PP modified were characterized by XPS using a Physical Electronics 5400 ESCA. Survey spectra were collected at 187.85 eV pass energy and higher resolution spectra were collected with 29.35 eV pass energy. Prior to XPS investigation, NaOH/GO modified Bamboo surfaces were rinsed multiple time with DI water to remove physically bonded GO. Lap Shear Test. Lap Shear specimens were prepared as shown in Figure 14.

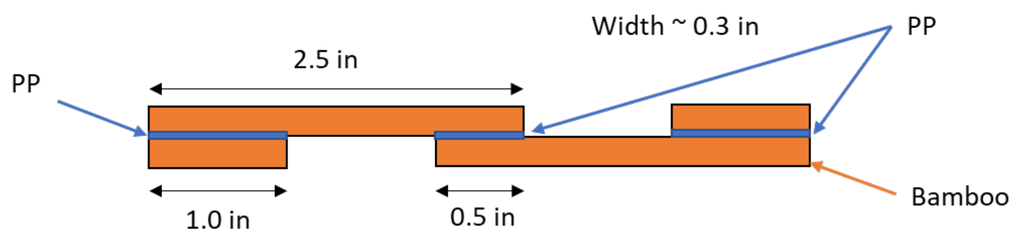


Figure 14. Schematic diagram of the Bamboo+ PP Lap Shear Specimen.

Lap Shear tests were conducted on a United Testing Systems SFM-20 load frame using a 1000-pound load cell and a cross-head motion of 0.05 in/min. Optical microscopy was used to determine if the failure mode was interfacial or within the bamboo.

6.2 Results and discussion (Surface treatment)

After the alkali treatment with NaOH solution, the surface materials (consisting of hemicelluloses, lignin, pectin, wax and impurities were partially removed. The surface of the Bamboo is rougher due to the removal of the surface materials. This roughness may be beneficial to promote mechanical interlocking between the bamboo surface and the polymer. After NaOH treatment, the fiber bundles are more prominent and can be distinguished. The bamboo fibers have diameters ranging from 10 to 40 microns. The treatment with 5 wt.% NaOH solution used in this work was effective has been shown to be effective in cleaning the surface without degrading the fiber integrity and mechanical properties.

The surface chemical composition of Bamboo surface and the treated Bamboo surface was determined by XPS. The wide-scan survey spectra with elemental assignments are shown on Figure 15.

All the spectra exhibited the main Bamboo surface constituent peaks assigned to carbon (C1s) and oxygen (O1s) and also detected a sodium peak (Na1s), due to the alkali treatment. Even the non-treated Bamboo surface has a small amount of Na (0.9%) resulting from the NaOH to extract the fibers from the bamboo culm at the supplier.

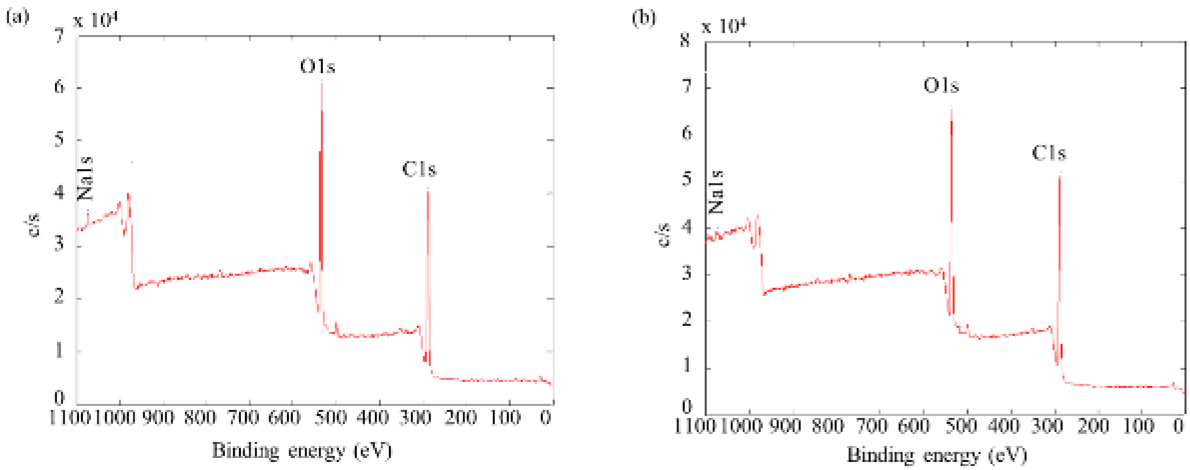


Figure 15. XPS survey of (a) Bamboo Surface (b) NaOH modified Bamboo Surface

The elemental atomic composition and the carbon to oxygen ratio (C/O) of the fibers are summarized in Table 3. Bamboo surface had a carbon content of 66% that increased to 70% after treatment with NaOH.

Table 3. Percent element composition for Bamboo Culm Surface (b) NaOH modified Bamboo Culm Surface.

Sample	C/O	C1s	O1s	Na1s	Ca2p
BF	2.0	66	33	0.9	0.6
NaOH modified BF	2.4	70	29	0.7	0.4

The deconvolution of C1s peak for Bamboo Surface and the NaOH modified Bamboo Surface are given in Figure 16 and summarizes the relative amount of C1s components, which includes C1: C-C, C2: C-O-C, C-O and C3: O-C-O, C=O. The C1s spectrum of Bamboo surface and NaOH modified Bamboo surface are relative similar. This signifies C1s spectrum for C-C, C-

O-C and O-C=O components with similar binding energy of 284 eV. This provides an indication of the overall reactivity of the surface.

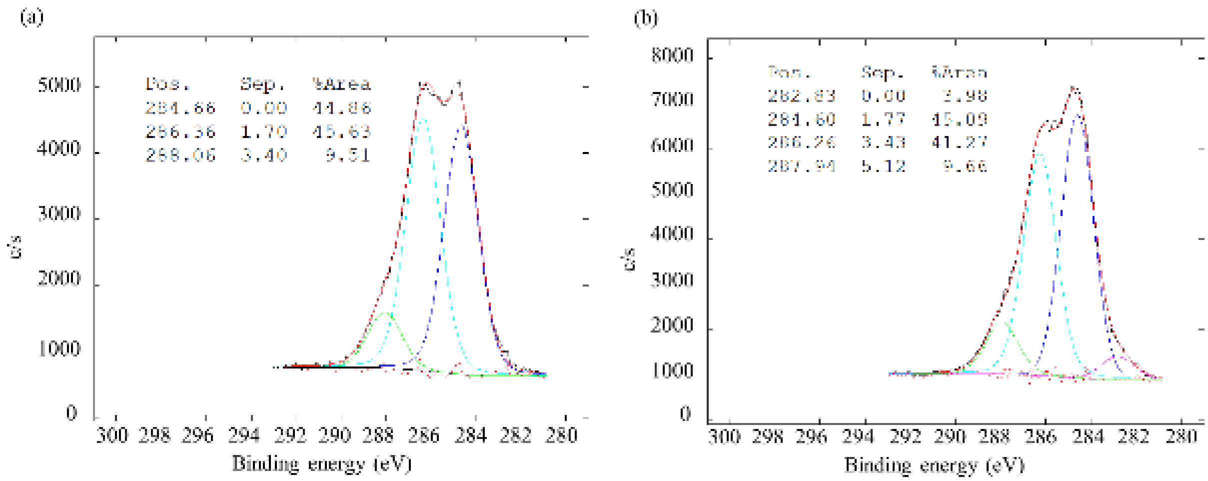


Figure 16. Deconvolution of C1s peak for (a) BF, (b) NaOH modified Bamboo.

Table 4. Relative amount of C1s components (%) for Bamboo, NaOH modified Bamboo.

Sample	C1	C2	C3
BF	45	46	10
NaOH modified BF	45	41	10

6.3 Lap Shear tests of Bamboo Culm Surface

NaOH surface Treatment. The as received and NaOH treated Bamboo Culm surfaces were fabricated into lap shear specimens as shown in Figure 16. The lap shear results for the as received bamboo are shown in Figure 17. The images of the fracture surfaces show a clear difference in failure mode from interfacial to cohesive in the polypropylene matrix after the NaOH treatment. The 18% increase in the lap shear strength for the NaOH modified Bamboo surface can be due to the removal of non-cellulosic materials during the alkali treatment[14].

Table 5. Lap share results before and after NaOH treatment

	Lap Shear Strength		
	Average	Std	% increase
BS	3.6	0.5	
NaOH BS	4.3	0.5	18%

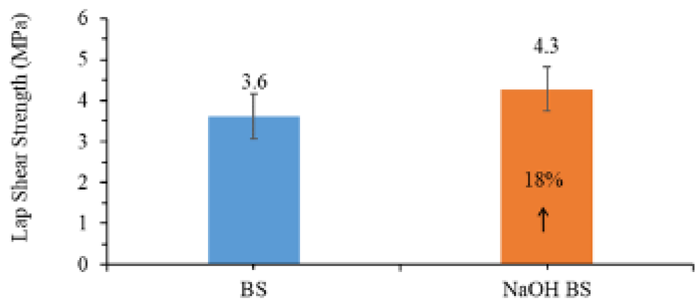


Figure 17. Deconvolution of C1s peak for (a) BF, (b) NaOH modified Bamboo.

Maleic Anhydride-PP Treated Bamboo. The maleic anhydride modified polypropylene (MA-PP) emulsion Michem® Emulsion 91735 was applied to the NaOH treated Bamboo as described earlier and then fabricated into Lap Shear coupons. The results (Figure 18) show that the addition of the ma-PP further improved the lap shear strength and the failure mode showed a greater degree of mixed mode failure.

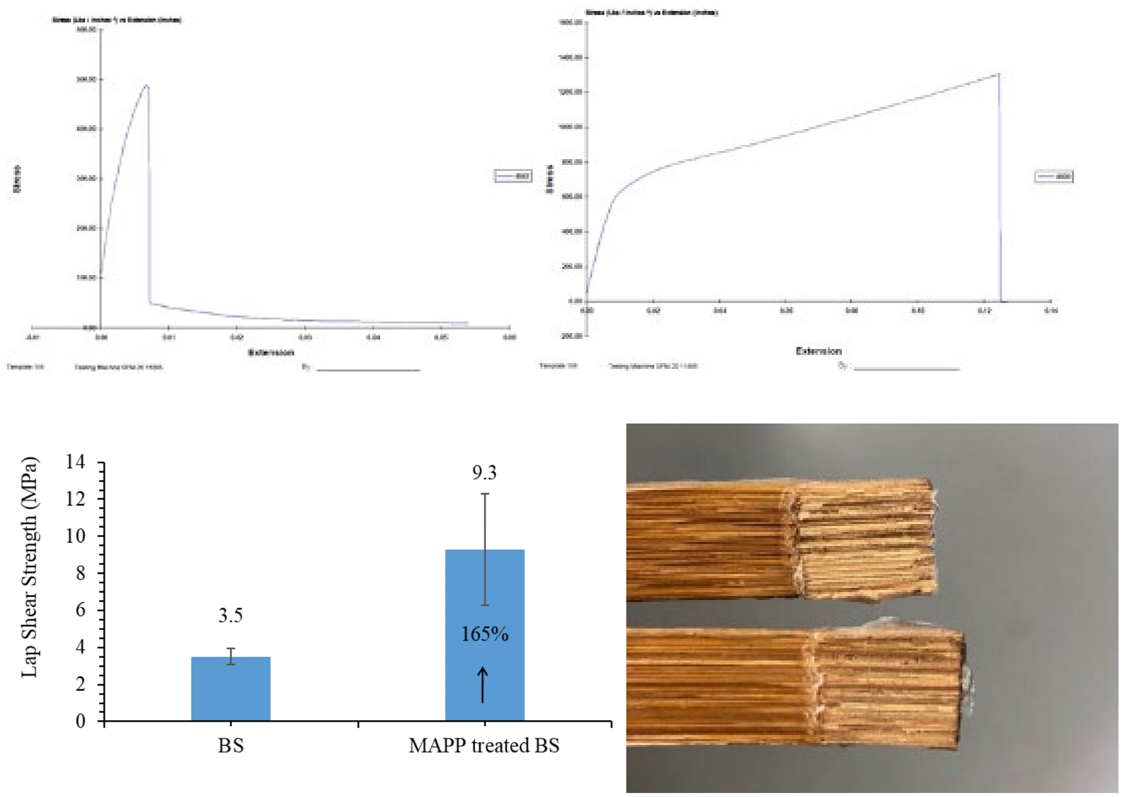


Figure 18. Typical load-displacement curves for NaOH treated and ma-PP treated bamboo surfaces (BS). The failure surfaces exhibited a larger degree of mired mode failure.

The strain-to-failure of the coupons increased from about 1%, and interfacial failure to about 12% demonstrating primarily cohesive failure. The maximum shear stress at failure increased from 3.5 to 9.3 MPa an increase of 165%. It was also noticed that the scatter in the failure stress was quite high (~30%). This could be the results of the variation in the thickness of the ma-PP emulsion.

6.4 Fluorescent-PP Adhesion to Bamboo.

An additional requirement for the project was to determine the surface treatment and adhesion of a fluorescent coating for the bamboo surfaces. Fluorescent Masterbatches and Compounds were identified as available from the RTP Company (Winona, MN). A sample of their Green Phosphorescent Polypropylene Masterbatch RTP 199X 98579 C SSC-63778 (FPP) containing 50% phosphorescent filler was obtained from the company as recommended for compatibility with PP. Lap Shear coupons were prepared using the same procedures identified earlier for the neat PP. The RTP compound (FPP) was compressed into a film and applied to the Bamboo surface with and without the ma-PP emulsion.

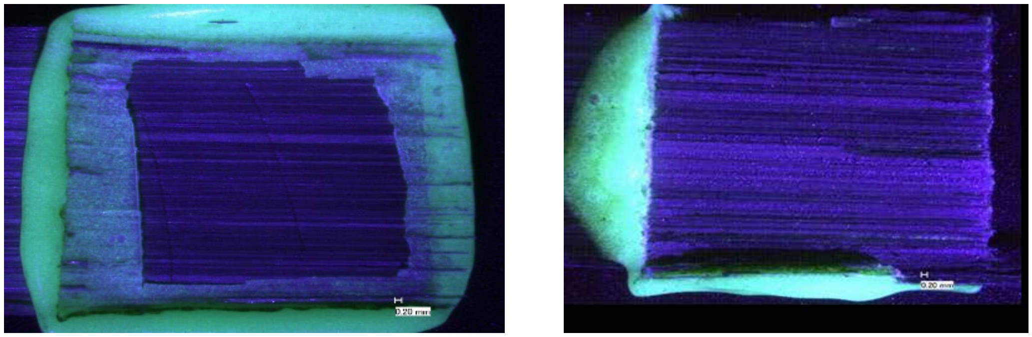


Figure 19. Failure surface between as-received Bamboo (left) and ma-PP treated bamboo (right)

The failure surfaces of the lap shear strength coupons are shown in Figure 19. The ma-PP emulsion coupling agent treatment resulted in a more cohesive failure compared to the as-received coupon.

Figure 20 displays the lap shear strength of both the FPP and PP lap shear coupons. The lap shear strength values for the FPP/ma-pp composites were slightly less but comparable to the PP/ma-PP system 7.4 MPa vs 8.2 MPa.

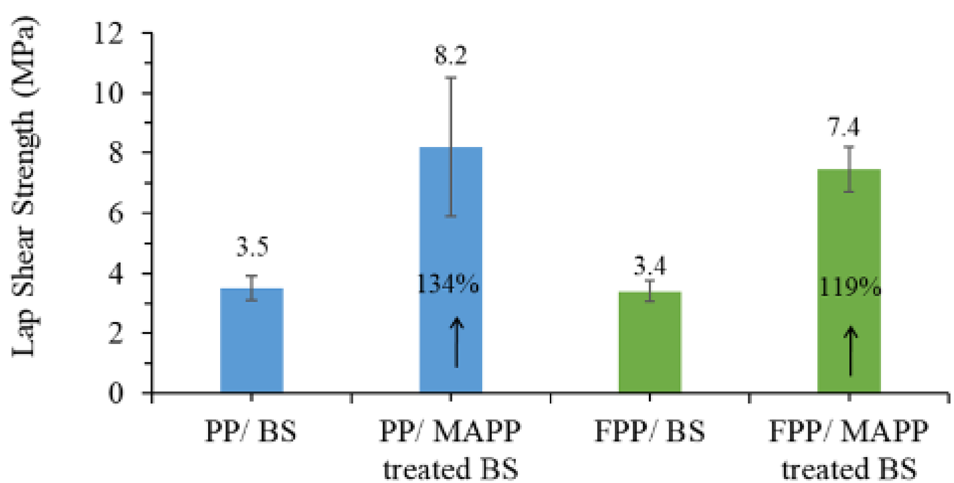


Figure 20. Lap Shear Strength results for PP and FPP with as-received and ma-PP treated bamboo.

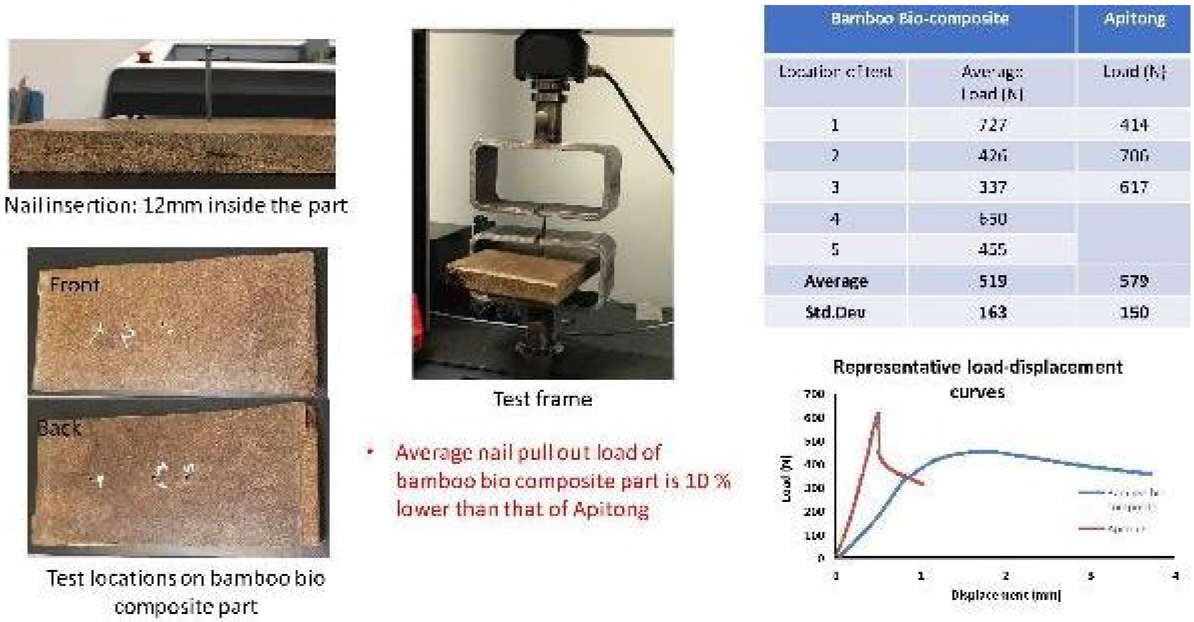
6.5 Bamboo Surface Treatment Recommendations:

In order to ensure optimum adhesion of the polypropylene to the bamboo surface, the bamboo surface must be prepared properly. This portion of the project investigated the conditions and surface treatments required to provide acceptable levels of adhesion of polypropylene and phosphorescent modified polypropylene to bamboo. Results indicate that several factors need to be addressed to optimize adhesion: removal of native bamboo surface by mechanical sanding; chemical treatment of the bamboo to chemically activate the surface for adhesion to maleic anhydride functional polypropylene compiling agent; adequate drying conditions to remove absorbed and adsorbed water; and the correct combination of temperature and pressure.

6.6 Nail pull-out

Nail pull-out is a critical test for truck decking since cargo and dunnage often gets nailed to the decking. Apitong has an inherent self-sealing attribute because it is a hard wood with the natural resin from the plant serving this function of self-healing. In this work our team devised a nail pull-out test (Figure 21) for a standard nail of 0.149" diameter. The nail was driven into the plank and pulled on a Test Resources test frame in tension at low test speed of 0.1 mm/min. Table 6 provides a summary of the nail pull out results and compares it to apitong as the baseline. Variability was observed for both bamboo-PP and apitong. The pull out ranged from 337 to 727 N (SD=163) for bamboo-PP and 414 to 706 N (SD = 150 N) for apitong. Average nail pull out load for bamboo-PP was 10% lower than Apitong. The failure modes were similar in both cases, Figure 22. The hole left by the nail pull out was 0.149" for Apitong while it was 0.140" for bamboo-PP indicating excellent self-healing attributed to the ductility of the PP within the bamboo constituent. The figure also illustrates a bolt attached in the bamboo-PP panel, typical of use as part of assembly. RF completed in-house weatherization testing and observed the moisture content to be stable, i.e. additional moisture ingress did not occur. This illustrates the effectiveness of bamboo PP to hold fixture of different diameters and thread types, i.e. the threads would not become loose due to moisture ingression

Table 6. Embedded within Figure 21- Nail pull-out results



Bamboo Bio-composite		Apitong
Location of test	Average Load (N)	Load (N)
1	727	414
2	426	706
3	337	617
4	650	
5	455	
Average	519	579
Std.Dev	163	150

Figure 21. Illustration of nail pull out in bamboo-PP plank. The figure shows a nail 12 mm inside the part, the front of the specimen and the specimen in the nail pull out fixture in a load frame. The corresponding load displacement curves are also shown for apitong and bamboo-PP. The blue is the bamboo-PP and the red is apitong. The high ductility of the PP constituent is beneficial to the bamboo-PP solutions.

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Nail 0.149”　　Apitong hole 0.149”　　Bamboo hole 0.140”

Figure 22. Hole dimensions after nail pull out in apitong and bamboo-PLA respectively. The rightmost figure is a bolt used as part of assembly. This also illustrates the effectiveness of bamboo PP to hold nail pull out of different diameters and thread types.

7 Full scale fabrication at SURF and UT

Full scale decking panel development was undertaken based on the initial trials discussed up to this point in the report. Although a production path may utilize a pultrusion process to co-pultrude the bamboo core strips with the outer discontinuous bamboo jacket, that was not an option in this program due to budget and asset constraints. Instead, the approach taken was to develop a representative length (section) that represents the decking panel, and that was still testable at Fontaine Trailers, the industrial partner.

When it was determined that an alternative processing strategy would be needed, we decided to produce bamboo-PP extrusion compression molded plates to jacket the long bamboo strips. Since a large number of plates were needed, preliminary tests were run to evaluate the feasibility of producing them. Figure 23 illustrates a simple blended ECM panel with 50 wt% bamboo with PP to produce a sample approximately 1.125" thick. This process was then used to produce ~200 plates at UT using the ECM process.

Figure 23. Representative trials for bamboo-PP panel(s) to be used as skin (jacket) in the production of the full scale deck panel

To produce the 200 panels, (see Figure 25) bamboo-PP pellets were compounded at Techmer PM as shown in Figure 24 (left). About 2000 lbs of bamboo-PP was compounded and used in the production of the 200 plates described here. Figure 24 (right) shows the full length bamboo strips that would be placed as core in the full length decking panel during molding at SURF.

Figure 24. Simple blending 50% conditioned bamboo fiber with PP and long solid strips of bamboo core 1.125" thick:

Figure 25. Some of 200 panels of bamboo-PP made via ECM at the UT FCMF. The panels were edge trimmed to size to fit in the deck mold (tool) in line.

7.1 Processing of deck panels at UT

Based on discussions with Fontaine it was determined that a 4 foot length would be acceptable for field testing. UT had just commissioned a 75 ton Dake compression press with a 5 ft daylight opening. The RF tool was modified to fit the UT Dake press with platen size 40"x40" and arranging the layup diagonally in the press platens. Cartridge heaters were added to the tool for heating. We also incorporated resistive heating with copper wires/mesh inside the bamboo layers, which were connected to a heater controller. Results achieved included:

- Four-foot plank weighs 17 pounds; density measures 41.82 lb/ft^3, 9.09 % lighter than apitong. The areal density of the panels was in the 4.7 to 5.1 per sq ft range.
- We developed a process using the modified tool.
- We achieved improvements but had some flow issues using the pre-cast ECM bamboo-PLA plates. In a production tool this can be readily addressed.
- We achieved flow on the top, sides, and ends but had issue with full encapsulation without degradation of the material in a reflow process.
- Scaling up current 0.6 ft^2 to 100 ft^2 and 0.029 m^3 to 1 m^3 decking

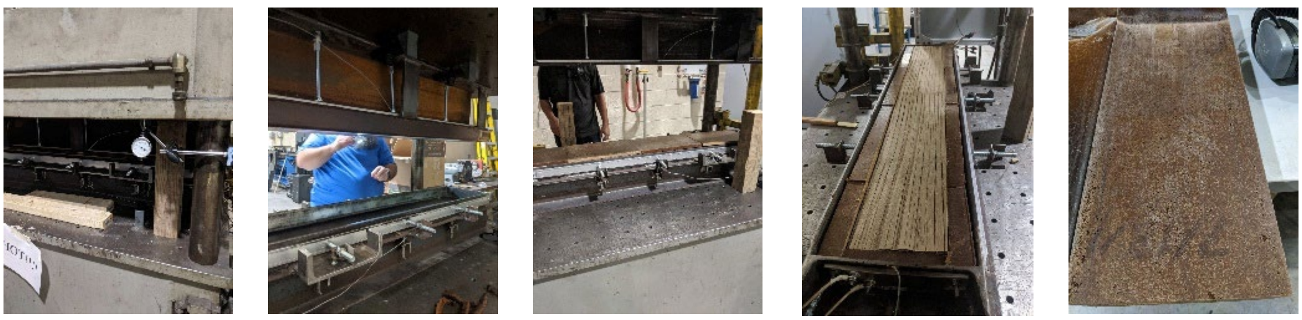

Figure 26. Various steps of processing 4 feet bamboo-PP panels at UT on the Dake press

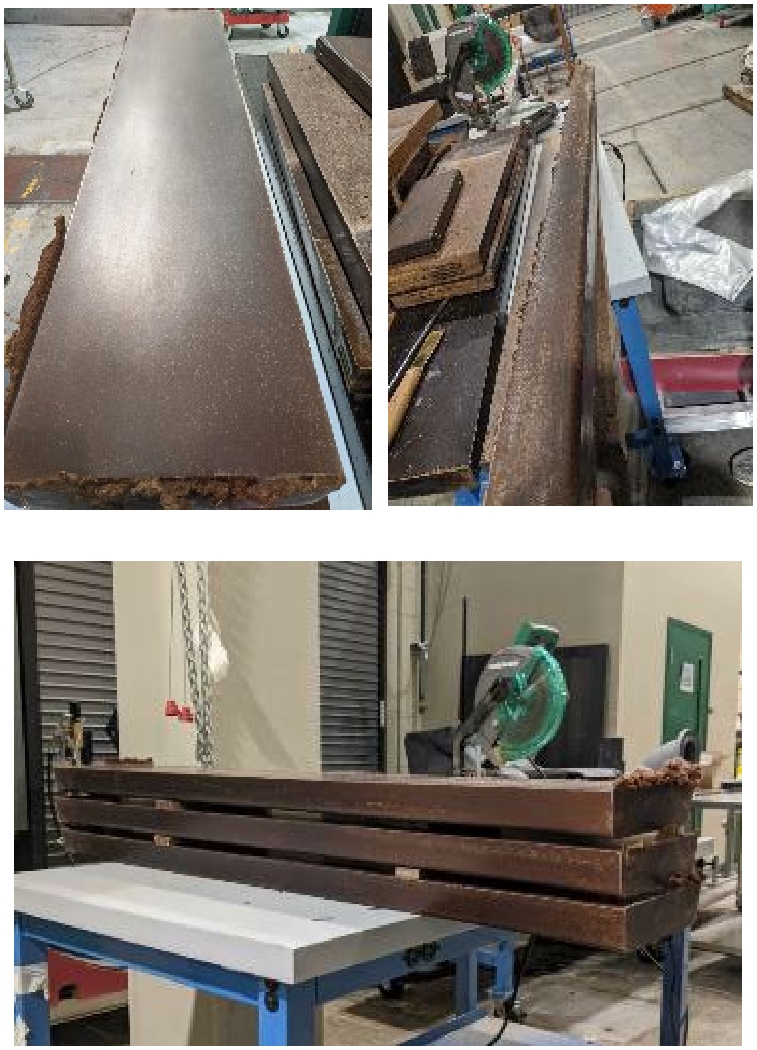

Figure 27. Bamboo decking panels produced at UT

7.2 Full scale testing at Fontaine Trailers, Jasper, Alabama

The decking planks produced at UT were then sent to Fontaine Trailers, Jasper, Alabama for testing. Fontaine used a Caterpillar CAT 349F (107,200 lb) to cyclically drive onto and off a Magnitude 55-ton low boy. This test evaluates the planking toughness due to breakover impact and plank hardness due to grouser tractive forces. Grousers are devices intended to increase the traction of continuous tracks, especially in loose material such as soil or snow. This is done by increasing contact with the ground with protrusions, similar to conventional tire treads, and analogous to athletes' cleated shoes. On tanks and armoured vehicles, grousers are usually pads attached to the tracks; but on construction vehicles they may take the form of flat plates or bars. The combination of 750 load cycles were completed. The planks were rearranged based on which ones failed and where they failed. Due to the excavator track width, which was greater than the plank width, the outriggers were deployed with apitong. Hence the apitong plank and bamboo-PP blank were side by side. Therefore, at any given time, the tested plank shared half track width with an apitong plank. This negatively impacted the test as the outrigger planks are the most damaged during breakover.

Assuming 4-inch width and a plank inertia value of $4.875in^4$, a bending stress of 9.4Ksi is calculated. This gives roughly a safety factor of two for apitong which is rated at 19.9KSI modulus of rupture.

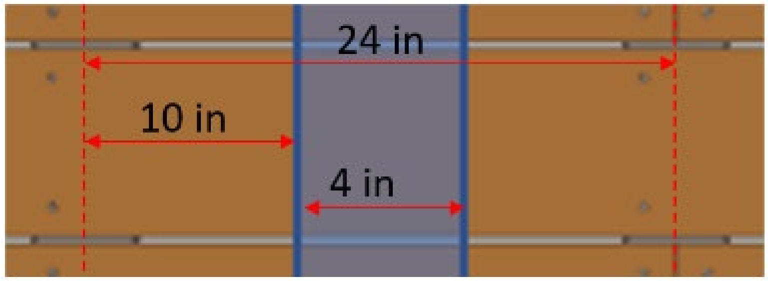

Figure 28. Representative layout of panel overlay on substructure

Figure 28 and 29 illustrate the entire picture story of the CAT testing. The figure captions provide guidance to the reader and so are not separately elaborated here.

Figure 29. Edge view of the Resource Fiber panels used in the testing. The bamboo strips core and the jacket made from ECM bamboo-PP are clearly seen. The core is not fully wet out with the resin as can also be seen

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Figure 30. 110,000 lb CAT used to conduct the proof testing. There is sludge and wet soil due to heavy rains before the tests.

Figure 31. Progressive images for 40, 50 and 80 (bottom row) cycles of loading and unloading of the CAT. See tread marks on the surfaces and the treads stay intact (no progressive spalling of the surface) The microcracks at the edges at the supports occurred early on and did not grow to any level of concern.

Figure 32. Illustration of survivability of bamboo decking for cycles 130, 180 and 225 respectively, Same comments about no indications of failure progression were observed.

7.3 Key observations for field testing

The Caterpillar CAT 349F (107,200 lb) used to test the bamboo planks alongside other materials represents the most aggressive condition that any material is expected to experience.

Bamboo-PP planks performed very well through 400 cycles. The key onset of failure was the microcracking and transverse cracking at the edges, where the plank was on supports. This represents a most aggressive form of loading. Notably, the surface of the bamboo-PP survived the track contacts as the vehicle moved in and out of the bed. Only pit marks were observed similar to that for Apitong and other comparable materials.

Despite the process challenges such as heating through the thickness and less than optimal tool, the planks survived extreme loading conditions. With optimization of the bamboo strips, core to jacket interface, and design of a production tool with optimal heating the plank quality can be dramatically improved. This ought to contain/limit the edge cracking. The surface texture and make-up of bamboo-PP ECM performed optimally, and no further optimization is needed.

8 Embodied Energy of Resource Fiber's Biocomposite Trailer/Truck Decking Systems

8.1 Introduction

The embodied energy (EE) of Resource Fiber's Trailer/Truck decking was calculated using the SimaPro Life Cycle Assessment (LCA) software v.9.0.0.33[1] incorporating the Cumulative Energy Demand (CED) method [2] with a physical allocation by mass approach to all process steps catering to the ISO 14040 and 14044 standards [3, 4]. A cradle-to-gate analysis of the impacts related to Resource Fiber's product was analyzed. By comparing the various process steps throughout the product's life cycle and providing calculations and qualitative information alongside impact data, Resource Fiber can determine how to reduce impacts by targeting aspects of the supply chain which can be further optimized. Furthermore, this information will present the environmental advantages of Resource Fiber's decking system over conventional products in the market.

8.2 Background

Life Cycle Assessments (LCAs) allow industries, governments, and consumer entities to determine the sustainable applications of a product [5]. The goal is to evaluate the sustainability of Resource Fiber's trailer/truck decking system to allow comparisons to other products used in similar applications. The impact categories analyze the cumulative energy demand (combining both conventional and renewable sources of energy), including primary or source energy.

1. [1] PRé. (September 2019). LCA software for fact-based sustainability. Available: https://simapro.com/

8.3 Results and Discussion (LCA)

The functional unit of the final product considered for this study is 1 biocomposite truck/trailer decking plank with dimensions 10' x 7.3125" x 2" (1755 cu in) weighing 26 kg. The core material consists of bamboo strips with an outer jacketed portion made of compounded bamboo-polypropylene (PP) in 50:50 ratio. The core strips are considered to weigh 40% of the total weight (10.34 kg).

Initially, several prototypes were created for optimization. The schematics related to the first four prototypes can be found in Figures 33-34. Options included utilizing bamboo-polylactic acid (PLA), 3D printing, and extrusion-compression options. The final product has undergone several modifications from the prototype versions.

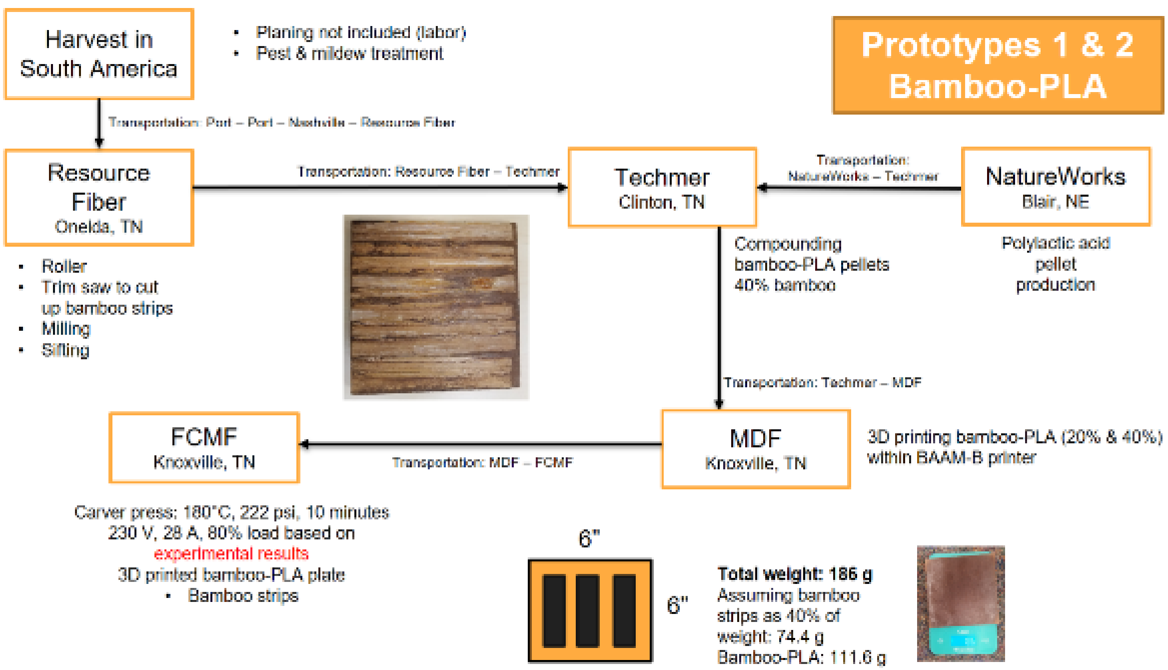


Figure 33. Schematic representation of the initial prototypes taken for study. Prototype 1 considers bamboo-PLA material with 3D printing and heated compression in 30% and Prototype 2 in 40% fiber fractions

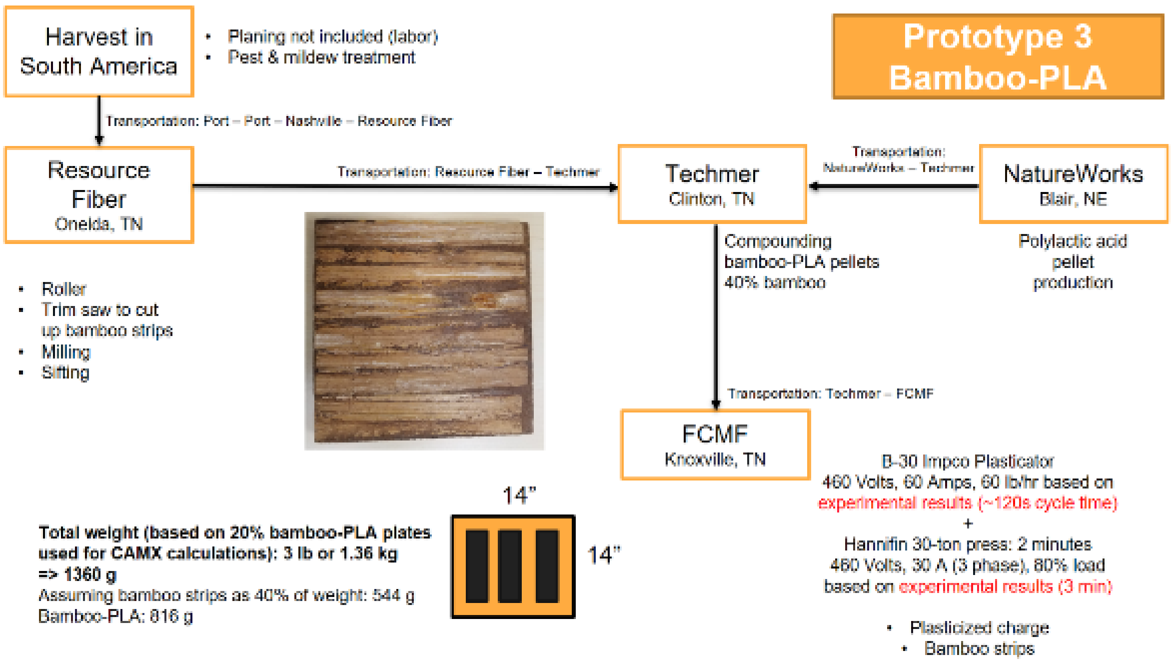


Figure 34. Schematic of earlier Prototype 3 which considers bamboo-PLA with an extrusion-compression molding setup.

It was ultimately decided that the final product will incorporate extruded-pultruded bamboo-PP jacketed core strip as the decking.

8.4 Energy credits

The supply chain encounters two co-products during bamboo processing steps, one of which is burned to generate heat required for the oven drying step and the other is used to compound the PP for jacketing. The bamboo co-products are as follows:

Bamboo harvest → Bamboo scrap from planing + Bamboo scrap created from milling

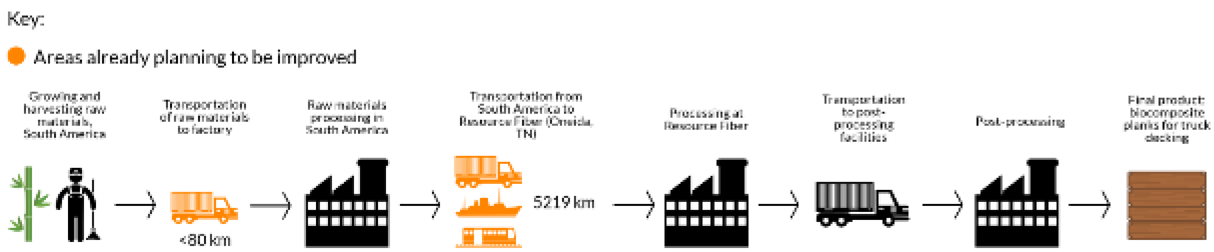
18.20309 kg → 0.10309 kg + 7.76 kg

18.20309 kg – 0.10309 → 18.1 kg used for final product

During the planing step, 0.10309 kg per mat is lost. A credit can be obtained once a bioproduct (bamboo, wood, etc.) is burned for electricity or heat [6]. In this case, a co-product (bamboo scrap or dust) that is planed and oven dried is utilized as fuel for the next set of bamboo mats that are dried. As this is a continuous process, the higher heating value (fuel characteristics) of G. angustifolia is considered [7]. In literature, this value is recorded at 18.75 MJ/kg. While 226.8 (500 lb.) of bamboo is burned for every oven drying cycle to dry 2200 mats, the energy released is 4252.425 MJ. For each mat, this equates to 1.93 MJ/bamboo strip. As a result, the co-product acts as an avoided product as it is reused in the same supply chain and can therefore avoid incurring impacts from disposal [8]. Similarly, the scrap from the milling step is collected and sent for compounding into bamboo-PP pellets, which acts as the jacketing for the final decking system. Thus, 10.44 kg is weight of the reusable bamboo mats within the same setup as an alternative to being discarded. Steps 1-3 consider 18.20309 kg and the subsequent steps are calculated based on 18.1 kg which is the total bamboo weight considered to make the final part with mass-energy balance maintained.

For the oven drying step (Step 3), since motors are used to pump the water and circulate hot air, the combined power rating comes up to 4.5 HP (3.36 kWh) with 100.8 kWh energy (362.88 MJ) as it is run for 30 hours per cycle. This equates to 0.165 MJ/decking. Therefore, the final energy after subtracting energy credit from burning bamboo is: 0.165 – 1.93 MJ/decking = -1.765 MJ/decking.

SCENARIO 1: Bamboo imported from South America



SCENARIO 2: Bamboo imported from Alabama, U.S.A

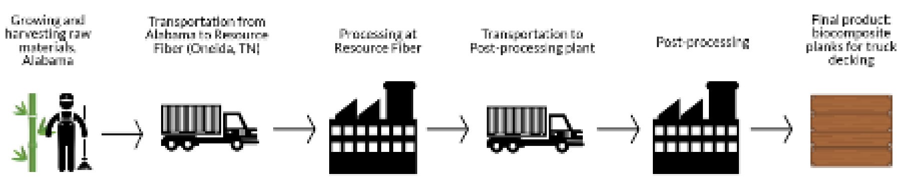


Figure 35. Final schematic representation of a biocomposite truck decking system with bamboo procured from South America (Scenario 1) and Alabama, USA (Scenario 2)

Since these scenarios consider transport distances for various locations, energy from distribution gets added. The materials include primarily bamboo from the crop. The processing steps for continuous bamboo stock include – opening of the bamboo stems, alignment for directionality, surface conditioning such as with NaOH. The discontinuous bamboo is shredded into lengths of 1”, 2” etc and sieved through screens. The waste (dust, scrap) is collected separately for compounding and reuse as skin. The simple blending with thermoplastic PP or PLA resins is done to designed fiber weight percent. Then either ECM or compression molding is used to consolidate the bamboo into panelized as done in this work.

The embodied energy without any transport distances (considering only materials and processing steps), would be **725 MJ/final part or 84 MJ/kg,** reducing the percentage further by 5%. The difference between the original South American scenario and sans transportation scenario is 10%. Therefore, it would be beneficial to optimize the shipping and transportation routes. The study considers all decking materials to have a 25-year lifetime.

9 BENEFITS ASSESSMENT

The benefits of bamboo biocomposite over apitong trailer decking include lighter weight (~9.09% lighter than Apitong), -domestic sourcing of bamboo, renewable and sustainable raw material sourcing, and improved carbon sequestration, while Additionally, production in the USA increases local jobs given that the supply chain is domestic, with bamboo harvested in Eutaw, Alabama and processed in Oneida, Tennessee. The company has operations in both Alabama and Tennessee in terms of vertical integration, i.e. equipment to process the harvested bamboo into strips and a radio frequency (RF) press for consolidation. In addition, it plans to add compression presses for batch processes. Resource Fiber will engaged a US pultrusion company for scale up to full scale continuous processes. The energy consumption depends greatly on the geographic region. In the US the harvesting cost for wood (since exact numbers for bamboo are unavailable) range from 140-215 MJ/m^3 and converting to wood is 2720 to 3720 MJ/m^3 [2] . While exact energy numbers to harvest Apitong are unavailable, it can be noted that Apitong is a depleting resource and largely outside the US (Indonesia, Malaysia, Philippines, Sabah, Sarawak, Brunei, Pakistan, India, Burma, Borneo, Thailand, Sri Lanka and Kampuchea). The domestic supply chain for bamboo alternative can be compelling compared to harvesting and transportation cost of Apitong for the US market. Cost: Typically an Apitong trailer plank 2 ft x 8 ft retails at $8.29 per linear foot[3], We estimate the bamboo composite plank to be $6.19 per linear foot for the same dimension. The bamboo estimate is based on bamboo plank and its conversion into composite decking. The assumption is production of at least 100,000 linear feet. Even with a conservative estimate this is a 25.33% lower cost of the bamboo composite compared to Apitong. This is a very rough estimate and only shows the potential for bamboo composite as a replacement to Aptiong.

10 COMMERCIALIZATION

Resource Fiber is growing bamboo in Western Alabama (Eutaw, Alabama) and will process raw material for production. The Company will outsource the compounding of bamboo with matrices. Initially, the Company will outsource the pultrusion process of making trailer planks as this requires specialized equipment, tooling, and expertise.

Secondary markets include car decking, as well as commercial and marine decking. Resource Fiber will market and sell trailer decking directly to the primary trailer decking manufacturers and military operations in North America. The Company will also market to commercial users, potentially selling through commercial distributors.

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[2] [2] Identifying Sustainable Wood Sources for the Construction Industry: A Case Study January 2018, Sustainability 10(1):139 ., DOI: 10.3390/su10010139 Shenghan LiHuanyu WuHuanyu WuZhikun DingZhikun Ding

[3] https://www.trailerdecking.com/Products.aspx?FilterstoAdd=529

Barriers to commercialization include funding for custom tooling and contracting with pultrusion processors to produce initial product for further testing. Beta testing is also expensive and time consuming.

11 ACCOMPLISHMENTS

Resource Fiber filed a patent application for its design of bamboo fiber mats layered and jacketed with a mixture of bamboo fiber and polymer forming a fibrous biocomposite material for encapsulation of the conditioned solid fiber bamboo fiber mats to form a plank for use in truck trailer decking and/or other planking products.

12 CONCLUSIONS

This project concluded that the jacketed bamboo biocomposite decking can be constructed as an alternative to apitong that is as strong, lighter weight, and uses less energy. Other benefits include the ability to use a domestic, renewable, and sustainable source of raw material that sequesters more carbon than apitong. Additionally, production of bamboo decking in the US increases local jobs. Lessons learned include the limited ability of producing test product in a lab setting and the need for commercial production of product for final testing.

The conclusions in terms of the development goals that were set out are summarized below.

A. Decreased weight when compared to Apitong and Gen 1, thereby reducing operating costs and petroleum usage due to increased miles per gallon. The studies demonstrated that the bamboo solution developed in this work resulted in the bamboo composites were 9.09% lighter than the incumbent Apitong. The reduced operating costs could not be quantified directly since a number of operating variables are involved but the study points to such compounded weight savings.

B. Flexibility to allow camber design into trailers. A number of variants were studied within these designs including additively printed bamboo, bamboo strips as core, long fiber discontinuous bamboo for jacketing effect and synergies within them that demonstrated flexibility of the design. The aggressive wear testing with the Caterpillar excavator illustrated the damage tolerance of the bamboo composites.

C. Luminescence to increase safety during low light and dark conditions. This will successfully demonstrated by compounding luminescence and this can be readily integrated in full scale parts.

D. Composite material to maximize use of bamboo bio-composites as substitute for petroleum-based composites. All constituents in the study were derived off bamboo fibers. The only synthetic constituent was polypropylene which is recycleable. It can be surmised that future work can pursue bio-degradable thermoplastics as synergistic to polypropylene.

E. Embedded layer(s) of conditioned bamboo for added strength and stability. This was demonstrated by the core strips to provide the sandwich effect to jacketed long fiber bamboo polypropylene in the full scale parts.

F. Improved safety over Apitong by temporary cargo indentation in planks for better stability. The treads within the jacketed long fiber bamboo polypropylene did not wear readily even after multiple cycles. This demonstrates high degree of resistance to cargo indentation and hence better stability of the planks. Apitong is excellent as well, but once cracked does not have the mechanism that thermoplastic polypropylene offers in complement of bamboo.

G. Cradle-to-cradle design so end-of-life becomes beginning-of-life for other products. The material being entirely recycled or biobased is fully renewable.

Hence all the set objectives were met as part of this project.

13 RECOMMENDATIONS

With additional funding, Resource Fiber may produce product using commercial tooling and processes. Product can then be tested in commercial settings, using similar methods as done in the project. There are number of design features within the sandwich construction that can be incorporated for enhancef flexural stiffness. The primary onset of failure was the interface of the core to the jacketed skin. This can be readily improved by surface treatment and resin rich skin to enable adhering of the skin to the core. The high insulation of bamboo made it difficult to get heat to the interface of the skin to the core. However, some tailored conductivity at the interface would solve this problem. Future solutions can progress from batch scale to continuous pultrusion profiles, which would make it economical in commercial production. All the material studies progressed very well in this work and can be extended into production.

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