Natural Composites Team

Final Report

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ABSTRACT

Composites are unique materials which exhibit specific and useful material properties and characteristics that generally offer a high strength to weight ratio. This project investigates a natural fiber composite composed primarily of sable palm fronds reinforced by an eco-friendly bioresin. Unlike similar materials, these palm fronds are sourced from a large, existing waste stream. This eliminates the need for planting and harvesting and allows potential manufacturers to reduce the amount of material sent to landfills. This increases the overall sustainability of the product which was thoroughly considered and analyzed. The material was originally developed in collaboration between Oregon State University (OSU) and University of West Florida.

The goal of the project is to prove additional material viability to venture capitalists and other potential investors through characterization, analysis and prototyping. This document details the work done by the OSU team to develop manufacturing documentation for material testing samples and surfboard fin prototypes. The manufactured samples were used in both tensile and three point bending tests to begin characterizing the material. To ensure the sustainability of the product, a complete life cycle analysis (LCA) was also conducted. This LCA analyzes the material from cradle to grave and considers all aspects of the procurement, shipping, manufacturing, and waste methods.

ACKNOWLEDGEMENTS

The first group to be acknowledged is the OSU student team that authored the capstone project. The team is composed of five mechanical engineering undergraduate students: David Brown, Jensen Davis, Scout Eagar, Karl Kabeiseman, and Nicholas Ventenilla. Each student worked diligently in each aspect of the project, from material characterization to product development to usage analysis.

The team would like to thank the additional researchers and the advising team involved in the project's development. These contributors include Dr. Joseph Piacenza (project's team specific client, co-founder of Palmeira Composites, and OSU Director of Multidisciplinary Capstone Programs), Dr. John Parmigiani (OSU Prototype Development Lab), John Greeven (OSU HP additive manufacturing), Adam Carlson (OSU graduate student and Global Formula Racing aerodynamics/composites lead), Nicole Gislason (UWF Haas Center Executive Director), and Murilo Basso (UWF Sea 3D Additive Manufacturing Laboratory). The advising team worked closely with the OSU capstone team to ensure that their needs and requirements were met.

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1 BACKGROUND

1.1 Introduction

Within the past few decades, sustainable materials and products have grown in desirability and usage. Subsequently, this market has exploded. A substantial sector of this market are wood composite materials, including cross laminated timber, bamboo, and now, palm fronds. Palm fronds are the foliage-filled branches of palm trees. The palm fronds, specifically the leaf stock, can be dried, layered with a resin, and used as a wood composite material. Currently, the research, development, and application of palm fronds as a wood composite material is in its infancy. This project will have three areas of focus regarding palm fronds: material characterization, product development and testing, as well as customer development and usage analysis.

Originally developed in collaboration between Oregon State University (OSU) and University of West Florida (UWF), the material has proven viability in manufacturing as a wood composite product. Through the Palmiera Composites and UWF teams' work and research, a palm frond-based skateboard with epoxy resin was constructed. Building upon this research, the OSU Capstone team has been tasked with establishing material characterization of the palm frond material and developing alternate applications over the course of Fall Term 2022 and Winter Term 2023.

Over the past five months, the team has successfully conducted a life cycle assessment of the palm frond material, created four palm frond testing planks, applied resin and fiberglass to two of the planks, and conducted material testing. The team has also constructed a set of surfboard fins from the palm frond material as a final deliverable in partnership with Buni Boards LLC, a Corvallis surf shop.

1.2 Project Scope

Throughout the project, the team has worked to further establish the material properties of the product through the development of test specimens using documentation outlining the manufacturing process for wood-based composites of similar materials [1]. Using these specimens, the team performed material characterization tests. The team seeks to characterize the tensile strength, hardness, and flexural strength. Testing was conducted according to standard ASTM D1037 test methods for evaluating wood based fiber panel materials [2]. This standard establishes specimen size and experiment procedures to be followed. However, due to the size of the equipment available to the team, certain specimen dimensions had to be reworked to conduct the testing. This will be further discussed in the Design Solution section of the report.

Evaluation of the material was conducted according to standard ASTM D-7031 methods for evaluating mechanical and physical properties of wood plastic composite products [3]. This standard establishes specimen preparation for experimental validity based on test methods to be used. The team also performed a complete Life Cycle Analysis (LCA) on the material. The LCA evaluates every aspect of the material from cradle to grave to determine the environmental effects of manufacturing and disposal of the product. This LCA was performed in comparison to bamboo, a similar product, and considers factors including: bio-resin, shipping, farming, and waste. The development of a set of surfboard fins was completed in collaboration with Buni Boards LLC as a showpiece and selling point for presentations and stakeholders.

2 DESIGN PROCESS

The capstone team's design process was cyclic, so ideas were brought to the group by our mentor Joseph Piacenza on Monday meetings, those ideas were implemented and changed by the team over the week as work moved forward, and Piacenza and the team had another meeting to discuss the past work, what needed to get done, and what could change for the next week. For example, after the capstone team glued together one board and shared this with Piacenza, it was decided that the flatness of the board could be improved, so the next gluing session unutilized aluminum plates to sandwich the board, rather than just wood planks and cardboard.

The first few weeks of the project were mostly used to get a better sense of what was to be expected from the capstone team. At this stage, the project was very diffuse. There was little direction for the capstone team other than Piacenza explaining he would like the team to help in material design and fabrication. This left the capstone team with a very open-ended task. It had to be decided how to design the material, how to quantify its physical properties, and how to use the material. The following outlines the process for determining the best way the capstone team found to meet Piacenza's goals as well as completing the capstone class.

The capstone team first discussed with Piacenza how past palm frond boards were made. This process was developed before this team became part of this project so it was simply adopted in. The method used is as follows: The fronds are trimmed and cleaned up with a vertical band saw to remove the heavily curved sections on either side first, as seen in the bottom pile of fronds in figure two. After that, the fronds are put through a planer to flatten and trim the top and bottom surfaces. This flattened frond is then run through a table saw twice to create two straight, side edges. A light hand sanding is then done to remove any splintering and the finished, rectangular prism of palm frond is then wood glued together with many other parallel fronds, as seen in figures three and four.

After clamped and left to dry for two to three days, the board is removed from the clamps, and run through the planer again to flatten it. The ends are then chopped off to create a more homogenous and equal length board. Early on, the team discussed how else these could be manufactured. Methods such as crushing the fronds before cutting, and high pressure processing to strengthen the composite boards were mentioned [4]. This processing takes many layers of material at high temperature and pressure, and sandwiches them together with resin to create a strong, hard composite material. However, in the end the known process of creating boards was decided to be used as a basis for construction. This was due to the time and equipment constraints of the capstone project, and perfecting a known process was decided to be more important.

This process took some trial and error to hone in. For the initial attempts to make boards, the team did not trim the edges on the bandsaw first, causing the boards to pass through the planer in a warped manner. This created an uneven surface and the boards then needed extra care to be cleaned up. The attempt to cut the edges of the frond on the table saw before the planer stage was another initial processing issue. This also produced a warped edge, so an initial pass through the planar was put in place to create a flat surface the table saw operator could use as a guide, creating a smoother cut. A final issue we ran into was the fact that the compression from the clamps on the side of the fronds while gluing was uneven. To resolve this we cut two strips of hard plastic to clamp to, rather than clamping directly to the fronds. This plastic distributed the clamping load more evenly along the fronds and produced a board with better adhesion and fewer gaps between fronds.

3 DESIGN PROPOSAL – First Term

3.1 Proposed Design

3.1.1 Design Description

The proposed design is an in-depth testing procedure to reveal material characteristics and physical properties of various layups of palm frond boards. This was done through cutting, planning, and gluing fronds together into boards first, then cutting the boards into specific sizes determined by ASTM standards [2] for the required tests, noted in *Figure 1*. These tests include a tensile test, a hardness test, and a bending strength test. There were a total of 12 tests planned for each test type: 3 tests of an untreated board, 3 tests of a board with 4 ounce fiberglass coating, 3 tests of a board with 6 ounce fiberglass coating, and 3 tests of a board with a carbon fiber coating. Due to time constraints and issues with equipment availability, the team was not able to complete the hardness testing.

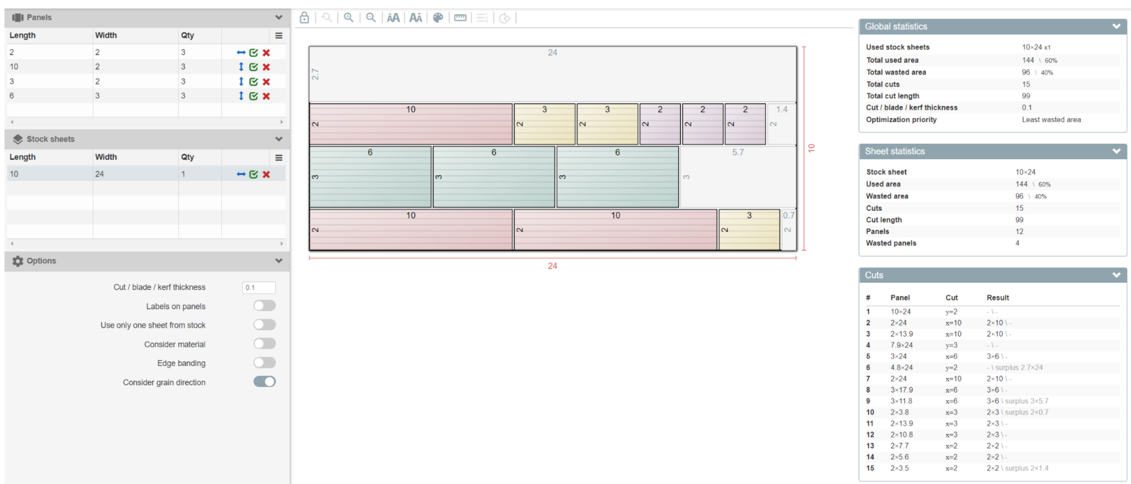

Figure 1. The specified sizes necessary for standard ASTM testing.

The team has gathered a preliminary idea of the physical attributes of various versions of the palm frond boards from these tests. These attributes will assist in generating ideas of how this material can be utilized most effectively and what sort of product prototypes future capstone teams could make.

3.1.2 Prototype Discussion

The first board manufactured by the team presented a strong opportunity to build out the understanding of the material and how to manufacture and plan for it in the future. As a result of the prototype, it was learned that a more rigid and heavy sheet was needed to clamp and compress the fronds between for the gluing stage. Throughout this stage, the team was also able to optimize a manufacturing line to utilize time spent cutting and prepping fronds more efficiently.

Figure 2. Before and after cutting the fronds into rectangular pieces.

Figure 3. First attempt at gluing the board using wood to compress the fronds into a plane.

Figure 4. Revised method for gluing the second board using aluminum plate to create a flatter final board.

Figure 5. Test specimens cut from board #2.

Through the development of these two boards, it was learned that using a stiffer material such as aluminum for the gluing portion yielded a much straighter final product. Small changes were also made to the production of the individual rectangular pieces such as planning them to a similar height prior to gluing and trimming off the long sharp edges on each frond prior to any other processing.

3.2 Implementation Plan

3.2.1 General Description of Implementation Plan

During the second half of the project, the team continued to use the second iteration of the board gluing method as it yielded a much flatter board. A second shipment of palm fronds was also received for continued manufacturing. After the construction of all the boards, the Resin Research Bio Science Epoxy Resin as well as both 4 oz and 6 oz fiberglass was applied to samples. The three completed sets of specimens are the bare board samples, 4 oz fiberglass samples, and 6 oz fiberglass samples. After all test specimens were manufactured, static bending and tensile tests were conducted across all three variations on the palm fronds. Data was collected and compiled into a spreadsheet for future reference and evaluation.

3.2.2 Resources Needed for Implementation

Resources required for each term of implementation were similar. Access to the wood shop and composites lab are the primary work spaces needed for production of pieces for testing and the final manufacturing. The team was required to go through certification seminars for access to both of these areas. During the second term of work, the two types of fiberglass were required as well as the bio science epoxy resin and hardener. Potentially useful software will be material property databases like GRANTA to compare results with and software for recording and processing data from testing. Materials needed are listed in *Table 1*.

3.2.3 Bill of Materials

Outsourcing and labor costs are not a concern for this project.

Item	**Description**	**Quantity**
Palm Frond	Material of interest, shipped from West Florida.	Minimum 15 fronds per 7.5 in board, 3 boards remaining for testing, and excess needed for final product
Wood Glue	Titebond Original Aliphatic Resin based wood glue	Roughly 1 bottle should last the entire testing phase
Resin	Resin Research Bio Science Epoxy Resin	An additional set of resin and hardener was ordered for the project
4 oz Fiberglass	4 oz fiberglass weave, from Dr. Piacenza's lab	1 board (24 in by 7.5in) 3 layers, min. 540 in^2
6 oz Fiberglass	6 oz fiberglass weave, from Dr. Piacenza's lab	1 board (24 in by 7.5in) 3 layers, min. 540 in^2
PrePreg Carbon fiber	Pre impregnated carbon fiber from GFR Team	1 board (24 in by 7.5in) 3 layers, min. 540 in^2

Table 1. Bill of Materials for all testing samples.

3.2.4 Schedule of Implementation in Second Term

Our tentative schedule was as follows:

- Over winter break, we hope to complete at least a few initial measurements to determine if there is anything wrong with our approach and if we need to modify our process in any way. This is to make sure we don't run into issues in the middle of the term and need to scramble for a solution.
- For the first week or two, we plan to complete the manufacturing of the remaining boards and coat them with fiberglass and carbon fiber.
- For the next few weeks, weeks 3 and 4, we plan to complete the remainder of the material characteristic tests.
- For weeks 5 and onward, after completing all the measurements on all the board variations, we plan to work to create a working prototype of a possible product made of the palm frond boards. This product is currently planned to be a skimboard.
- There will also be various ENGR 416 assignments spread out through the term that will be completed.

The team was unable to adhere to this schedule. Due to the long processing time of each board, a smaller prototype was chosen in favor of the skimboard. After a meeting with Parker from Buni Boards LLC, the team decided to move forward with the prototyping of surfboard fins rather than an entire skimboard. The team also ran into many issues trying to get access to the material testing lab. After no success reaching out to the provided contacts for weeks, Professor Scott Campbell was finally available to walk us through the material testing lab and show us how to use the equipment near the end of week 9. However, because the material testing lab in Dearborn Hall is intended for metal testing, none of the equipment available was large enough to accommodate the samples we had prepared according to the ASTM standards D1037 [2]. Because of this, the team was forced to significantly reduce the size of all samples to fit into the machines available. Testing speed was also reevaluated to accommodate the smaller sized samples.

3.3 Testing Procedures (TPs)

The engineering specifications selected, which are decreased weight, increased sustainability, decreased cost, decreased time of production, increased elasticity, and increased collision strength, were chosen with the plan of manufacturing flooring from the palm fronds. Each of the tests selected were done in order to both satisfy the requirements we selected as well as to gain a broader understanding of the materials properties in order to compare it with other similar materials. We plan to use the information gained from testing to expand our scope of manufacturing options. Engineering specifications 1-4 (decreased weight, increased sustainability, decreased cost, and decreased time of production) are not specifically tested within the tests below, but rather will be factored in when selecting the final laminate product between 4 oz fiberglass, 6 oz fiberglass, and carbon fiber. See Appendix A for final testing results.

3.3.1 Testing Procedure 1: Tensile Test

This test will serve to satisfy engineering specification 5: Increase Elasticity. The tensile test will follow the standards laid out in the ASTM D1037 - 12 [2], by clamping the sample and applying force parallel to the surface until failure. The testing procedures adhered to the ASTM D1037 standards, but the size of the samples was reduced from 2x10" to 1x6" to fit inside of the smaller than expected clamps available in the lab.

3.3.1a Testing Procedure 1: Objective

By measuring the force applied to the board, as well as the elongation of the board before breaking, this test will be able to determine the tensile strength in the plane of the panel, as well as the modulus of elasticity. From the palm frond board we glued, we will cut three 2" x 10" x ¼" pieces, we then cut out the dogbone outlined in the ASTM document using a router to the geometry specified. As mentioned earlier, upon arrival at the lab, it was revealed to the team that the equipment available was intended for smaller metallic samples. Because of this, the sample sizes for tensile testing were reduced to 1” x 6” x ¼”. Once the three pieces were cut to shape, the ends were clamped into the INSTRON for tensile testing.

3.3.1b Testing Procedure 1: Resources Required

Resources required are the palm frond boards cut to the dimensions specified, the INSTRON capable of applying and recording a continually increasing force, self-aligning self-centering grips, and an extensometer to measure deformation at the center of the sample.

3.3.1c Testing Procedure 1: Schedule

The three samples of this test across three tests each will take an approximate two hours to complete with additional three hours to collect all the data and photographs of the samples. Photos were also taken prior to testing and descriptions of any defect in the material were recorded. All material tests were performed during week 9 of winter term.

3.3.2 Testing Procedure 2: Hardness test

This test will serve to satisfy engineering specification 6: Increase Collision Strength. This test will be performed to the ASTM standard D1037-12, section 17, *hardness.* The standard will be followed for the test sequence; however, due to size requirements of existing samples, the sample size will be 2” x 2” x ¾”. The Janka-ball hardness test will use a 0.444” ball of steel pressed into the sample to one half its diameter. The load will then be measured at this point. The point of impact will be just off center of the square, as to have the ball connect above one of the frond centers and not a seam between fronds. The speed at which the ball compresses into the sample will be 0.25 inch/min.

Unfortunately, the material testing lab in Dearborn does not have a .444” Janka-ball head available. The largest ball in the lab is a .25” head. Because of the team’s late access to the lab and the unavailability of the required equipment, the hardness testing was not able to move forward.

3.3.2a Testing Procedure 2: Objective

The objective of this test is to determine the hardness of the palm frond board samples. The team does not want the product to be easily dented and scratched, so determining the hardness of each sample type will be important.

3.3.2b Testing Procedure 2: Resources Required

The resources we need to perform this test are the hardness testing machine with a .444” Janka-ball attachment. It was assumed these were available in the material labs in the Dearborn Hall basement. Samples of bare, 4 oz fiberglass, and 6 oz fiberglass prepared palm frond boards were prepared for the tests, but never tested.

3.3.2c Testing Procedure 2: Schedule

The three samples of this test across three tests each will take an approximate two hours to complete with additional three hours to collect all the data and photographs of the samples. Photos were also taken prior to testing and descriptions of any defect in the material were recorded. Due to the unavailability of equipment, the hardness tests were never performed.

3.3.3 Testing Procedure 3: Three Point Bending Test

This test will also serve to satisfy engineering specification 5: Increase Elasticity. This test will be performed to the ASTM standard D1037-12 [2], section 9, *static bending.* The sample sizes were 3” x 6” x 1⁄4” but once again, due to equipment issues in the Dearborn lab, these specimen sizes were reduced to 2” x 6” x ¼”. The two ends of the test specimen will be supported from underneath by rounded supports.

Then a force will be applied at a uniform rate to the center of the board from above by the INSTRON. Deflection at the center and force will be measured.

3.3.3a Testing Procedure 3: Objective

This test is designed to measure the flexural properties of the material such as the modulus of rupture. This test will help to gain an understanding of the limits of the material as well as possible applications. Based on the three variations on the material, we are expecting to find the ideal layup options for use in flooring or other applications.

3.3.3b Testing Procedure 3: Resources Required

This test will require a 3 point bending test machine, the INSTRON, capable of measuring and applying a uniformly increasing load. The prepared samples of bare board, 4 oz board, and 6 oz board will also be required.

3.3.3c Testing Procedure 3: Schedule

The three samples of this test across three tests each will take an approximate two hours to complete with additional three hours to collect all the data and photographs of the samples. Photos were also taken prior to testing and descriptions of any defect in the material were recorded. All material tests were performed during week 9 of winter term. The INSTRON compression test is very simple and went much faster than forecasted.

3.4 Safety Plan

The team participated in safety seminars for both of the realization laboratories (the woodshop and the composites lab). The team will mitigate potential safety issues by wearing closed toed shoes and eye protection, as well as following all other safety guidelines for the wood shop and material labs. Potential safety hazards are the various saws and sharp objects in the wood shop, which require care and precaution when operating, particularly when involving the table saw. During testing and manufacturing, splinters from the palm fronds could also potentially pose a hazard.

The team is also taking into account the hazards that accompany the epoxying and lamination of the boards. The composite lab in Graf is a ventilated area which was utilized to do the epoxying and fiberglass/carbon fiber lamination. Protective gear like gloves, goggles, and respirators were also worn. The epoxy gives off very little fumes, but it is preferred to have too many safety precautions rather than too few.

Safety glasses were also worn during the material testing phase of the project. During the destructive tests, it is possible that small pieces of palm frond, epoxy, or fiberglass could break off of the samples and become projectiles. Because of this, it was important for the team to wear protective equipment in this lab.

3.5 Standards, Codes, and Regulations

Standard Number or Code	Title of Standard	How it applies to Project
ASTM D-1037 - 12	Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials	Defines the standard testing procedures used to measure material properties of composite wood materials, such as test piece dimension/geometries.
ISO 14025, 14040, 14044, and 21930	Environmental Labels and Declarations - Principles and Procedures	Provides characterization factors that we used to conduct our life cycle analysis through the TRACI database.

Table 2. Standards of Practice as Applied to this Project.

The ASTM standard led the team in guidance of material testing. The standard aided in decision making regarding dimensions of tested materials and testing procedures. The ISO standards form the basis for the TRACI database used in the life cycle assessment of the wood composite product [5]. There was minimal direct interaction between the team and the ISO standards outside of the life cycle analysis.

3.6 Risk Analysis and Mitigation

Failure mode and effects analysis allows project designers to assess the areas within a product that may pose the greatest risk of failure. For the Natural Fiber Composites team, there were only five possible total failures found. With the simplicity of the surfboard fin product, use of only three materials, and no mechanical components, failure of the product will likely only come from user error or mistreatment. Regardless, the team designed the product to minimize these possible failure modes.

3.6.1 FMEA

With a non-mechanical product with only three distinct materials, there are very few examples of failure. In *Table 2*, those unlikely failures are discussed.

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
Palm Frond	Crack of Fronds	Structural failure	Severe impact	128	Ensure no prior structural damage to fronds
Palm Frond	Splinter of Fronds	Edge structural damage	Edge abrasion	40	Ensure no prior structural damage to fronds
Wood Glue	Break between Fronds	Structural failure	Severe impact	128	Ensure even glue distribution during manufacturing process

Wood Glue	Melting of Wood Glue	Structural Failure	Excessive heat	64	Provide maximum and minimum operation temperatures to consumer
Carbon Fiber	Surface Damage	Aesthetic damage and water damage	Surface abrasion	60	Determine most effective carbon fiber thickness during testing

Table 3. Shortened FMEA Chart.

3.6.2 Critical Failures

With the palm frond, there were two identified critical failures: crack of fronds and splinter of fronds. For both of these possible critical failures, the team will ensure that there is no prior structural damage to the fronds through quality control analysis. Additionally, throughout the manufacturing process, end pieces and preexisting abnormalities are cut and removed. By using the best quality of fronds available, the product will have greater strength and durability.

For the wood glue, there were also two identified critical failures: break between fronds and melting of glue. For breaks between fronds, the team will ensure that the glue is evenly distributed during the manufacturing process. Gloved hands are used to spread the glue evenly, while at least 48 hours of drying time is required. Lateral clamps to the board during the drying phase ensures that the fronds are compact while gluing. For melting of the glue, the team plans to include a guidance for the final product regarding maximum and minimum operation and storage temperatures. If not exposed to excessive heat, this failure should be avoided.

For the carbon fiber, there was only one identified critical failure: surface damage. Damage to the carbon fiber would likely only occur from violent surface abrasions. During operation, the team does not expect severe damage to the product. To ensure durability, the team will determine the most appropriate carbon fiber thickness. The team will also make operational recommendations to use some surfing wax on the skim board product for optimal results.

3.6.2 Risks and Trade-offs Analysis

With the simplicity of the product, there are no negative tradeoffs to mitigating one potential failure for another. Improving the quality of fronds used will only improve the performance of the glue and vice versa. Improving the operational efficiency of the carbon fiber will only improve the durability of the fronds and glue held within the wrapping. The only trade-offs will come from customer requirements. Higher thickness of carbon fiber will improve the durability of the board but may reduce the aesthetic appeal of the board, as the fronds would be blocked by the thick wrapping. With a product that has no mechanical components and only three materials, there are very few negative trade-offs to mitigating failure risks for one material compared to another.

4 Design Solution

Our team's final design and submission for this capstone project involved conducting material testing on the palm frond composite and creating a product using the material. Due to limitations in time and available materials, our team chose to manufacture surfboard fins as opposed to a skimboard. However, we faced challenges in adhering to some aspects of the ASTM-D1037 standards due to the unavailability of testing equipment capable of handling larger samples. As a solution, we constructed smaller testing samples in order to complete the testing process. using the knowledge gained from working with the palm fronds our team refined the manufacturing process and created our own unique set of surfboard fins.

4.1 Description of Solution

Our team's solution for completing the material testing despite the lack of proper testing equipment was to cut smaller test samples from the already constructed three-point bending test samples. This allowed us to conduct tests for tensile and three-point bending. Although these tests did not adhere to ASTM standards, we were still able to calculate the stress needed for the failure of all three variations of our board - untreated, 4oz fiberglass, and 6oz fiberglass. This solution also allowed us to save the full-size tensile test samples which adhere to ASTM standards for future tests when the proper equipment becomes available.

For the final design of our fins, we received advice from Parker at Buni Boards LLC and decided to manufacture a set of three fins that would fit within a Futures brand fin box. Based on a design recommendation from Parker our team chose to manufacture the fins with the palm fronds oriented at an angle rather than parallel to the surface of the board to increase strength. We used a CAD file provided by Parker to profile the shape of the board and manufactured a part that would interface with the Futures fin box.

4.2 Project Results

The results of our project yielded useful data regarding the maximum stress that our palm frond boards could withstand and indicated a steady increase in strength as heavier weaves of fiberglass were added. The information gained from these tests will help to better understand this new material's properties as well as classify it among other materials. Other results from this project were a better understanding of the manufacturing process required and how to streamline it.

4.3 Life Cycle Analysis

It was suggested to the capstone team that an assessment occur regarding the sustainability of our palm frond material as compared to a competitor wood material: bamboo. The functional unit for the LCA is 1 m^3 of wood composite material. Each product contained three materials: pine wood, polyethylene (PE) wood glue, and polyvinyl chloride (PVC) epoxy resin. Neither bamboo nor palm frond material are included within the openLCA database. The solution to this was modifying the mass of pine wood to equate to the carbon embodiment listed for the two materials in another LCA database: SustainableMinds. Figure 6 and Figure 7 display the system boundary for both the palm frond plank and the bamboo plank.

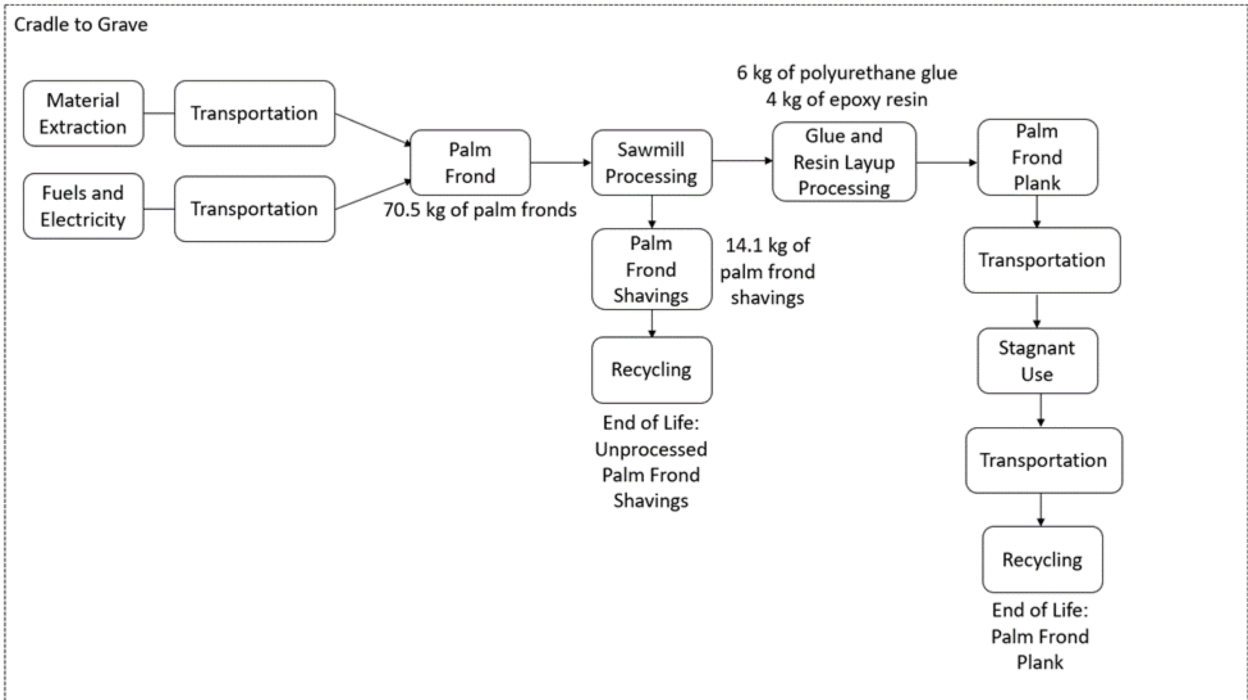

Figure 6. System boundary of palm frond plank.

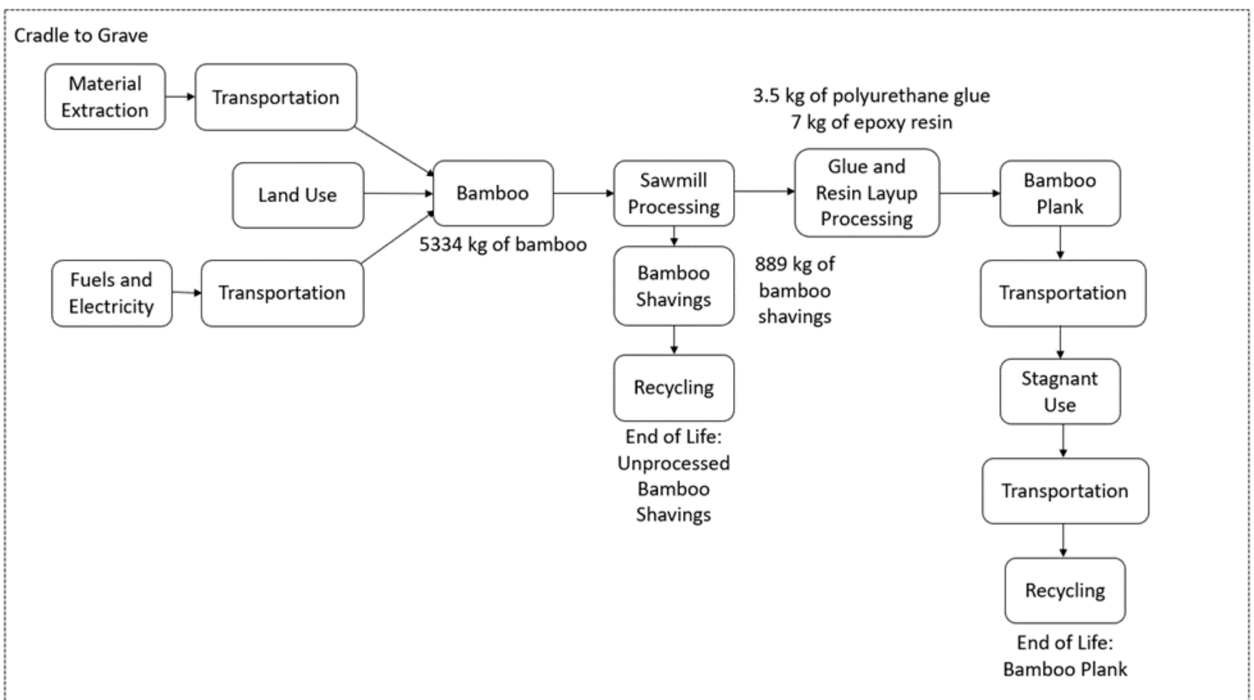

Figure 7. System boundary of bamboo plank.

With the necessary modifications, the next step was to establish transportation distances and methods. The palm frond material is sourced from the University of West Florida (UWF) and flown to the Portland International Airport (PDX), where it is then driven to Oregon State University (OSU) in Corvallis, Oregon. The bamboo material is sourced from Shanghai, China and shipped on a shipping container to Los Angeles, California, where it is then driven to Oregon State University (OSU) in Corvallis, Oregon. There is no land use involved for the palm fronds as they are sourced from naturally grown trees and not farmed, unlike bamboo. Figure 8 and Figure 9 display the inputs for both the palm frond plank and the bamboo plank.

Flow	Amount	Unit	Description
pine wood	56.40000	kg	Palm Frond wood modified to 0.282 mass to equate impact (SustainableMinds)
polyethylene low density foil(PE-LD)	6.00000	kg	Wood Glue
polyvinylchloride resin (E-PVC)	4.00000	kg	Resin
transport in t*km	1.70258E4	kg*km	Truck from PDX to Corvallis (150 miles)
transport in t*km	2.95113E5	kg*km	Plane from UWF to PDX
waste incineration of untreated wood...	14.10000	kg	Disposal of Wood Shavings during Production
waste incineration of wood products ...	66.40000	kg	Disposal of plank after use

Figure 8. System Inputs of palm frond plank.

Flow	Amount	Unit	Description
Occupation, forest, intensive, clear-cut...	20.00000	m2*a	Land use for farmed bamboo
pine wood	4445.00000	kg	Bamboo wood modified to 12.7 mass to equate impact (SustainableMinds)
polyethylene low density foil(PE-LD)	3.50000	kg	Wood Glue
polyvinylchloride resin (E-PVC)	7.00000	kg	Resin
transport in t*km	5.58203E7	kg*km	Shipping Boat from China to LA
transport in t*km	7.72897E6	kg*km	Truck from LA to Corvallis
waste incineration of untreated wood ...	889.00000	kg	Disposal of Wood Shavings during Production
waste incineration of wood products (...	4455.50000	kg	Disposal of plank after use

Figure 9. System inputs of bamboo plank.

Following the conduction of the LCA comparison, three main impact factors were examined: global warming potential, terrestrial acidification, and human carcinogenic toxicity. These impact factors were selected due to their common use in academic discussion and relevant application to the project. The results of the study can be seen in Table 4.

Impact Factor	Global Warming	Terrestrial Acidification	Human Carcinogenic Toxicity
Bamboo Plank	1266 kg CO2 eq	19.57 kg SO2 eq	7.585 kg 1,4-DCB
Palm Frond Plank	722 kg CO2 eq	1.875 kg SO2 eq	4.794 kg 1,4-DCB
Reductions:	43% reduction	90% reduction	37% reduction

Table 4. Environmental impact factor comparison between 1 m^3 of bamboo and palm frond composite.

The conduction of the LCA notes significant environmental impact reductions for the use of palm fronds compared to bamboo. This data can be pushed forward to the stakeholders of the project for further evidence of the advantages of palm fronds as a viable wood composite material alternative.

5 LOOKING FORWARD

Further work on this project should be focused on streamlining the production process further, especially in regard to where the processing and construction of work should be done, as well as creating more end-use products from the fronds. This year's capstone team has improved to great lengths the manufacturing process of the fronds from tree to board, such that the process can be followed without much variation by anyone working on this project in the future. However, if this work can be done without shipping the fronds across the country from Florida to Oregon, the mission of the team of a more sustainable material will be better realized due to the reduction of transport-related carbon emissions.

With the materials testing the capstone team had done, the strengths of the material are now quantifiably known and thus the next group working on this project should work to take advantage of these strengths and find a product they can make. This product will likely fill the niche of a more sustainable form of an existing wood product, but could even be its own unique innovation. The current capstone team built surfboard fins, and with that entered into the sustainable watersports realm, where there has been a push recently to bolster this market. People are looking for more sustainable options so as to reduce ocean plastic and trash accumulation. Maybe a skimboard is the future for the group that takes over this work.

6 CONCLUSIONS

Overall our team's project was to classify a new palm frond-based composite through material testing and to create an original product using this material. The team applied engineering design principles such as lean manufacturing and material science to produce a product that met the specified engineering requirements while keeping sustainability at the forefront. By utilizing palm fronds, a material that has traditionally gone to waste, we were able to create a very eco-friendly product. Additionally, our team also utilized a more sustainable bio-based resin which also served to reduce its environmental impact. Through our work in the past 2 terms, we were able to refine the manufacturing process and gather useful data regarding the characteristics of this material. To do this our team constructed various test samples and measured characteristics such as tensile strength, hardness, and bending strength. Using the knowledge we gained through hands-on manufacturing and testing we were able to manufacture a set of three surfboard fins that would appeal to an audience that desired performance as well as minimize the environmental effects of manufacturing.

7 REFERENCES

[1] Dorren, Brett, 2013, *"Analyzing the Flexural Properties of Self-Constructed Bamboo Laminates"*, California Polytechnic State University, San Luis Obispo, CA.

[2] ASTM standard D1037, 2020, "*Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials"*, ASTM International, West Conshohocken, PA.

[3] ASTM standard D-7031-11, 2019, "*Standard Guide for Evaluating Mechanical and Physical Properties of Wood Plastic Composite Products"*, ASTM International, West Conshohocken, PA.

[4] Funder America Inc., 2007, "Laminating Composite Panels Technical Bulletin." from https://funderamerica.com/wp-content/uploads/CPA-LaminatingCompositePanels.pdf

[5] "ISO 14025:2006 - Environmental labels and declarations — Type III environmental declarations — Principles and procedures." *ISO.org*, 16 November 2007, https://www.iso.org/standard/38131.html. Accessed 12 March 2023.

8 APPENDICES

8.1 Appendix A: Testing Portfolio

Testing Portfolio

Tensile Strength approximately 0.9x6 inch pieces

Resin Type	Result #1 (lb/in^2)	Result #2 lb/in^2	Result #3 lb/in^2	Result Average lb/in^2	Test Image #1	Test Image #2	Test Image #3
None	3695.9	3695.4	3744.1	3711.8			
4oz Fiberglass	3387.1	4889.1	5732.8	4669.666667			
6oz Fiberglass	N/A	4300.1	5560.5	4930.3			

Three Point Bending (Elastic Modulus) 3x6

Resin Type	Result #1 (psi)	Result #2 (psi)	Result #3 (psi)	Result Average (psi)	Test Image #1	Test Image #2	Test Image #3
None	1382400	1866240	2004480	1751040			
4oz Fiberglass	3456000	4147200	2880576	3494592			
6oz Fiberglass	2524608	3317760	2592000	2811456			

8.2 Appendix B: House of Quality

PROJECT HOUSE OF QUALITY
ENGR 415

Project:	Natural Fiber Composites
Date:	11/28/22
	Input areas are in yellow

ES #	Engineering Specifications (auto-entered)	1	2	3	4	5
1	Decrease weight					
2	Increase sustainability	^				
3	Decrease cost					
4	Decrease time of production	v		^		
5	Increase elasticity					
6	Increase collision strength	-				^
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						

Survey Legend	
A	Current product
B	Competitor B
C	Competitor C

#	Customer Requirements (CR)	Customer Weights		Decrease weight	Increase sustainability	Decrease cost	Decrease time of production	Increase elasticity	Increase collision strength	Customer Opinion Survey
		Direction								
1	Sustainable	3		1	9	1	1			
2	Low-Cost	3		1	1	9	3			
3	Aesthetically Pleasing	9							9	
4	Scuff-Resistant	9		1				9	9	
5	Water-Resistant	3		1				1	1	
6	Slip-Resistant	9		1				3	1	
7	Ease of Install	1		3			1			
8	Durable	3		1				9	9	
9										
10										
11										
12										
13										
14										
15										
ES Ranking Calculations	Raw score			33	30	30	13	138	201	
	Scaled			791045	537313	537313	661692	671642	1	
	Relative Weight			7%	7%	7%	3%	31%	45%	
	Rank			3	4	4	6	2	1	
CR Benchmarking	Best in Class									
	AVE									
	Worst in Class									
Technical Difficulty										
Engineering Specification Units										
Engineering Specification Targets										
Technical Requriement USL										
Engineering Specification LSL										
ES Test Procedure #										

HOQ LEGEND

HoQ roof (ES-ES relationships):

Λ	Indicates strong positive relationship
+	Indicates positive relationship
-	Indicates negative relationship
V	Indicates strong negative relationship

ES directional objective:

≥	Objective is to maximize (more is better)
≤	Objective is to minimize (less is better)
T	Objective is to hit the target

CR Kano type (optional):

B	Basic requirement (must be present)
L	Linear (performance needs; must be present, can be better)
D	Delighter requirement (not needed but if present exceeds expectations)

HoQ body (ES-to-CR relationship strength):

9	Very strong relationship
3	Strong relationship
1	Weak relationship
Blank	No relationship