Mangrove Boardwalk Project

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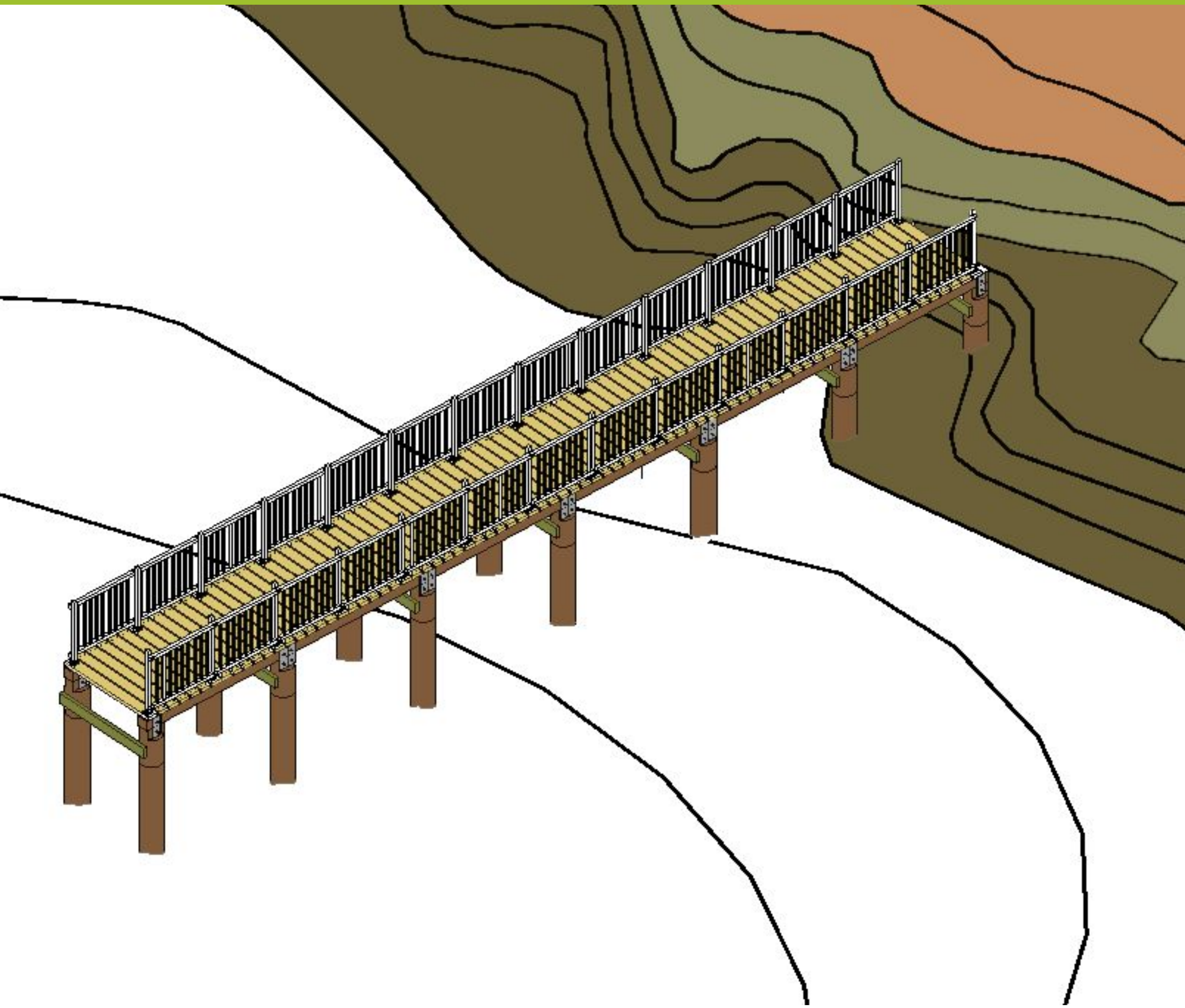
Project Advisor - Dr. Aaron Sakulich



Mangrove Boardwalk Project

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Abstract

In collaboration with Oteima Technological University, a boardwalk was designed to traverse the Mangrove Swamp at Batipa Field Station with minimal impact on the sensitive ecosystem while also providing a safe and stable surface for foot traffic. The design was intended to improve accessibility to the area for researchers and to be accommodating for public access to increase ecotourism. Final deliverables included design drawings and supporting calculations based on information from site assessment, literature review, and boardwalk prototype test results.

Acknowledgments

We would like to express our gratitude to all of the individuals who contributed to the success of this project. First, thank you to our project sponsor, Oteima Technological University (OTU) for allowing us the opportunity, providing support, and making resources available to us. Among the supporting staff at OTU, we would like to especially thank Edmundo Gonzalez, director of Batipa Field Institute, for expressing his enthusiasm and knowledge and for hosting our two-week trip to David, Panama. His guidance, passion, and expertise had a great impact on the project's completion and effectiveness.

We would also like to express our sincere appreciation to the staff of Worcester Polytechnic Institute (WPI) for all assistance with our project and experience abroad. A special thanks to Associate Professor of Teaching Grant Burrier, for contributing to the logistical aspects of our trip to David and helping to immerse us in the local culture. Finally, the biggest thank you to our project advisor, Associate Professor Aaron Sakulich, for his guidance, technical expertise, feedback, and enthusiasm.

Authorship

Deidra:
Deidra completed a series of organizational tasks including master editor and organization of the report and deliverables. She also designed the prototypes, produced the final presentation, and served as the safety manager for on-site tasks.

Luke:
Luke served as the primary structural analysis lead in preparing calculations for the final boardwalk design. He also researched material properties, member connections, and design manuals.

Lenny:
Lenny was the lead drafter, completing the prototype and final boardwalk designs in AutoCAD. Lenny also worked through the final design calculations and wrote the executive summary.

Sarah:
Sarah was the primary researcher for environmental topics including soil, water, tides, and material interactions. She also organized the research citations and completed a multitude of editing tasks by addressing comments throughout the report.

Timothy:
Timothy served as the constructability lead for acquiring materials and testing prototypes on-site. He also constructed the topography map using Revit, established CAD standards, and produced the final boardwalk details in AutoCAD.

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Executive Summary

Panama contains some of the most diverse ecosystems on the planet. The nation's tropical climate and location in Central America make it home to a peak concentration of mangrove ecosystems [3]. Mangrove ecosystems are important because of the multitude of benefits they provide to plants, animals, and humans. Their complex root systems provide shelter for small aquatic and terrestrial life while also acting as spawning grounds for various species of fish. They also play a role in temperature regulation, water filtration, and coastal protection. Because of this, communities living near mangrove ecosystems enjoy the protections provided or even depend on them to support valuable parts of the economy such as fisheries [3]. One issue plaguing Panama is losses in its mangrove ecosystems. This is mainly a result of erosion, logging, deforestation, and contamination from industrial or agricultural sources [11].

Oteima Technological University (OTU) is a private institution located in the City of David, Chiriquí, that focuses on technology, research, and environmental action. Batipa Field Institute (BFI) is a satellite campus of the university located in the Batipa Peninsula focusing its research in education, agroecology, natural resource management, and similar fields. Batipa Field Station (BFS) acts as a base of operations for BFI. The roughly 4,900 acres (2,000 hectares) of land constituting BFI provide a home for Howler monkeys, cattle farms, a teak (*Tectona grandis)* plantation, and many species of wildlife endemic to the region. An additional 4,900 acres (2,000 hectares) is also dedicated to a complex mangrove ecosystem.

The university expressed interest in conducting research in the mangrove area and making it available for ecotourism. Thus, they wanted to create a means for people to access the Mangrove Swamp located in BFS. The goal of this project was to design a boardwalk to be constructed in the Mangrove Swamp. Granting researchers and tourists access to the area would help in furthering BFI's existing mangrove conservation efforts as well as allow visitors to the area to better understand and appreciate the importance of these ecosystems. Teak was identified as the material to be used in the construction of the Batipa Boardwalk as it is abundantly available on the site. OTU also hoped this would minimize the environmental impact the boardwalk would have on the delicate and biodiverse mangrove ecosystem. Before starting the design process, four main objectives were identified:

- Objective 1: Site Assessment
- Objective 2: Literature Research
- Objective 3: Design, Build, and Test Batipa Boardwalk Prototypes
- Objective 4: Produce Final Batipa Boardwalk Design and Deliverables

Objective 1 was created to develop an understanding of the existing conditions at the proposed site. To accomplish this goal, multiple site visits were conducted at both high and low tide since the Mangrove Swamp experiences changes in water level of up to 4 feet (1.2 m), as discovered by measuring the height of the water against the body of the project sponsor. The GPS coordinates of the boardwalk's start and end points were recorded using the GPS on an

iPhone 12 Pro and a 3D scan of the area was produced using the phone's built-in Light Detection and Ranging (LiDAR) scanner. The LiDAR scan was then imported into Autodesk Fusion 360 and converted into a 3D model and a topographical map. Additionally, the Stick Test was conducted to develop information about the soil profile present. Ten locations in the swamp were probed using a large branch to estimate a point of refusal. The ground surface was found to be composed mainly of muddy, weak, and unstable soil. It is not until roughly six inches below the ground that a harder material, assumed to be rock or hard soil is found. The uncertainty surrounding the geotechnical aspects of this project was flagged to be researched in Objective 2, as the equipment needed to achieve a satisfactory estimate of the soil profile was not available.

During literature research, the primary focus was understanding the properties of the proposed material, teak, and its interaction with the sensitive environment. Engines such as Google Scholar and the databases provided through the WPI Gordon Library including ScienceDirect, ChemLibreText, and JSTOR were used by inputting key terms for the desired topics. These engines were chosen because they only contain peer-reviewed sources which are more reliable than sources obtained using conventional search engines like Google. Values for the mechanical properties of teak wood (tensile strength, bending strength, and compressive strength) were gathered from multiple sources and compared to the experimental values developed later in Objective 3. Google Sheets was used to tabulate all of the gathered data and produce a scatter plot of the specific gravity against elasticity. As mentioned, the Mangrove Swamp is a delicate environment but also contains saltwater which is known to cause damage to conventional construction materials. Research was conducted on the effect practices such as pile driving and the use of precast concrete foundations have in saltwater environments. Additionally, different types of timber member connections and the necessary components such as bolts, nuts, or washers were researched and their properties tabulated. Lastly, design references were selected to assist in the analysis calculations produced in Objective 4. The *ASCE 7 Standard* was selected to identify governing load combination equations and The *National Design Specification* (NDS) was chosen to identify design strength values. These were selected because they are design aids that were familiar from previous coursework and internship experience. Despite both being American for structure design, they are each referenced in the International Building Code (IBC) so were deemed reliable references for analysis after adjusting them to the site conditions. Since NDS is concerned with North American species, Douglas Fir-Larch No. 2 was selected to be used in calculations since it was a wood proven to be mechanically weaker than teak, thus NDS could be used while in analysis. Calculations also therefore had an additional factor of safety.

During Objective 3, three prototype designs were created to be tested and built. The main purpose of these prototypes was to assess constructability and the material properties of the available teak. Since no significant live loads or dead loads were anticipated for the prototypes, no calculations were performed before their construction.

Prototype 1 was built to conduct a deflection test, and the remaining two prototypes were meant to test the constructability of their respective designs in the field. Each design was drafted in AutoCAD before construction and was used to make a materials list so that the necessary tools could be purchased. Internal safety rules were established before construction among team members and the workers at BFS. Once all of the preparation was complete, the three prototypes were constructed over the course of three days. Since the wood provided by the sponsor was deemed unfit for sale, Prototype 1 served both as a means of visually assessing the quality of the wood and of helping to calculate the Modulus of Elasticity (MOE) of the material. Six trials of the deflection test were performed using six teak planks with an unsupported length of 51.6 in (131 cm). One of the team members with a known weight, Deidra, performed the deflection test. The deflection from her standing at the center of each of the 1" thick, 6 in (15 cm) wide planks was used to obtain an average MOE value of 13 GPa.

For Prototype 2, the connections between the members consisted of very large bolts and drill bits to create large openings which were difficult to obtain at the local hardware stores. Additionally, the logs proposed in the design were larger than the timber available at the Batipa Harvest Site. The issues encountered while attempting to build this design provided a solid understanding of the materials available to the sponsor and the constraints for the final design.

Prototype 3 was designed with the intent of fixing many of the issues with Prototype 2. The design called for 21 teak wood planks measuring 39.4 in x 5.9 in x 1 in (100 cm x 15 cm x 2.5 cm) to be used as the deck, supported by six columns and four girders with diameters of 12 inches (30 cm) and 7.8 in (20 cm) respectively. A much simpler, girder-column connection was developed, as seen in Figure ES1.

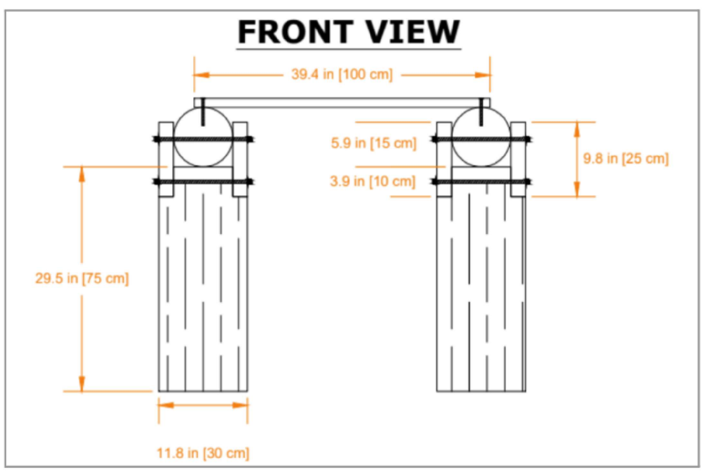


Figure ES1: Prototype 3 Connections

It involved the girder resting on top of the column and being held together by two threaded rods secured by a 9.84 in x 9.84 in x 2 in (25 cm x 25 cm x 2.5 cm) wooden block on either side of the members. Upon viewing the constructed prototype, it was requested by the sponsor that the width for the final design be increased from the proposed 3 feet (1 m) to 5 feet (1.5 m). Additionally, the girder logs were used as they were harvested from the site, which made them prone to rolling if they were not fully secured. This inspired the decision to flatten all sides of the log for the final design to ensure only flat surfaces were making contact within the connections. This design change has the added benefit of making it easier to secure the planks onto the girders. The construction of Prototype 3 revealed that the tools available at the site were not as precise as previously thought, so the significant figures for the design values were reduced. Lastly, steel plates were proposed as a lighter and stronger alternative to the square blocks used to secure the girder-column connections. While it may come at a slightly higher cost, rust-resistant metals like steel are not as prone to the abrupt failures typically seen in hardwoods.

The final objective consisted of drafting the final design and producing the deliverables for OTU and BFS. The primary deliverables of this design project were a set of drawings drafted in Autodesk AutoCAD and Revit. The girders were modified to be cut so that they have a square cross-section, minimizing the risk of them rolling when a load is applied. As requested by the sponsor, the walkable width of the boardwalk was increased to 4 ft (1.2m) to accommodate two occupants side-by-side at the same time. An additional 6 in (15 cm) was left on either side for the railing connection. The thickness of the deck planks was doubled to 2 in (5 cm) instead of the 1 in (2.5 cm) used in Prototype 3 to make up for the longer length. Steel plates were chosen for the girder-column connections instead of the wooden blocks used in Prototype 3. Rust-resistant metal such as stainless steel was discovered to be a more reliable means of keeping the members together than the wood which may be prone to rotting over time. The final design is seen in Figure ES2.

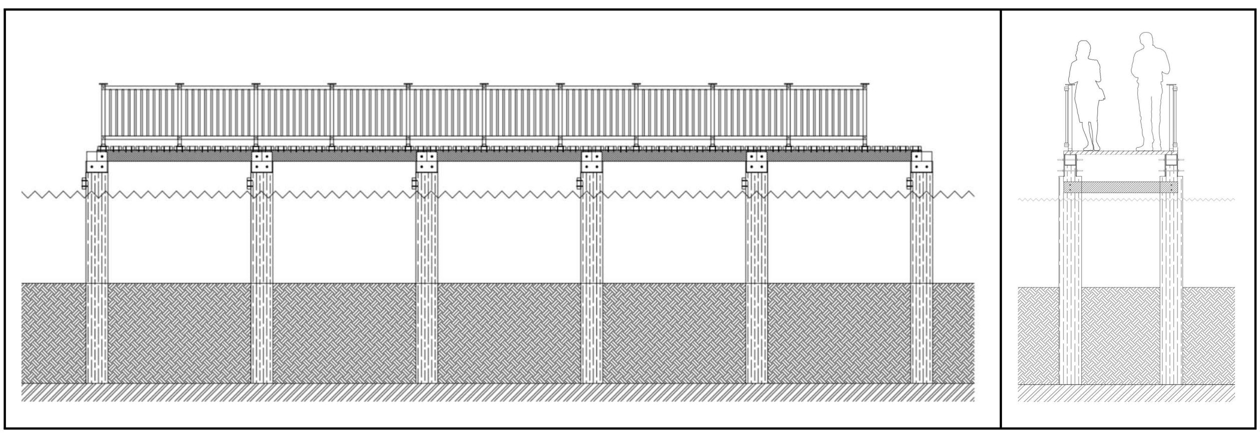


Figure ES2: Final Design Elevation View (Left) & Section View (Right)

After having drafted the design in AutoCAD, analysis was done using the references outlined in Objective 2. All calculations were performed for one section of the boardwalk. A simplified model of the structure was created in the structural analysis software RISA-3D. Dead load, live load, wind load, and fluid load were the four load types expected to be applied onto the structure and were each calculated. The dead load, the weight of the structure itself, was calculated to be 430 lbf (1.9 kN). The live load, the loading from the temporary occupancy, was determined to be 2,000 lbf (8.9 kN) and was based on a maximum occupancy of 10 occupants per section at an average weight of 200 lbf (90.7 kg) per person. A maximum lateral wind load was calculated to be 6.13 per ft^2 (0.57 per m^2) using the *American Society of Civil Engineers* (ASCE) *7-10 guide to Wind Load Provisions* and regional wind speed data. The fluid load applied laterally from seawater in the swamp at high tide, was calculated to be 250 lbf/ft (3.65 kN/m) at the maximum depth of columns. Calculated loading values were applied to the RISA model using the *ASCE 7 Standard* load combinations adjusted for Load Resistance Factor Design (LRFD). When the RISA model was solved, the stresses exerted on structural components were found to be much less than the allowable stresses of the Douglas Fir-Larch No. 2 calculated using the NDS Specification. Key components such as the columns and girders were found to not be stressed beyond 15% of their total capacity. Likewise, the maximum shear force in the structure, found to be at girder-column connections, was also less than the maximum allowable shear force calculated in NDS. The low capacities produced for a Douglas Fir-Larch No. 2 version of the structure were a good indicator that the Batipa teak would also perform well under the same loading. A package containing the final design drawings alongside construction details and 3D renderings produced with Autodesk Revit was delivered to the sponsor.

1.0 Introduction

Panama is a Central American nation characterized by the Panama Canal and the transit connections the Canal brings between the Pacific and the Atlantic Oceans. As a country near the equator, Panama has a dynamic tropical climate composed of year-round high temperatures and humidity while also prone to frequent rainfall, large tidal changes, and occasional seismic activity [1]. Over time, the environmental conditions have resulted in a range of diverse species of plants and animals, creating an array of ecosystems unique to tropical climates.

One such ecosystem found frequently across Panama is the mangrove ecosystem. This biodiverse ecosystem is characterized by mangrove trees, vast root systems, and abundant nutrients that provide a suitable habitat for a variety of species [2]. Mangrove ecosystems also provide many ecological benefits to both animals and humans. Mangrove trees play a role in mitigating the impact of the sun's ultraviolet rays, reducing local temperatures, and absorbing carbon dioxide from the air [3].

Despite many mangrove areas remaining under national protection, the mangrove population still dwindles due to weak enforcement of protective laws and unchecked development [4]. As climate change continues to impact the world, it is important to understand the value mangroves provide to their ecosystems and the environment. This can be accomplished by continuing to study and learn about mangroves and informing the general public about their importance.

Batipa Field Station (BFS), a part of Oteima Technological University (OTU), is a remote site within the Batipa peninsula that is used to research the surrounding environment and promote education about the area, conservation, and sustainability efforts. The area's mangroves are a primary focus and are studied to further demonstrate their significance in the environment.

Building a boardwalk to improve accessibility to a mangrove ecosystem would make it easier to research the mangroves and promote their ecological importance. However, constructing a lasting boardwalk within a complex mangrove ecosystem is challenging to do without harming the environment. Through site assessment, literature research, and testing small-scale prototypes, a boardwalk to be located in the Mangrove Swamp within the BFS was designed and presented to OTU.

2.0 Background

The Republic of Panama is located on a narrow stretch of land that bridges Costa Rica and Colombia. Panama is the southernmost country of Central America with the Pacific Ocean bordering its southern coast and the Caribbean Sea bordering its northern coast [5]. It has a tropical climate, characterized by year-round hot temperatures and high humidity. The rainy season lasts from May to January and the average annual rainfall is approximately 748 in (19,000 mm). Panama's average maximum temperature is between 88.0°F and 94.1°F (31.1°C–34.5°C) and its average minimum temperature is between 68.2°F and 72.3°F (20.1°C–22.4°C) [1]. The warm waters of the Caribbean Sea and equatorial Pacific Ocean create conditions suitable for tropical storms or hurricanes, however, due to Panama's location, these storms rarely reach the country. In the Pacific Ocean, hurricanes usually form off the coast of southern Mexico and travel north, leaving Panama largely unaffected [6].

Chiriquí, a province in Western Panama, covers about 2,528 mi^2 (6,547.7 km^2) and borders Costa Rica and the Pacific Ocean [7]. This province has a typical Panamanian climate in terms of temperature, but due to the tall mountains, Chiriquí is wetter than most other provinces. On average, the province receives 106 in (2,690 mm) of rainfall annually [8]. Batipa is a small coastal peninsula within Chiriquí near the city of David as seen in Figure 1. The region contains a vast mangrove ecosystem, which plays a large role in the area's microclimate.

Figure 1: Batipa Region in the Province of Chiriquí [9]

The high growth density and extensive root systems of mangroves supply an abundance of natural resources beneficial to plants and animals. Their complex root system provides shelter for marine and terrestrial life during natural disturbances like tropical storms, floods, and erosion [2]. The sheltered area is used as a spawning area for animals as it can be a refuge from predators. Mangrove ecosystems also provide many benefits for human life such as: reducing temperatures, safeguarding against ultraviolet radiation, and reducing CO_2. Additional benefits include biodiversity, coastal protection, and water filtration.

Approximately 170,000 acres (70,000 hectares) of mangrove area in Panama are protected under the National System of Protected Areas [10]. Despite this, many of these areas are still prone to deforestation and pollution as products of both climate change and human infrastructure projects. A study conducted determined that between 1996 and 2008, the mangrove area in Panama was reduced by 13% [11]. Although there are established policies in place to preserve Panama's mangroves, they are ultimately ineffective as a result of light enforcement and minimal monitoring [4]. As the world experiences the effects of climate change, it is vital to protect mangrove ecosystems due to their significant role in helping the environment.

Oteima Technological University (OTU) is a private institution located in David, Chiriquí, that focuses on technology, research, and environmental action [12]. The university has largely directed its resources to contribute to sustainable development in Panama, including the conservation of mangrove ecosystems in the region. Batipa Field Institute (BFI), a satellite campus of OTU, promotes research in education, agroecology, natural resource management, and similar fields. Batipa Field Station (BFS) serves as a base of operations for all projects undertaken by BFI, including a classroom and a biology center. The location of BFS is denoted by the blue dot in Figure 1.

BFI conducts research to learn more about Batipa's mangroves and share it with the general public. One way to further their involvement in the protection of mangroves would be to make it easier to access the ecosystem, as the environment is only traversable at the Mangrove Swamps' low tide. Even at low tide, the Mangrove Swamp has a marshy terrain and a remote location. Accessibility to mangroves could be increased by adding a boardwalk, a wooden walkway that helps travel across any sand, marshy ground, or other difficult terrains [13]. As seen in Figure 2, a boardwalk over an area of changing tide must be higher than even the surge level, so the walking surface is above water, even during extreme weather events. There are many environmental influences that can factor into a boardwalk's feasibility, including the effects of seismic activity, water, and soil composition of the area. Aside from external influences, the selection of building materials also plays a large role in the feasibility of a boardwalk.

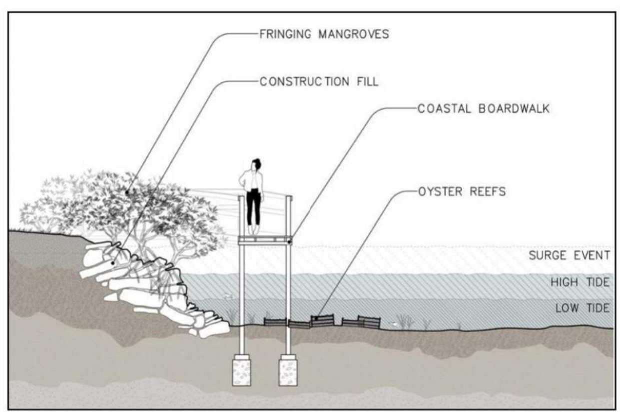


Figure 2: Typical Elevated Boardwalk [14]

Panama exists on the fault line between the Cocos and Caribbean tectonic plates, along with the rest of Central America. Earthquakes in Panama occur but are minor compared to those in Costa Rica and Honduras, which are closer to fault lines [15]. The tectonic activity along this fault line fosters the formation of tsunamis and volcanic eruptions. While tsunamis occur in this region, the low strength of earthquakes in Panama makes them rare and weak [16]. The volcanic and tectonic activity in Panama was investigated and found to be negligible for design purposes. While Panamanian volcanoes are generally dormant and less frequent than those in surrounding countries, it has led to the unique topography in the country.

Batipa has a great variation in the landscape throughout the peninsula. One of the most vital of these landforms is tidal creeks, which are long and narrow coastal waterways with a mean tidal range above 13 ft (4 m). Tidal creeks have negligible freshwater flow, with shallow water levels that fluctuate based on tidal conditions. The constant flow of ocean water in and out of tidal creeks has a large impact on turbidity, which is the amount of total suspended solids in a body of water, such as algae, sand, silt, nutrients, and microorganisms.

Turbidity in water is beneficial to ecosystems in moderation. Water that is too turbid does not allow sunlight to reach the seafloor, preventing photosynthesis in deep waters. This in turn reduces the cover of plants that eggs need for protection from predators in the water above. [17]. Very turbid water can decrease the eyesight and gill capacity of fish, reducing their ability to hunt effectively and protect their eggs. Excessively turbid water disrupts fish spawning areas and eggs as they cannot survive under these conditions [18]. However, water with no turbidity has no nutrients and cannot sustain life for many organisms. In mangrove ecosystems, the water is moderately turbid, which allows nutrients to float on the water's surface and serve as a food source. The turbidity around mangrove roots allows for the growth of small plants and algae on the floor nearby, which is another food source and layer of protection for young animals.

The fluctuation of water in tidal creeks has an impact not only on natural life but also on manmade structures. The high salinity of seawater negatively impacts some construction materials, so successful structural designs in these environments incorporate protection against damage caused by salt water. For example, building through a saltwater area can reduce the compressive strength of concrete over time, so a preventative mix would be needed to withstand the saltwater conditions [19]. Salt damage in wood structures, though not catastrophic, was also found to negatively impact resistance to high loads over time [20].

These water fluctuations affect not only the construction materials but also other geotechnical factors such as soil that are considered in structural designs. The soil within tidal creeks is saturated with water and does a poor job of absorbing additional water, making maritime construction design challenging [21]. Tidal forces create a constant motion of sediment to and from the ocean causing existing soil to be constantly eroded and replaced with new soil. Sediment from the tidal creek is washed out into the ocean due to marine flushing, and ocean sediment returns to the creek during infilling.

Soils in Panama fall under three categories: andosols, acrisols, and nitisols. The soil in Batipa is classified as haplic acrisols, a category characterized by acidity and a high clay content. [22]. Haplic acrisols are common in tropical climates and contain high levels of phosphorus, a natural plant fertilizer, that forms a layer of topsoil rich in nutrients, creating ideal conditions for a mangrove ecosystem [23]. The soil in Batipa is easily disturbed and moved by heavy rainfall due to its small particle sizes, making it prone to mudslides [24]. Due to the high levels of nutrients in haplic acrisols and the topsoil layer it produces, when mudslides occur, they can carry these nutrients into bodies of water, such as mangrove ecosystems, in high quantities [23]. Additionally, the high amount of water required for mudslides is added to the mangrove ecosystem, which causes conditions similar to tidal surges. Therefore, it is important to account for surge events caused by mudslides when determining the elevation of a structure in this environment. The Batipa Boardwalk was designed to accommodate these factors.

Wood is a commonly used material in boardwalk construction as it is inexpensive and provides adequate capacity for loads [25]. Generally, trees are stronger the more time they are given to grow, as the trees grow thicker, thus, becoming stronger. One way to qualitatively group wood species by strength is by categorizing species by softwoods and hardwoods [26]. Softwood species are less dense but cheaper than hardwoods. Hardwood species are often more expensive than softwoods but perform better due to their greater density. Two quantitative measures to gauge wood strength are the wood species' specific gravity and modulus of elasticity [27]. Specific gravity is the property representing the ratio between the density of a material and the density of water. The modulus of elasticity (MOE) indicates how much a material is susceptible to deflection.

Mechanically, wood is more susceptible to failure than other construction materials, such as concrete or steel, but is often still adequate for building applications. Wood is also a hygroscopic material, meaning it will swell and shrink from absorbed and released moisture in the material, but only if it goes below its fiber saturation point [28]. The dynamic changes in a wood's volume may alter its mechanical strength, which can lead to material failure. Since wood is also an organic material it is susceptible to a higher degree of deterioration than other materials that may rot due to the presence of water and fungi. When wood is not structurally viable, concrete is often the next cheapest adequate alternative, at the cost of aesthetics and any environmental degradation [25]. For more intensive loading conditions, structural steel can be used as a primary construction material.

Batipa has two lucrative businesses: cattle and wood. At Batipa, teak (*Tectona grandis*) is the main hardwood species grown, harvested, and sold to foreign markets. Batipa dedicates approximately 2,350 acres (950 hectares) to the farming of teak trees. Teak trees are grown at a 20-year cycle for a total of 100 – 120 acres (40 – 50 hectares) of cut annually. The Batipa Harvest Site is a location at which the recently harvested teak is cut into its final shipping dimensions and organized between wood deemed sellable and wood deemed unsuitable for sale.

The uniqueness of Batipa, both through its landscape, industries, and opportunities is currently very limited. In order to attract more ecotourists to the beautiful and rare Mangrove Swamp, the muddy area needs to become more accessible. To accomplish this, the Batipa Boardwalk was designed and built by constructing prototypes with the materials available at Batipa. The next section covers this process.

3.0 Methodology

The purpose of this project was to design a boardwalk for OTU to construct in the Mangrove Swamp at BFS. The Batipa Boardwalk was predominately designed with the intention of improving accessibility to the mangrove trees for researchers who study mangrove ecosystems. It was also requested that the boardwalk be accommodating for public access to increase ecotourism by encouraging visitors to learn more about mangroves. The Batipa Boardwalk was designed to have minimal impact on the sensitive ecosystem while providing a safe and stable surface for foot traffic. Furthermore, the Batipa Boardwalk was designed to be at least 5 ft (1.5m) above ground level to accommodate fluctuating tide levels in the Mangrove Swamp. At the request of OTU, the primary construction material of the Batipa Boardwalk would be teak wood, which is produced at the Batipa Harvest Site. To meet these requirements and create a functional design, the following objectives were established:

- Objective 1: Site Assessment
- Objective 2: Literature Research
- Objective 3: Design, Build, and Test Batipa Boardwalk Prototypes
- Objective 4: Produce Final Batipa Boardwalk Design and Deliverables

3.1 Objective 1: Site Assessment

Objective 1 was to develop an idea of the proposed building site and the mangrove ecosystem at BFS. This objective involved conducting site visits to the Mangrove Swamp to survey the land, identify areas of concern, and determine the preliminary dimensions of the Batipa Boardwalk. The area of focus was the limited accessibility to the Mangrove Swamp due to the presence of large roots in the path of travel and a steep drop-off from the adjacent walking path to the bottom of the swamp. These concerns were identified through observation and experience, such as sinking or loss of footing due to mud in the swampy area. In order to document the observations made, photos were taken to reflect any notable remark.

The Mangrove Swamp was known to have a significant change in the tide; therefore, site visits were conducted at both low and high tide to gauge the starting depth of the boardwalk foundation and the necessary deck height to still be serviceable at high tide. Most site visits were conducted during low tide when the Mangrove Swamp was traversable, but the change in water level was also noted by the project sponsor standing in the water during high tide. A tape was used to measure the height of water on his body.

The target entry location of the boardwalk was recorded using an iPhone GPS. The distance between the entry location and the target endpoint was indicated by the sponsor and measured using a tape measure. A 3D model of the area was produced using an iPhone application, *Polycam 3D Scanner*, using the iPhone 12 Pro's built-in Light Detection and Ranging (LiDAR) scanner. The LiDAR scan of the Mangrove Swamp and adjacent hill was then uploaded to Autodesk Fusion 360 and converted into a 3D model to provide a visual of the relevant topography.

The Mangrove Swamp was inspected to identify potential hazards or obstructions that interfere with the design, including the Stick Test, probing the area to estimate the depth of the swamp before hitting refusal. The Stick Test was conducted at low tide using a large branch and forcing it into the ground as far as it would go. Any uncertainty indicated by Objective 1, such as material and geotechnical information created the topics to be researched in the literature review.

3.2 Objective 2: Literature Research

Objective 2 was to conduct literature research regarding the design and construction of the boardwalk. Building a stable wooden structure in a sensitive environment requires a strong understanding of construction material properties, the interactions between these materials and the environment, and effective structural elements in this type of structure. In Objective 2, search engines such as Google Scholar as well as databases through the WPI Gordon Library website including ScienceDirect, ChemLibreText, and JSTOR were used by searching key terms to find sources for each topic. These sources were chosen because the results are peer-reviewed and more reliable than Google. Research topics included the physical properties of teak wood, environmental conditions, soil types, and different types of wood joints and connections. The selected research topics fulfill one of two roles, the first of which is to provide supplemental information to conditions observed in Objective 1. The second contributes to the information on a topic that, while it was not observed in Objective 1, was relevant and necessary to design the final boardwalk.

As an organic material, the properties of any wood can vary between different species. The mechanical properties of the teak were established to be compared with experimental values found on the available teak at BFS (which is covered in Objective 3). Values for density, elasticity, tensile strength, bending strength, and compressive strength of teak wood were gathered from multiple reports and databases. For each source, the location grown, age cut, and log diameter were recorded and tabulated. Using the information from this table, a scatter plot of specific gravity against elasticity was produced using Google Sheets to present all the values together.

The Batipa Boardwalk required a lasting foundation in the swamp's soil and resistance to the effects of the high-salinity water typical in coastal swamp environments. To accomplish this, conventional boardwalk designs in mangrove areas with little disruption to the environment were found to identify functional foundation and boardwalk designs. Practices such as pile-driving, the use of pre-cast concrete in boardwalk foundations, and the refusal point of the soil were identified by consulting the academic papers of groups who have successfully completed a project in a similar environment, including engineers and scientists worldwide.

In addition to researching teak properties, different styles of timber member connections were tabulated. Sources provided details on typical simple joints between beams, girders, and columns and the techniques and tools used to construct them. Supplementary sources were researched to ensure that logs, despite being shaped differently than planks, can still be feasibly prepared to work in typical joints. Additionally, typical means of securing member connections were also noted between two square beams, which are the use of steel plates, threaded rods, bolts, nuts, and washers. A threaded rod is essentially a long and this screw is without a head. These rods are sold in 3 ft (0.9 m) lengths and can be cut after installation to an appropriate length for their particular use. Threaded rods are also thicker than screws and can be more than an in (2.5 cm) in diameter. Using this material allows for strong, high-friction connections. These connection methods were determined by research regarding strong connection methods on search engines such as Google Scholar and through experimental feasibility via building the prototypes.

Lastly, reference manuals and sources were identified to be used for calculations that would prove the structure of the final design is stable for all anticipated loading. This included finding official references that would identify applicable types of loading, design equations for each loading type, loading combinations, design material and connector strength values, and equations to adjust design strength values based on material and sizing. The research scope also included American and international design standards to maximize available sources to consider implementing.

Each source was also evaluated for applicability to the Batipa Boardwalk design and limitations of using the reference for the analysis process were determined. For references to design strength values, the evaluation also included identifying what range of construction techniques were mathematically verified. Some manuals that were considered are as follows: the *National Design Specification* (NDS) for Wood Construction, the American Society of Civil Engineers (ASCE) *ASCE 7 Standard*, and The International Building Code (IBC). The manuals were found based on familiarity from previous academic and internship experiences.

The information gathered in Objectives 1 and 2 identified constraints and opportunities involved with the boardwalk location, material properties, connection patterns, and boardwalk design practices. These aspects were acknowledged and implemented into the design process in Objective 4.

3.3 Objective 3: Design, Build, and Test Batipa Boardwalk Prototypes

Design, Build, and Test Process Overview

To further investigate how a boardwalk could be implemented at BFS, prototypes were designed, built, and tested. Prototypes served as an opportunity to determine the material properties of the available teak and its constructability. Since prototypes were not done to support a significant live load or dead load, but rather, for testing purposes, calculations were not done beforehand. A total of three prototypes were designed. Prototype 1 was designed to perform a deflection test for the deck and Prototypes 2 and 3 were designed to study constructability in the field. Prototypes were designed to be built at a low height to the ground, allowing each prototype to pose limited risk to builders. Preliminary drawings of each prototype were designed by hand and then internally cross-examined to ensure they were practical and free of measurement errors. Once reviewed, prototype construction drawings were finalized in AutoCAD. Based on these drawings, a material list was made and used to gather the necessary tools and materials needed for testing the prototypes. Safety rules were established to be used to prepare for material preparation and construction. Once preparation was complete, prototypes were built and tested. The design and construction of each prototype will be explained in further detail later in their own sections.

Design Process

Before designing, a set of terminology was established for consistency across all prototypes as seen in Figure 3. The **deck** refers to the series of planks that create the walking surface of the structure. The **girders** are the horizontal supports that hold the deck and the **railing,** which provide pedestrian safety along the travel path. Girders face the direction of travel and rest on **columns**, which are the vertical supports. **Connecting plates** are used to secure the connection between girders and columns. **Stringers** are members that provide lateral support to the columns. Stringers and columns compose the boardwalk's substructure. The substructure supports live loads such as pedestrian activity as well as the superstructure dead load, which includes the girders, deck, and railing. **Roundwood** is a term used to describe wood that is cylinder-shaped, such as logs, and is measured in diameter and length. **Dimensional wood** is shaped like a rectangular prism, such as planks, and is measured in length, width, and thickness.

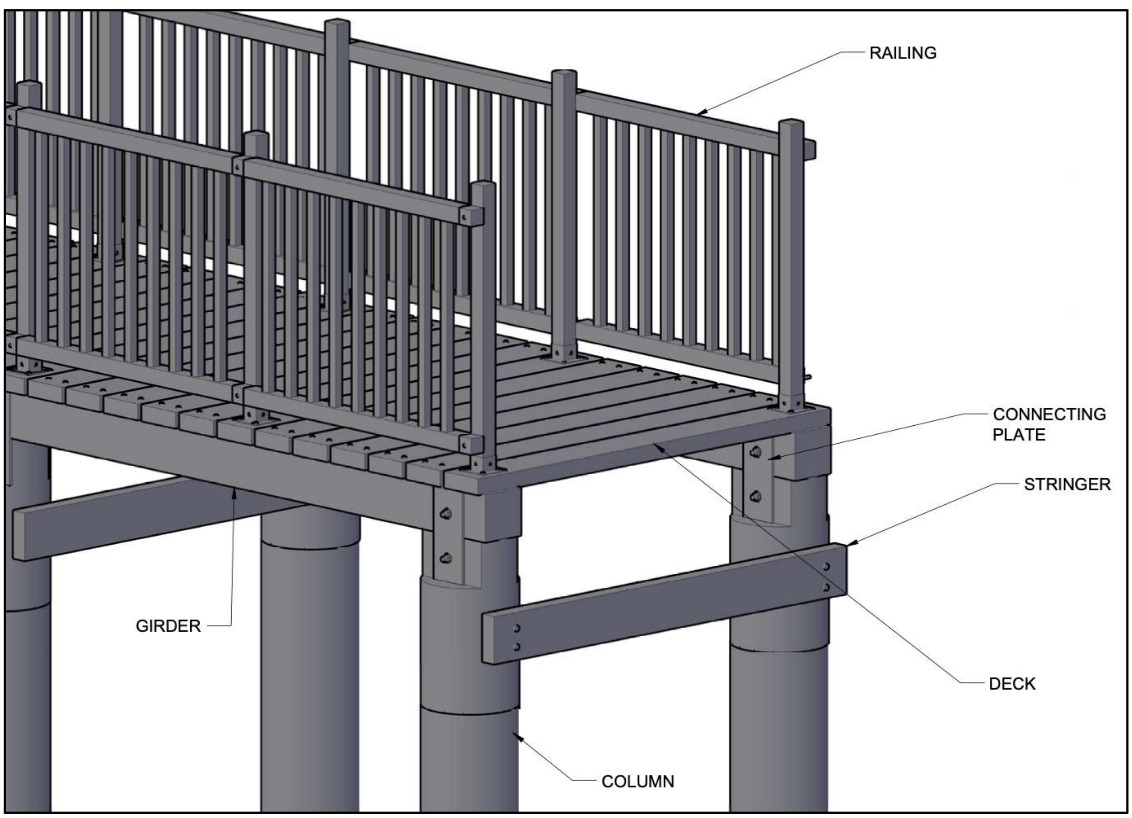


Figure 3: Sample Boardwalk with Element Terminology

Build & Test Process

Prior to preparing for construction, proper safety procedures were established and implemented to ensure the safety of all individuals, including both those involved in construction and bystanders. These procedures were developed based on recommendations made by OSHA regarding Personal Protective Equipment (PPE) and protecting individuals operating tools and machinery [29]. OSHA is a United States Government organization that focuses on maintaining a safe workplace in construction, offices, and industrial settings and is deemed a reliable source due to its consistency and reputation in the construction field. These best practices were established by years of data collection by OSHA and by following these guidelines, injuries during construction have decreased from 11 incidents per 100 workers in 1972 to 3 per 100 workers in 2020 [30]. For these reasons, OSHA guidelines were adopted into the safety standards for the construction of prototypes for the Batipa Boardwalk. The standards established are shown in Table 1.

Table 1: Established Safety Information Standards

PROTOTYPE CONSTRUCTION SAFETY RULES

- Any person operating a tool or interacting with a raw material had to abide by the following safety rules:
    - Safety glasses, closed-toed shoes, and gloves must be worn at all times
- Wood-cutting machines such as chainsaws and table saws were operated solely by trained operators
    - Bystanders were not to be in the vicinity of an active tool
    - Active operators were only approached by others when communications were announced, eye contact was made, and tools were turned off
- Workers were required to announce their location when beginning to use a tool
- Any job site safety hazards were announced prior to the start of construction
    - Newly developed safety hazards were communicated immediately if they arose

After establishing proper safety procedures, materials and tools were acquired. Teak wood elements were selected and cut at the Batipa Harvest Site and transported to BFS. Both dimensional deck planks and Roundwood girders were cut to the desired specifications and transported to BFS for construction and testing. Using the list of materials as a guide, connectors and construction tools were purchased at *Cochez,* a hardware store located in David, Panama.

Each prototype was built on a flat, dry, surface to eliminate injury due to falling hazards and undue sinking of the prototype into the ground. Upon completion of construction, the three boardwalk prototypes were tested based on their respective purpose, unique to each prototype.

Prototype 1

Prototype 1 was designed and built to conduct a deflection test on the planks of a boardwalk deck. The amount a material deflects is based on the function of the weight of the load applied, the length of the material, the inertia of the material's cross-section, and the MOE of the material. A deflection test can be conducted using a known weight and measuring the deflection of a member with a known length. There are many known deflection equations for different loading conditions on simply supported beams. Prototype 1 was designed for a singular point load at the center of the plank, as shown in Figure 4.

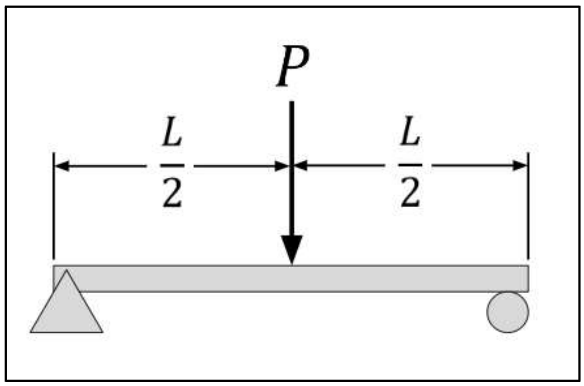


Figure 4: Load Diagram of a Simply-Supported Beam with Centered Load

This loading schematic has a known deflection equation, as seen in Equation 1 where δ represents the maximum deflection, P represents the applied load, L represents the unsupported length of the plank, I_x represents the inertia of the material (determined from the material cross-section), and E represents the material MOE. Loading Prototype 1 with the loading condition shown in Figure 4 allowed the MOE of the teak at Batipa to be experimentally solved using this equation.

$$\delta = \frac{PL^3}{48EI_x} \quad (1)[31]$$

Figure 5 shows the design drawing of Prototype 1. The deck consisted of six deck planks connected to two girders. Deck planks were, on average, 55.1 in (140 cm) long, 7.9 in (20 cm) wide, and 1 in (2.5 cm) thick. Each plank was designed to be spaced 2 in (5 cm) apart and secured to each girder with two 3 in (7.6 cm) stainless steel wood screws. Each girder was designed to rest on the ground with a length of 79.7 in (200 cm), a diameter of 12 in (30 cm), and a spacing of 47.2 in (120 cm) apart from the other girder. The material list for Prototype 1 is shown in Table 2. To assemble, the log girders were laid on the ground with their respective spacing and then the planks were screwed in with a drill.

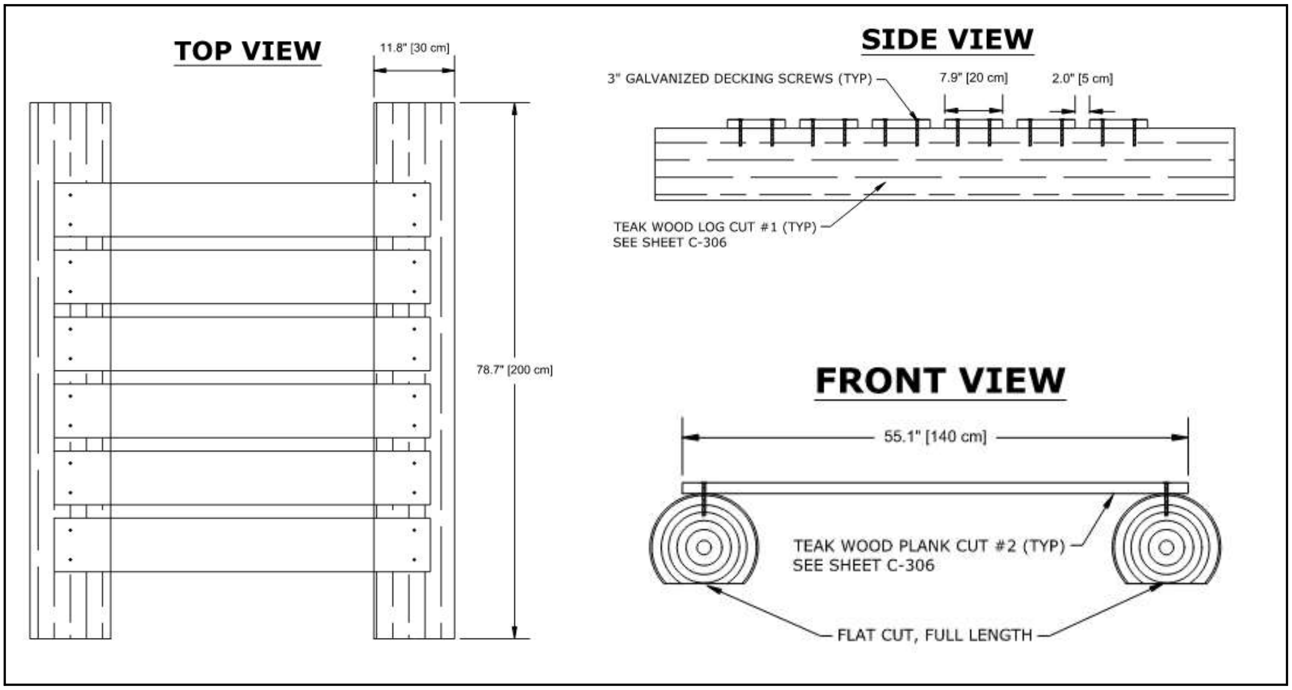


Figure 5: Prototype 1 Design Sheet

Table 2: Materials List for Prototype 1

Wood Type	Dimensions (cm)	Quantity
Teak Wood Plank	140 x 20 x 3	6
Teak Wood Logs	140 (L) x 30 (Dia.)	2
Stainless Steel Wood Screws	7.6	24

Key: 1 cm = 0.39 in

When the construction of Prototype 1 was complete, planks were measured for their width, thickness, and unsupported length across the span. The distance from the ground to the top of a plank was measured at the center span. This measurement was then retaken after a known weight, Deidra, was applied to the center of the plank. This process was repeated with the remaining six planks. All measurements were taken using a tape measure and recorded to the nearest tenth of a centimeter.

Data collected during the deflection test was used to calculate the elasticity of teak wood harvested at Batipa. By subtracting the initial and final height of the distance between the ground and the top of the plank, the distance the material deflected (δ) was determined. The deflection, width, thickness, and unsupported length, of each trial were averaged to have a single value for each category. The average width (b) and thickness (h) of the boards were used to determine the inertia (I_x) of the material as seen in Equation 2.

$$I_x = \frac{bh^3}{12} \quad (2)[31]$$

After determining the inertia, the MOE of the teak was solved in Equation 3, a rearranged form of Equation 1.

$$E = \frac{PL^3}{48I_x\delta} \quad (3)[31]$$

The experimental MOE value represents the elasticity present in the available teak at Batipa. This value was compared to the experimental MOE values of similar teak studies found in Objective 2 to determine if the teak harvested at Batipa is similar. An experimental value lower than the researched range, for example, would suggest that the teak at Batipa is generally weaker than expected, which would need to be addressed in the Batipa Boardwalk final design.

Prototype 2

Prototype 2 was designed to assess the constructability of a boardwalk. Since Batipa laborers are experienced in harvesting wood and do not regularly build structures, it was important to test Prototype 2 to ensure the constructability of building the final Batipa Boardwalk with the available tools.

The Prototype 2 deck consisted of ten planks connected to two girders. One column supports the ends of each girder, and two stringers connect to columns to provide lateral bracing at the ends of the boardwalk. Additionally, the design included two railings that were connected at the top of the columns.

All substructure members were designed as roundwood, the largest material sizes possible, to maximize strength. The deck consists of ten planks measuring 4.6 ft (1.4 m) in length, 0.7 ft (0.2 m) in width, and 1 in (2.5 cm) in height. Each plank was designed to be spaced 0.2 in (0.5 cm) apart and connected to girders with two 3 in (7.6 cm) stainless steel screws connected. Each girder has a length of 8.7 ft (2.645 m), a diameter of 7.9 in (2.4 m), and a spacing of 3.9 ft (1.2 m) apart center-to-center. Log columns have a length of 5.2 ft (1.58 m) and a diameter of 1 ft (0.3 m). Stringers were designed to be roundwood with a length of 6.7 ft (2 m) and a diameter of 0.7 ft (20 cm). Roundwood railings were designed to have the same dimensions as the girders.

One of the major areas of focus in testing and evaluating this design was the connections. Log member connections in Prototype 2 were designed to have large threaded rods drilled through the full width of the connecting logs. The design drawing of Prototype 2 is seen in Figure 6, and the prepared material list for Prototype 2 is shown in Table 3.

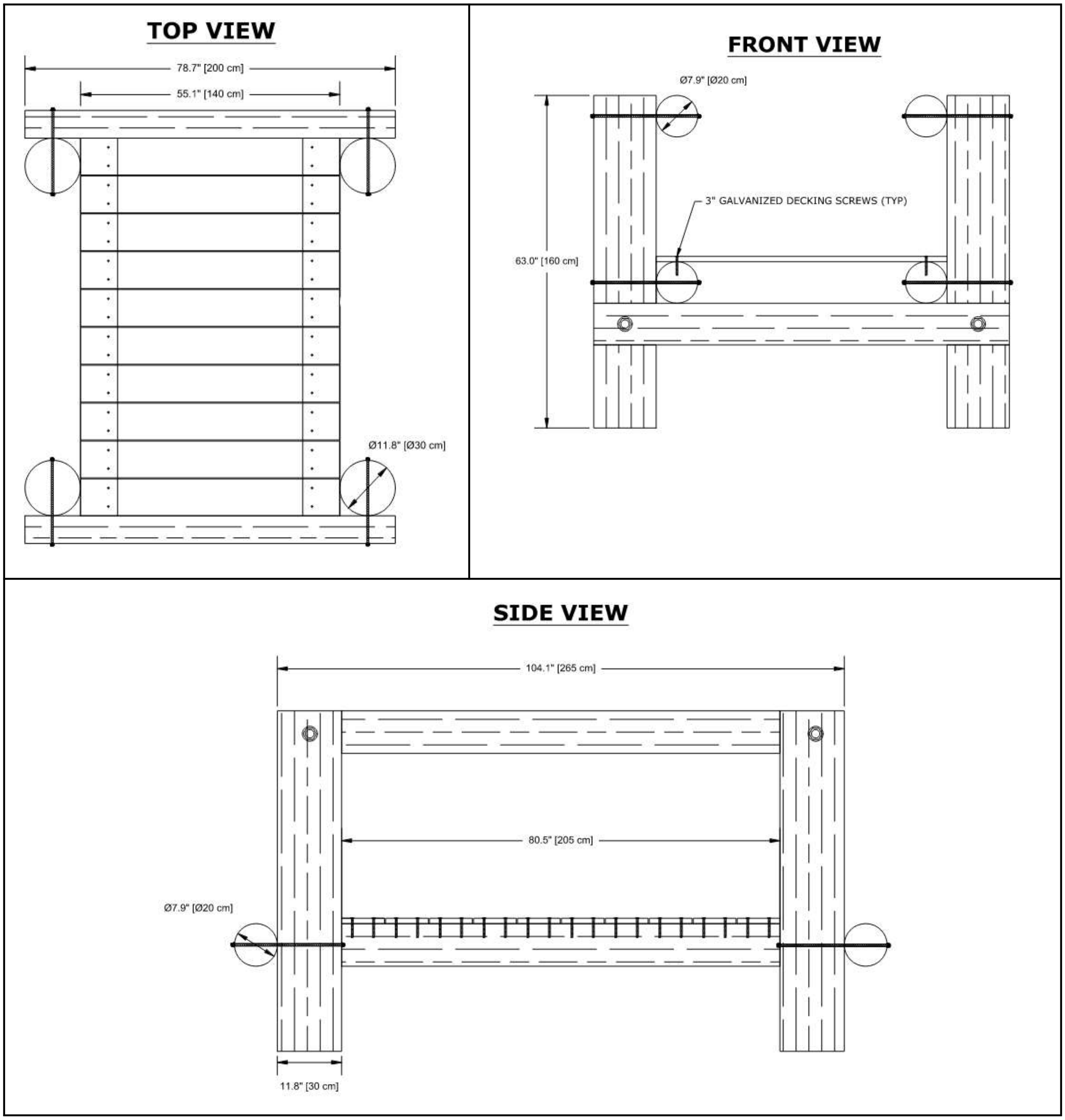


Figure 6: Prototype 2 Design Sheet

Table 3: Materials List for Prototype 2

Wood Type	Dimensions (cm)	Quantity	Fastener Type	Quantity
Teak Wood Plank	140 x 15 x 3	20	½” Galvanized Threaded Rod	28 ft
Teak Wood Log	265 (L) x 20 (Dia)	4	½” Stainless Steel Nut	32
Teak Wood Log	160 (L) x 30 (Dia)	4	½” Stainless Steel Lock Washer	32
Teak Wood Log	200 x 20	2	3” Stainless Steel Wood Screws	40

Key: 1 cm = 0.39; 1 in = 2.54

Prototype 3

Prototype 3 was designed as an alternative to Prototype 2, testing different connections, structural supports, and log sizes. Similar to Prototype 2, the focus was on the quality and performance of the structure. The design called for 21 teak wood planks measuring approximately 39.4 in x 5.9 in x 1 in (100 cm x 15 cm x 2.5 cm) to be used as the deck, supported by six columns and four girders. The six columns of 11.8 in (30 cm) teak logs were cut to approximately 29.5 in (75 cm) in height. The four girders measured 7.9 in (20 cm) in diameter and cut to 78.7 in (200 cm) in length. Twelve 9.8 in x 9.8 in x 2.0 in (25cm x 25 cm x 5cm) sections of teak wood were cut to be used to connect the girders and columns. 16 sections of ½ in (1.3 cm) galvanized threaded rods were cut to approximately 15.7 in (40 cm), with 32 nuts and lock washers to secure these rods. These components were connected as seen in Figure 7. The prepared material list for Prototype 2 is shown in Table 4.

The six columns were placed in two rows of three columns, with spacings of 78.7 in (200 cm) between columns and 47.2 in (120 cm) between rows. Once the columns were properly spaced and aligned, notches measuring 3.9 in (10 cm) in height and 2.5 in (5 cm) in depth were cut out of the top of each, with one notch on each side. Each girder was connected to two columns, with the middlemost column on each side supporting two girders. In this arrangement, each girder rested on an end column and a center column. The planks were then arranged perpendicular to the intended path of travel and spaced approximately 0.5 in (1.3 cm) apart. Once the planks were aligned, four pilot holes were drilled in each plank in a similar fashion to Prototype 1, aligning with the center of their respective girders and leaving at least 1 in (2.5 cm) spacing from the edge of the planks to prevent splitting. Three in (7.6 cm) stainless steel wood screws were driven through the pilot holes and into the girders. Figure 8 details the drilling used to connect columns and girders.

Once the deck was secured, the connections between the girders and columns were installed. On each girder and column, a marker was used to indicate where the threaded rod connections would be installed. A small pilot hole was drilled into each marking before a ½" hole was drilled through the full width of the girders and columns. The holes were widened with a ⅜" wood drill bit. A 9.8 in x 9.8 in x 2 in (25 cm x 25 cm x 5 cm) board was then placed on each notch and markings were made on the board, with each marking aligning with a hole. These boards had ⅜" holes drilled on each marking and were again placed on the notches to align with the holes. A threaded rod was pushed through each hole, and lock washers and nuts were attached to each end of the threaded rods. The nuts were tightened so that the threaded rod was secured and the boards tightly pressed against each side of the columns and girders. The excess rod was cut off with a metal hand saw to avoid sharp excess material sticking out of the structure. This procedure was repeated for each connection. Figure 9 shows the connection details.

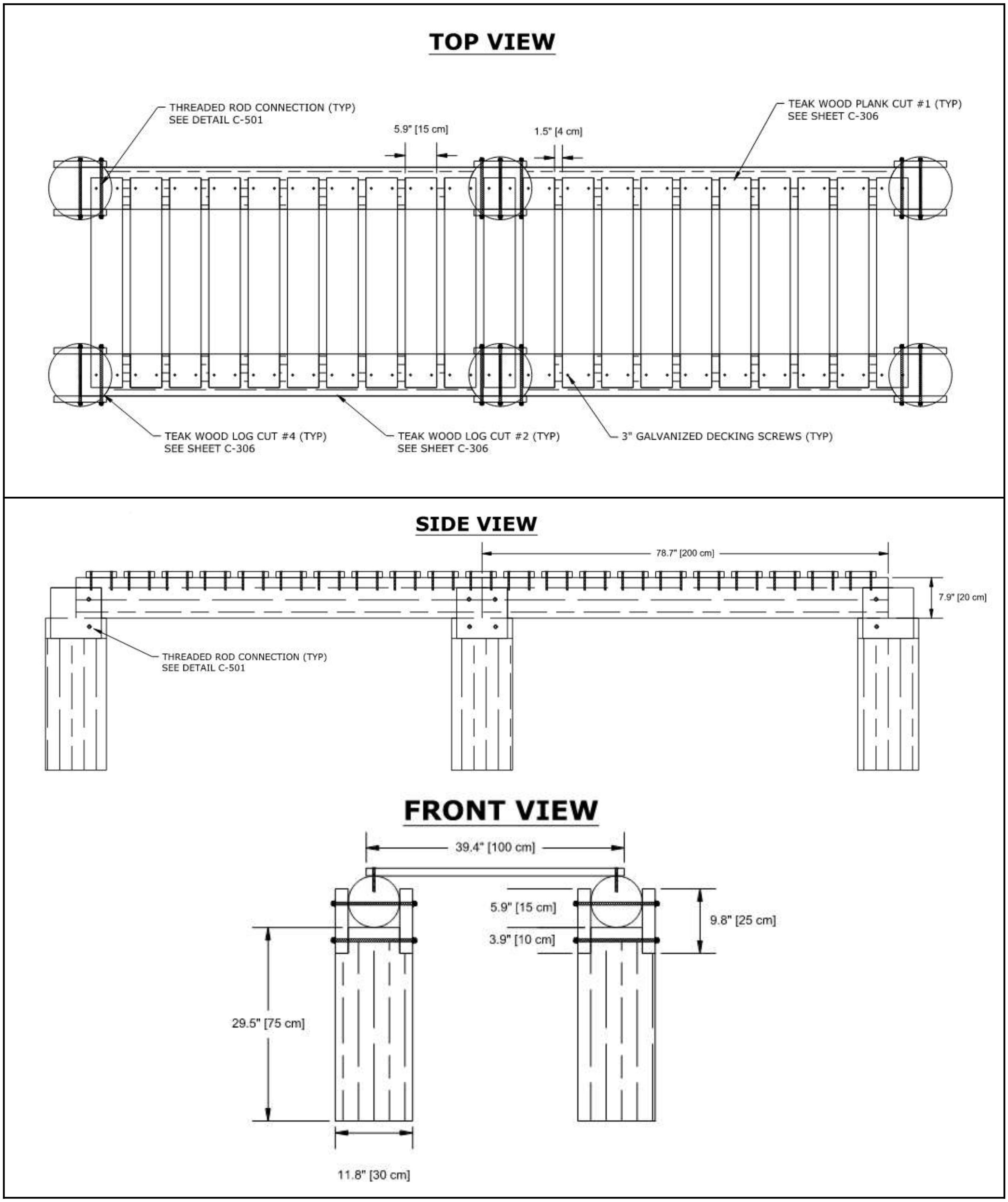


Figure 7: Prototype 3 Design Sheet

Table 4: Materials List for Prototype 3

Wood Type	Dimensions (cm)	Quantity	Fastener Type	
Teak Wood Plank	100 x 15 x 3	20	½” Galvanized Threaded Rod	20 ft
Teak Wood Plank	25 x 25 x 25	12	½” Stainless Steel Nut	32
Teak Wood Log	75 (L) x 30 (Dia)	6	½” Stainless Steel Lock Washer	32
Teak Wood Log	200 x 20	4	3” Stainless Steel Wood Screws	60

Key: 1 cm = 0.39 in; 1 in = 2.54 cm; 1 ft = 0.3

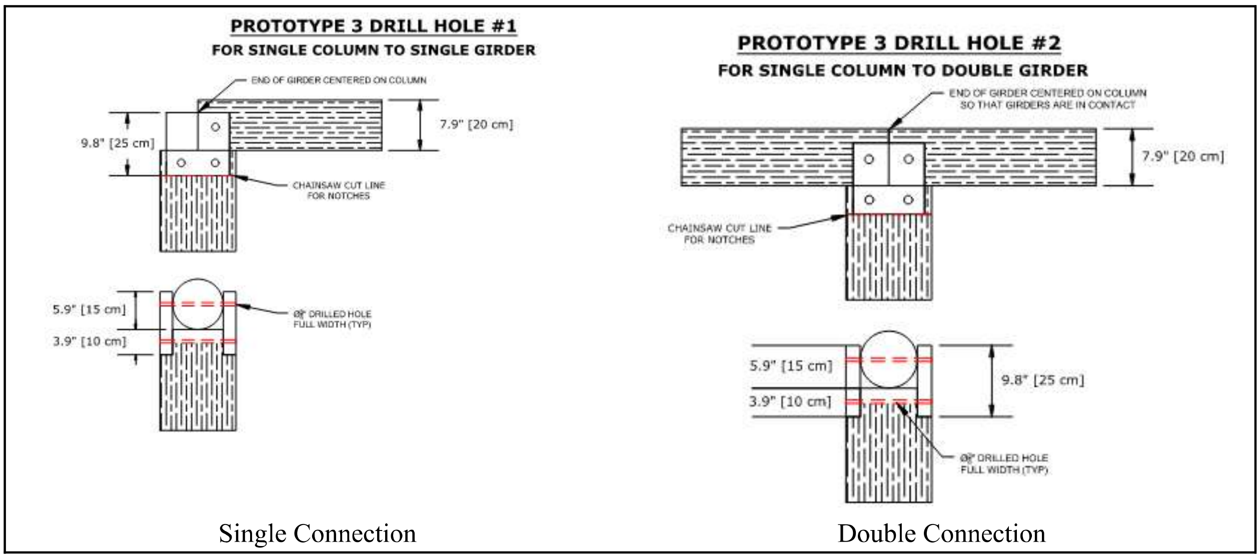


Figure 8: Prototype 3 Drill Hole Details

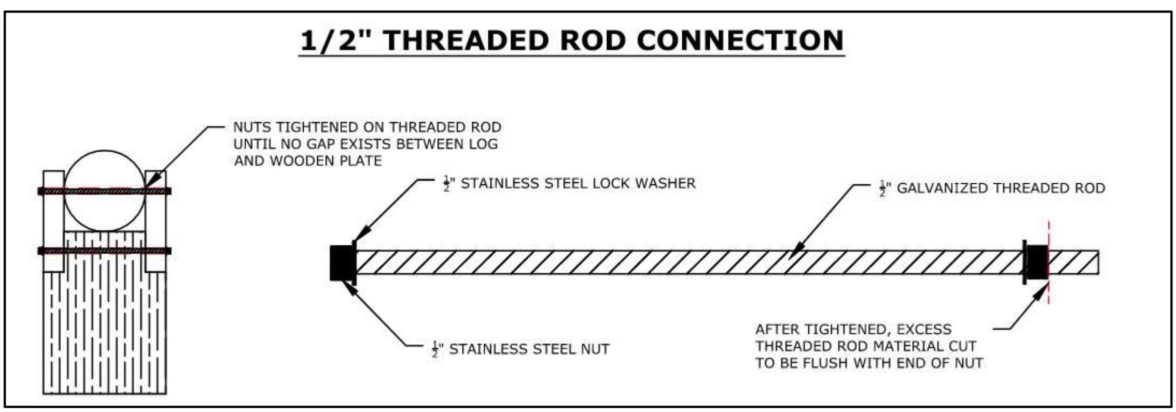


Figure 9: Prototype 3 Threaded Rod Connection Details

Upon completion, the structural stability of the completed structure was tested. Before allowing any weight to be applied to the planks, the columns were pushed horizontally, one at a time, to detect movement or loose connections. Once successful, weight was applied to the top of the boardwalk prototype to test stability once again. Climbing atop carefully, five students stood on top of Prototype 3. They walked across and even simultaneously jumped. In another test, ten employees sat on the prototype to test if it could hold the weight.

3.4 Objective 4: Final Design and Deliverables

Design

Between researched findings and prototype testing results, the final design of the Batipa Boardwalk was created. The Batipa Boardwalk final design was designed to be a stable structure built safely in a mangrove ecosystem and incorporated the information found on available material properties, environmental conditions, design constructability, and sponsor requests. A package of documents was delivered to the sponsor including the Batipa Boardwalk final drawings drafted with Computer Aided Design (CAD) software detailing dimensions, joints, and 3D renderings of the completed structure realized in Autodesk Revit. The package also contained safety instructions, which were established by OSHA standards in Objective 3.

Member and Connection Analysis

After completing the design of the Batipa Boardwalk, an analysis was conducted to prove that the boardwalk would be strong enough to endure all load conditions anticipated in the area. Analysis was done by recreating the boardwalk structure in the structural analysis software RISA-3D, categorizing and calculating load types, establishing load combinations, applying load combinations to the RISA model, solving the model for resulting forces and stresses, determining the design strength values for members and connection systems, and proving the design strengths were stronger than the acting forces and stresses.

To begin the analysis process, a RISA model of the boardwalk design was created. The model was a simplified version composed of girders, columns, and stringers that could be used to apply loading to and solve the model for critical forces and moments.

After setting up the RISA model, load types and load combinations were calculated and prepared. A total of four different load types that would be present in the Batipa Boardwalk were identified. These load types included dead load, live load, wind load, and fluid load. To calculate values for each load type, references were gathered from established manuals and sources researched in Objective 2 to provide guideline loading equations. The loading types are summarized with their reference source of origin in Table 5.

Table 5: Loading Types Analyzed on the Batipa Boardwalk

Load Type	Description	Reference Manual, Source or Strategy
Dead Load (D)	Vertical loading induced from the weight of structural components	ASCE 7-10, Specific Gravity values researched in Objective 2
Live Load (L)	Vertical loading induced from temporary loads, such as human occupancy and equipment	Recommended maximum occupancy and conservatively estimate occupant weights
Wind Load (W)	Lateral loading induced by wind forces; applied mostly at low tide	ASCE 7-10 Wind Loads: Guide to the Wind Load Provisions
Fluid Load (F)	Lateral loading induced by water pressure; applied most at high tide	ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures

A dead load equation was established and solved. The total volume of components was determined to calculate the mass of the structure and that value was then used to calculate the dead load as seen in Equation 4.

$$D = \Sigma\,(V \times \gamma) = \Sigma\,(V \times \gamma_w \times G) \tag{4}$$

In Equation 4, V represents material volume, γ represents material density, γ_w is the weight density of water, and G represents the material's specific gravity value. The specific gravity values input were based on the average value in Objective 2. Dead load was calculated for every member type and evenly applied across the entire structure. For boardwalk components not accounted for in the RISA Model, the total weight of those components was summed and distributed evenly as a linear load on the girder.

For live load, a strategy to conservatively estimate live load was determined. Since live load is determined based on temporary human occupancy, Equation 5 was established where p represents the weight of each person and n represents the total amount of persons allowed on the boardwalk.

$$L = (p \times n) \tag{5}$$

To utilize this equation, a maximum occupancy was determined so that the total live load of one repeat unit could be calculated. Similar to the dead load process for unaccounted components, the live load was then applied evenly as a uniformly distributed linear load across each girder.

Wind load was calculated following the equations identified in *ASCE 7-10 Wind Loads: Guide to the Wind Load Provisions* [32]. The equation used to determine the wind pressure is shown in Equation 6 where q_z indicates the effective velocity pressure on the structure, K_z, K_{zt}, and K_d are factors based on structure type and geography, and V is the basic wind speed (researched in Objective 2).

$$W = q_z = 0.00256 K_z K_{zt} K_d V^2 \qquad (6)[32]$$

Once the wind load was calculated, it was applied laterally as a uniformly distributed area load across the full above-ground structure.

Using the high tide measured in Objective 1, the fluid load was applied as a water pressure to all member sections that would be submerged under high tide. The fluid load force is linearly dependent on the depth. Equation 7 shows the equation used to calculate the largest fluid pressure in the structure where h represents the depth level and γ_w represents the density of water.

$$F = h \times \gamma_w \tag{7}$$

Once the fluid load was calculated, it was applied laterally as a uniformly distributed linear load across all submerged sections of the RISA model. To convert the fluid load from pressure to a force, the pressure was multiplied by the width of the submerged member.

After values for each load type were calculated, Load Resistance Factor Design (LRFD) was used to create load combinations to be applied to the boardwalk design. LRFD is a design method that multiplies the loads present in a system by factors to ensure a structure is designed to withstand extreme loading conditions. The following LRFD load combination equations were used as a basis to apply load combinations to the boardwalk design [33].

1. 1.4D
2. 1.2D + 1.6L + 0.5(Lr or S or R)
3. 1.2D + 1.6(L_r or S or R) + (L or 0.5W)
4. 1.2D + 1.0W + L + 0.5(L_r or S or R)
5. 1.2D + 1.0E + L + 0.2S
6. 0.9D + 1.0W
7. 0.9D + 1.0E

These seven equations are outlined in ASCE 7-10 as standards for structures, components, and foundations so that the strength of the design is equal to or stronger than the effects of these factored load combinations. However, these equations are established for typical American loading conditions and include loads such as snow load (*S*) that are not applicable to the environment at Batipa. Using the identified resources in Table 5, these equations were therefore modified to include only dead load, live load, wind load, and fluid load. After adjustment, the load combinations were applied to the RISA model, and the model was solved. The solved model identified the strongest moment, tensile force, compressive force, and shear force present across all girders, columns, and stringers in the design. These outputs were then converted in RISA-3D to be presented as stresses that could be compared with design strength values.

After obtaining the present bending, tensile, compressive, and shear stresses in the boardwalk, design strengths for members and connections were calculated. To evaluate the member strength, a softwood material was selected to be used in NDS Specification strength equations. If a softwood can withstand the loading conditions, the stronger teak hardwood can also withstand them. This would allow the analysis to be a more conservative estimate, ensuring the boardwalk would still easily stand under even worse conditions. Using researched mechanical values in Objective 2, a softwood was proven to be weaker than teak in elasticity and yield stresses and was then selected as the design strength material. Table 6 shows the NDS design strength value adjustment strength equations for the LRFD method. The initial design strength values of the softwood used were provided in the NDS Supplement [34]. Design strength adjustments were calculated for girders, columns, and stringers.

Table 6: NDS Design Strength Value Adjustment Equations for LRFD

Design Strength	Variable	LRFD Adjustment Equation
Bending Stress	F_b'	$F_b' = F_b C_M C_t C_L C_F C_{fu} C_i C_r K_F \Phi\lambda$
Tensile Stress	F_t'	$F_t' = F_t C_M C_t C_F C_i K_F \Phi\lambda$
Shear Stress	F_v'	$F_v' = F_v C_M C_t C_i K_F \Phi\lambda$
Compressive Stress*	$F_{c\perp}$'	$F_{c\perp}' = F_{c\perp} C_M C_t C_i C_b K_F \Phi\lambda$

*perpendicular to the wood grain

After both the actual system stresses and the maximum design stresses were calculated, the values were compared to each other, expressed as percentages of the actual stress divided by the maximum design stress. Percentages under 100% would indicate that the actual stresses in the system would be stable in the complete structure. Therefore, once all percentages were checked to be less than 100%, the members were proved to be structurally competent.

Connections in the final design were analyzed in a similar process. The largest lateral shear force was identified in the RISA model results and compared to a calculated design strength value. The adjusted design strength value was calculated for the connection type at the location of the strongest lateral shear force. Like member design strengths, NDS Specification was used to determine the design strength of connection points. Table 7 shows the NDS yield equations used to determine *Z*, the maximum strength of a connector before it fails.

Table 7: NDS Connection Design Strength Equations

Yield Mode	Single Shear Equation	Double Shear Equation
I_m	$Z = \frac{D l_m F_{em}}{R_d}$	$Z = \frac{D l_m F_{em}}{R_d}$
I_s	$Z = \frac{D l_s F_{es}}{R_d}$	$Z = \frac{2 D l_s F_{es}}{R_d}$
II	$Z = \frac{k_1 D l_s F_{es}}{R_d}$	
III_m	$Z = \frac{k_2 D l_m F_{em}}{(1+2R_e)R_d}$	
III_s	$Z = \frac{k_3 D l_s F_{em}}{(2+R_e)R_d}$	$Z = \frac{2k_3 D l_s F_{em}}{(2+R_e)R_d}$
IV	$Z = \frac{D^2}{R_d}\sqrt{\frac{2F_{em}F_{yb}}{3(1+R_e)}}$	$Z = \frac{2D^2}{R_d}\sqrt{\frac{2F_{em}F_{yb}}{3(1+R_e)}}$

These equations are based on the lengths (l_m & l_s) and bearing strengths (F_{em} & F_{es}) of the main member, the diameter of the connector (*D*), and adjustment factors (R_e, R_d, k_1, k_2, k_3). Equations are categorized based on whether the connection is made between one supporting object (single-shear) or two supporting objects (double-shear). The applicable design strength equations were calculated, and a minimum strength value (Z_{min}) was determined to be used in the LRFD adjustment equation, as seen in Equation 8.

$$Z_{min}' = Z_{min}C_MC_tC_gC_{eg}C_{di}C_{tn}K_F\Phi\lambda \qquad (8)[34]$$

The adjusted connector design strength (Z_{min}') was then multiplied to solve for the number of connectors used at the connection spot, and the number was compared to the strongest lateral shear force. Like the member comparison, a percentage and factor of safety were calculated, and connections were proved structurally competent when the percentage was less than 100%. Once both members and connections were proven to be strong enough to withstand the expected loading, the analysis process was completed.

4.0 Findings

In this section, the project findings are detailed in their respective project objectives. Prototype results and details of the Batipa Boardwalk design process are reported and explained. Recommendations, limitations, and areas of further research are also provided.

4.1 Objective 1: Site Assessment

Surveying the Mangrove Swamp provided information about the location details, general design specifications, ground surface conditions, and tide characteristics. The Mangrove Swamp was accessible at low tide by entering rough terrain supported by local trees; ten site visits were conducted with the sponsor.

There is a significant water level change due to tidal action in the Mangrove Swamp. The water level at high tide was measured compared to the height of the project sponsor, Edmundo, at approximately 4 ft (1.2 m) from the ground. Despite this height change, the mangrove trees and their complex root systems are still above water even at high tide.

Coordinates of the boardwalk's target starting location were recorded as 8.3317142 N and 82.2368849 W via iPhone. The target ending location was identified by the sponsor, which was measured to be 49.21 ft (15 m) away from the starting location. The Mangrove Swamp and its change in tide can be seen in Figure 10.

Figure 10: The Mangrove Swamp at High Tide (left) and Low Tide (right)

A LiDAR scan of the mangrove swamp and the path leading to it was conducted using an iPhone's built-in LiDAR scanner. The LiDAR scanner produced an accurate and to-scale 3D model of the scanned terrain. This model was then converted into a topography map using a combination of Revit and AutoCAD software. The LiDAR scan provided an accurate visualization of the proposed boardwalk location to be used when designing the boardwalk. The 3D model produced with LiDAR scan can be seen in Figure 11. Using the elevation map, the change in height from the ground surface to the walkway start point was determined to be 6.0 ft (1.83 m) and 2.0 ft (0.61 m) above average high tide level.

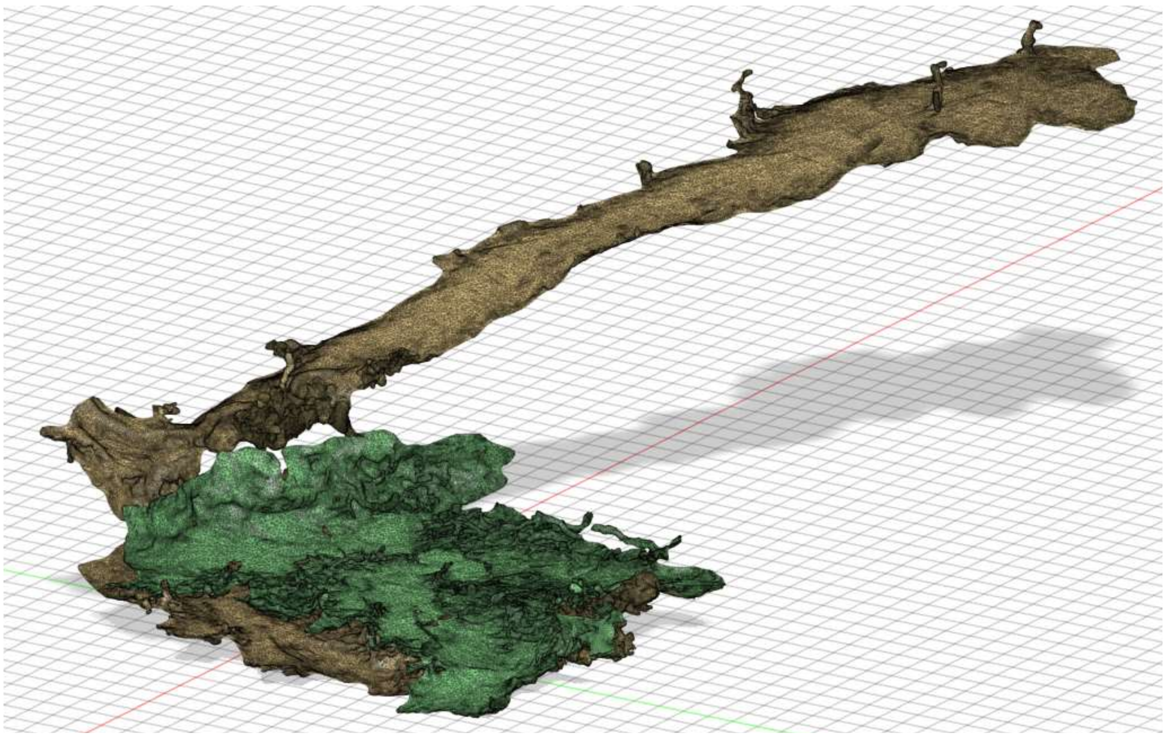


Figure 11: LiDAR Scan of the Mangrove Swamp

Characteristics of the ground surface were assessed at low tide. The ground surface was noted to be composed of muddy, weak, and unstable soil. As expected in the mangrove ecosystem, many bug and clam species were present. During the Stick Test, a hard material, presumably rock or dense soil, was identified approximately six in below the ground surface. This test was done in ten locations throughout the Mangrove Swamp and yielded the same result. The uncertainty and design concerns of the materials properties and geotechnical characteristics of the ecosystem were flagged to be studied further through literature research.

4.2 Objective 2: Literature Research

Teak Wood

Teak is a wood species easy to utilize in various applications and is classified as a hardwood; "The wood is well-known for its above-average durability, which makes teak wood objects easily last 40 years or more. It is fairly resistant to termites, decay and rot" [35]. Its strength is derived from a high silica content in its heartwood, the older and denser section of the wood at its center. Teak is also very workable for nailing, screwing, painting, and staining, making it a material that can be easily installed commercially.

Although the literature indicates that teak is solid and easy to use, the available teak at Batipa may not have the full extent of the known teak properties when it is harvested. Teak can take up to 40 to 50 years to develop its heartwood and natural oil coating [36]. Therefore, heartwood will not be as prominent in the teak harvested in 20-year cycles at Batipa. Instead, the teak at Batipa will have more sapwood, younger and softer wood, present across the outside of it. The research studies detailed below helped provide quantitative information about the mechanical differences between teak with shorter harvest cycles (short-rotation teak) and longer harvest cycles (long-rotation teak).

In the first report, the density and MOE were experimentally found for short-rotation teak sapwoods and heartwoods in Java, Indonesia [37]. The younger sapwood was found to have a lower density than its older heartwood counterparts. Despite this, the sapwood was found to have a higher MOE than the heartwood. The study argues that this could be because of a lack of time for the heartwood to grow its strength or that there is no correlation between mechanical strength and sapwood-heartwood composition.

The second report, also using samples from Java, tested both short-rotation and long-rotation teak [38]. As expected, MOE and density values were each lowest in short-rotation samples. Its results also identified that tectoquinone, the oil that Batipa employees mentioned is responsible for the wood's natural durability, was "very small in the extracts of short rotation teak." Furthermore, its conclusions also aligned with the concerns about using short-rotation teak: "Lower wood density and durability of the short rotation teak compared to the long rotation teak will restrict its utilization to some extent for both indoor and outdoor applications."

All of the mechanical values reported for short-rotation teak in these were compiled below in Table 8. Values are stated in the units and precision as reported in the source.

Table 8: Mechanical Properties of Short-Rotation Teak [37], [38]

Wood Age (years)	Wood Content	Density	MOE
8	Sapwood	578.16 kg/m^3	14848 N/mm^2
8	Heartwood	606.49 kg/m^3	13633 N/mm^2
15	Sapwood	556.4 kg/m^3	13703 N/mm^2
15	Heartwood	561.94 kg/m^3	12236 N/mm^2
10	Both	472 kg/m^3	9929.3 N/mm^2

Key: 1 kg/m^3 = 0.062 lbf/ft^3; 1 N/mm^2 = 145 psi

Across all studies involving short-rotation teak, tests determining ultimate strength capacities (tensile, bending, and compression) were not identified, potentially due to the limited use of short-rotation teak in structural applications. Thus, strengths for long-rotation teak were gathered from both a study and a timber database. The study reported the ultimate tensile, ultimate bending, and ultimate compressive strength of a long-rotation sample in Himachal Pradesh, India [39]. The timber database, the *Tropical Timber Atlas*, also provided values for the density, MOE, ultimate bending strength, and ultimate compressive strength of teak [40]. The atlas refers to many of its values being derived from the “most frequently exploited woods” so it can be assumed these values apply to typical long-rotation teak as that is the most common form of teak sold.

All of the mechanical values reported for long-rotation teak in these were compiled below in Table 8. Values are stated in the units and precision as reported in the source. One source presented material density by its specific gravity, *G*, which is determined by dividing the density of the material by the density of water.

Table 9: Mechanical Properties of Long-Rotation Teak [38], [39], [40]

Wood Age (years)	Density	Elasticity	Ultimate Tensile Strength (MPa)	Ultimate Bending Strength (MPa)	Ultimate Compressive Strength (MPa)
40	664 kg/m^3	12861.8 N/mm^2			
40			71.15	59.72	39.36
N/A	0.67 (G)	13740 MPa		98	56

Key: 1 kg/m^3 = 0.062 lbf/ft^3; 1 MPa = 1 N/mm^2 = 145 psi

Figure 12 summarizes the specific gravity and MOE values for short-rotation (blue) and long-rotation (red) teak samples on a scatter plot. The average MOE and specific gravity values of short-rotation teak samples were 12.87 GPa (1,870,000 psi) and 0.56 respectively. The average MOE was used in Objective 3 to be compared to the experimental MOE of the teak at Batipa, and the average specific gravity was used in Objective 4 to for analysis calculations.

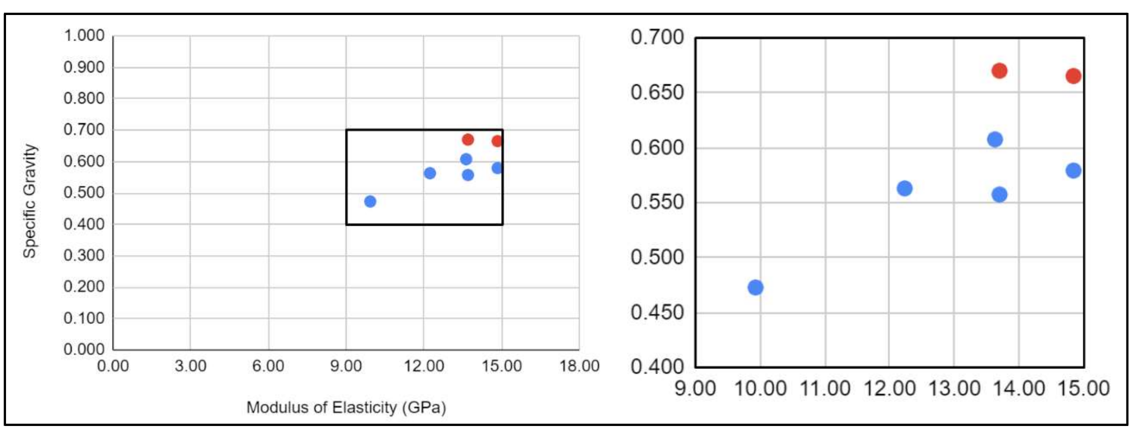


Figure 12: Researched MOE and Specific Gravity Values of Teak
Key: 1 GPa = 145,000 psi

Soil Types and Mangrove Swamp Refusal

The type of soil differs in each classification of the mangrove ecosystem and plays a large part in structural and material analysis. The classification of mangrove trees and soil type present determine an area's mangrove ecosystem type. Mangrove ecosystems are characterized by their access to water, soil type, and type of mangrove tree present. The three main types of mangrove trees are red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), and white mangrove (*Laguncularia racemosa*) [41]. All other mangrove tree species are subspecies of these three. In Panama, only the red and black mangrove trees are native, including two subspecies of red mangrove, Tea mangrove (*Pelliciera rhizophorae*) and Mangle Salado (*Avicennia bicolor*) [42].

Batipa is characterized as a fringe mangrove ecosystem, which is characterized by water from one side, and forest on the other [41]. Red mangrove trees, and their subspecies, have prop roots, which grow outwards from the tree trunk to provide additional support as the tree grows. In Batipa, only red mangroves are found, which is consistent with fringe mangrove ecosystems, which is shown in Figure 13.

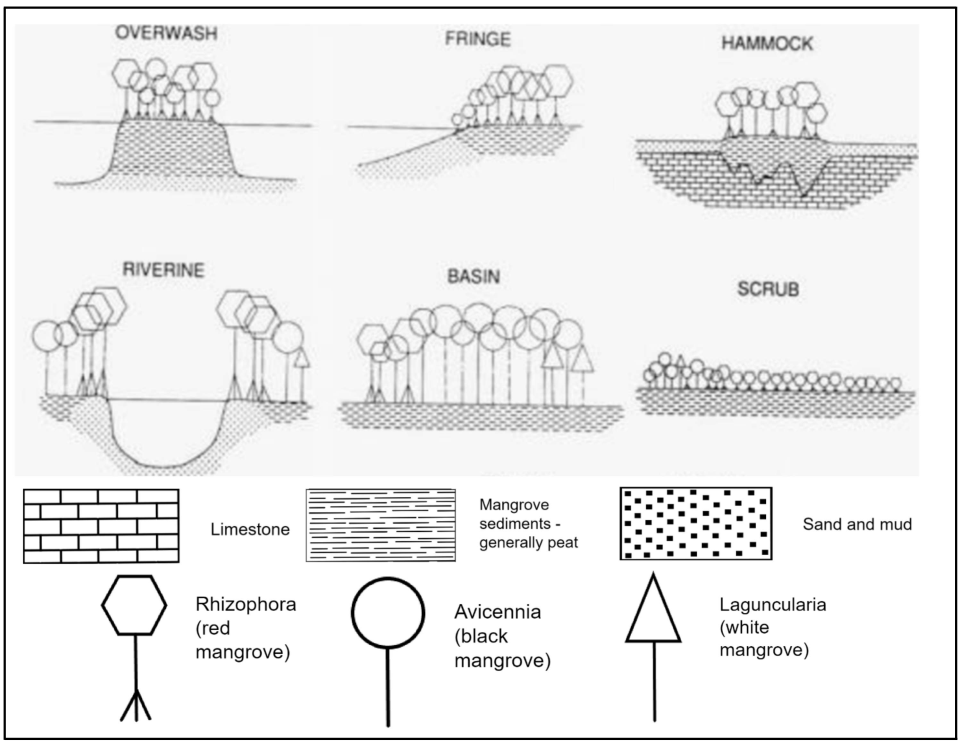


Figure 13: Types of Mangrove Ecosystems [41]

Haplic acrisols are the primary soil on the land of Batipa, but in the Mangrove Swamp, only the topsoil is land-based haplic acrisol, and the layer underneath is a mixture of organic matter from the mangrove ecosystem and a marine-based soil. The second layer, marine alluvium is a peat, which is a type of soil that is very dense and comprised of high quantities of organic matter and clay [43]. The topsoil layer is normally 2 – 8 in (5 – 20 cm) thick, and the peat layer is 9.8 – 16.4 ft (3 – 5 m) thick but is found to not exceed 24.6 ft (7.5 m) thick [44]. This is consistent with the results of the Stick Test done in Objective 1, as the Mangrove Swamp's topsoil layer was found to be around 6 in (15 cm) deep. This is due to the fact that the stick would not be able to penetrate the dense peat layer.

Haplic acrisols are formed from rocks that are highly acidic. Acrisols have poor nutrient-leaching qualities, meaning the nutrients are not absorbed deep into the soil, however, acrisols have strong base-leaching abilities. This means that any material or coating that is basic or creates hydroxide ions when submerged in water will be absorbed very quickly and deeply into the soil [45]. During leaching, the base can be neutralized by the acidic soil layer, or the base can pass the thin layer of haplic acrisol and move onto the thick layer of peat, where the base will not be neutralized. If not neutralized, this base will eventually be released into the environment. In a structure adjacent to the haplic acrisols, the hydroxide-containing molecules in the structure will be torn away from their previous bonds and rebound with the acids in the soil. Over time, as this process repeats, the structure will become weakened. This will be exacerbated by the erosion of the concrete due to tidal activity. These factors eliminate concrete to be used in Batipa's mangrove ecosystems, which contain hydroxide molecules, as their lifespan and strength in these soil types would be greatly reduced.

In fringe mangrove ecosystems, the typical maximum refusal point is 4.4 ft (1.35 m). 50% of refusal points were found at less than 23.6 in (60 cm), and 90% were found to be at less than 3.2 ft (1.0 m) [46]. The high density of the peat allows a structure to be stable without drilling into bedrock. Since the Batipa Boardwalk will be used by the general public, the most conservative estimate was used. Due to the 6 in (15 cm) depth of the haplic acrisol in the Mangrove Swamp, and the conservative figure of a 3.9 ft (1.2 m) refusal point, the foundation of the boardwalk will lay at a total depth of 4.4 ft (1.35 m) below ground level.

Determining the soil conditions is essential prior to building a structure. Having this knowledge allows designers to compensate for the natural tendencies of the soil and create the strongest and most durable structure. For the Batipa Boardwalk, this is especially prominent because swampy ecosystems are not ideal for building since the soil and tidal changes add design considerations. Additionally, the issue of constructability is much more significant not only in a swamp but also in a protected ecosystem such as the Mangrove Swamp.

<u>Material Interactions with the Mangrove Swamp</u>

Three materials considered for the foundation of the Batipa Boardwalk were concrete, steel, and teak. Each material comes with its own benefits and concerns. Simply, concrete is composed of cement, water, and aggregate. However, different additives are supplemented into concrete mixes to optimize strength. Portland cement, the most common type of cement used in a concrete mixture, contains calcium sulfate ($CaSO_4$) that controls the C_3A reaction and allows for increased hydration in the C_3S reaction [47]. Another compound found in concrete is $Ca(OH)_2$ which forms in concrete as crystals while it sets [48]. A common molecule in seawater is magnesium sulfate, $MgSO_4$ [49]. In a saltwater environment such as a mangrove ecosystem, concrete reacts with the saltwater, and the subsequent chemical reaction is found in Equation 9. In this reaction, the magnesium sulfate reacts with the calcium hydroxide in the concrete to produce calcium sulfate and magnesium hydroxide.

$$MgSO_4 + Ca(OH)_2 \rightarrow CaSO_4 + Mg(OH)_2 \quad (9)[50]$$

$MgSO_4$ and $CaSO_4$ have no negative impacts on the health of marine plants or animals and are neutral salts [51]. $Mg(OH)_2$ does not negatively impact the environment, but it is basic, containing hydroxide OH^- ions. Therefore, the haplic acrisol will quickly absorb it into the soil and neutralize the base, donating hydronium ions as seen in Equation 10. The acidic soil neutralizes the base, magnesium hydroxide, and creates water and magnesium ions.

$$2H_3O^+ + Mg(OH)_2 \rightarrow 4H_2O + Mg^{2+} \quad (10)[52]$$

Calcium hydroxide goes through a similar process of neutralization, where the hydronium ions in the soil combine with the calcium hydroxide to form water and calcium ions as seen in Equation 11. Calcium ions are also not harmful to the environment. However, interactions of calcium hydroxide and the base-leaching qualities of the haplic acrisol can cause concern. If the calcium hydroxide leaches too quickly and reaches the peat layer beyond the acrisol before it can be neutralized, the calcium hydroxide will enter the environment. When algae are exposed to calcium hydroxide, their growth rate is reduced, and plants can die [51]. Algae is a very important part of an ecosystem, particularly a nursery ecosystem like mangroves where it serves as a food source for many young and small animals.

$$2H_3O^+ + Ca(OH)_2 \rightarrow 4H_2O + Ca^{2+} \quad (11)[52]$$

In a saltwater environment such as the Mangrove Swamp, steel will corrode. When air reacts with steel, it forms rust or Fe_2O_3, however, when combined with water and air, the iron corrodes to form iron (III) hydroxide, $Fe(OH)_3$ [53]. In saltwater, steel will corrode both generally and locally, weakening the member throughout and decimating the strength at a single point [54]. Equation 12 shows the combination of air, water, and the iron in the steel to produce iron (III) hydroxide.

$$4Fe + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3 \quad (12)[53]$$

Iron (III) hydroxide is a base. Therefore, the acidic haplic acrisol will then react with the hydroxide group to neutralize it with hydronium ions as seen in Equation 13.

$$3H_3O^+ + Fe(OH)_3 \rightarrow 6H_2O + Fe^{3+} \quad (13)[55]$$

Iron (III) ions have no negative impact on the environment. However, similar to calcium hydroxide, there is a concern about the iron (III) hydroxide being leached to the peat layer prior to being neutralized. This is due to the fact that haplic acrisols have strong base-leaching qualities. Additionally, iron (III) hydroxide does have negative impacts on marine environments. While this chemical does not negatively impact adult species, it has been found to reduce the number of viable eggs in both fish and frog species [56]. This is a particularly large concern for mangrove habitats which serve as nurseries for many animal species.

In water, steel starts to rust after two to four days, but in saltwater environments, this process is five times faster. This means that in a mangrove ecosystem, steel can start to rust in as short as 10 hours [57]. Additionally, steel can be corroded by iron bacteria, a type of bacteria found in oceans and swamps, that feeds on iron and leaves iron oxide or rust as a byproduct [58]. This quickens the corrosion process even further. A significant amount of damage would occur very quickly, and this would reduce the load that the member can support. Further, this process is cumulative, so as more rust is formed, larger amounts of iron would be oxidized due to the increased surface area of exposed iron. These factors result in the conclusion that steel is not a viable material to use in the foundation of a boardwalk in this saltwater ecosystem. Additionally, if saltwater penetrates into reinforced concrete, the interior steel will corrode [54] and the structure will fail, so advanced precautionary measures would have to be taken such as chemical additives or supplemental protective materials.

Teak, the requested material by OTU for the Batipa Boardwalk, was the determined material to use in the mangrove ecosystem due to negative chemical reactions between other researched materials and the soil in the Mangrove Swamp. Both concrete and steel contain compounds that are either corroded by the soil or would harm the wildlife. However, teak is much stronger than initially thought, even though it is an uncommon building material for boardwalks. While concrete and steel will both degrade in the soils of the Mangrove Swamp, it is not certain that treated wood will, which is another reason why it was the chosen material to use for the Batipa Boardwalk.

Structural Concerns within the Mangrove Swamp

Since the substructure is completely submerged during high tide, the main concern for teak in the foundation is damage to the wood due to moisture, namely wet rot. Wet rot is most common when wood is in soil with a moisture content between 30 – 50% [59]. Submerged peat soil has a moisture content of around 900%. This means that the weight of the water in a sample of peat, when heated to 212 °F (100 °C), weighs nine times more than the dried peat [60]. However, this may not be a concern, as peat is very dense and bacteria in peat are anaerobic. Organisms that decay wood are aerobic and require oxygen, so wood that is submerged in the peat will not significantly decay [61].

There are other environmental concerns for teak, such as harmful insects like termites, which eat the fibers in wood and diminish their structural capacity. However, while termites do travel in underground tunnels, they do not prefer peat or wet environments. Rather, they will choose dry and easier-to-access wood for their food [62]. A non-toxic wood preservative that will not negatively impact aquatic ecosystems is borates or disodium octaborate tetrahydrate [63]. A benefit of this treatment is that it only needs to be applied once to a piece of wood, as it lasts indefinitely. Borate treatments are sold in spray form, where the chemical is bound to glycol to allow it to penetrate into wood. In order to mitigate glycol's impact on aquatic ecosystems, the treated wood must be allowed 48 hours to dry before being placed into the environment. This class of wood preservatives is most commonly used for high-moisture or submerged wood protection to prevent rot and decay by insects [64]. Glycol is known to harm only one species of marine animal, the *Crangon crangon,* or brown shrimp, which is found in the Mediterranean, White, Black, and Baltic Seas in Europe [65].

A group of engineers in Malaysia outlined their struggles and solutions when building in their mangrove environments. Their goal was to determine better practices for constructing large concrete buildings. The environment they describe is very similar to that of Batipa's Mangrove Swamp; both environments are dominated by mangroves and have the same soil type, making this paper a good comparison for practices in Batipa. They found that common issues for building structures in an environment that contains primarily peat are building sag, drainage problems, and environmental guidelines [66]. To mitigate these issues, several practices are known. To reduce sag, the weight of the structure must be decreased as much as possible without sacrificing safety. This can be accomplished by using high-strength concrete, which reduces the likelihood of a structural failure if there is a soil failure. Finally, using lightweight material on non-structural members decreases the load of the structure, which will in turn decrease the building sinkage into the mud [66].

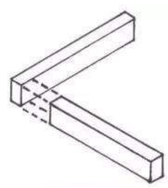
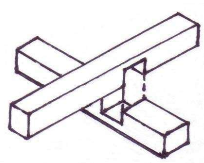
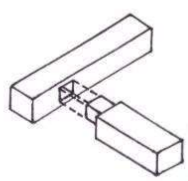
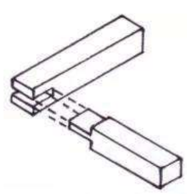
Weight was a consideration for the design of the Batipa Boardwalk. This was done by reducing the number of heavy materials such as steel and concrete. Additionally, these materials have been mostly excluded due to their negative environmental interactions. It was recognized that OTU and BFI value their pristine environment very highly and therefore a key part of the design is avoiding any negative environmental impacts. This intention is supplemented by their request that teak be the primary building material due to their private ownership of the Batipa.

The peat soil and swampy environment raise concerns about increased wood decay, but due to the anaerobic nature of peat, this concern is mitigated. Teak has natural water resistance and insect-repellant qualities and can be treated to reduce its risk of rotting by using wood preservatives such as borates. Additionally, research has been done by engineers in similar environments to highlight their issues when building in a mangrove ecosystem. The design of the Batipa Boardwalk incorporates their conclusions to increase the strength and lifespan of the boardwalk.

Joints & Connections

Research was also conducted on joints and connections, the means of fastening wooden members together. A joint is a location where the surfaces of one member contact the surfaces of another member. Most wood joints are created by cutting one or both of the timber members, however, with the reduced material at the joint location, the ends become weaker and are more susceptible to splits and tears [67]. Cuts must be made to join the members together while leaving sufficient material to bear loading capacity. Table 10 includes diagrams and details of some typical joints used in timber structures.

Table 10: Design Considerations for Typical Timber Joints [67], [68], [69]

Joint	Diagram	Design Considerations
Butt Joint		- Simplest joint to make; requires no cutting. - It is the weakest joint, as it does not provide any additional strength to the structure. - Mitre Joint: Butt joint where ends meet at 45° angles.
Lap Joint		- Each member is cut to create a pair of joining laps. - When used on ends, larger lap joints are more likely to break away from the inside, and smaller lap joints are more likely to break away from the outside (ends). - Halving joint: each member is the same thickness, and laps are cut to half-thickness.
Mortise and Tenon Joint		- Tenon is inserted into a mortise to create a flush joint. - Very effective for members meeting at 90° angles. - Requires more precision to match insertion depth, but fewer degrees of movement make it a stronger joint.
Bridle Joint		- Similar to mortise and tenon joints in that tenon length matches mortise thickness. - The cut on the mortise member is made starting from the top of the surface. Easier to create than a mortise and tenon joint but provides less strength.

Joints can be prepared using typical woodworking tools such as chainsaws and bowsaws. For joints requiring more precise cuts, such as those that use mortises and tendons, a froe and mallet may be required to create precise and straight cuts. [70]. Wood is most easily cut when still green, despite being susceptible to shrinkage [71].

The strength of a member is dependent on the material used, and the dimensions and shape of it. For example, this means that for two beams of the same material, one with a diameter of 10 in (25.4 cm) is stronger than another with a diameter of 5 in (12.7 cm). Further, Roundwood is considered to be over twice as strong as its dimensional wood counterparts [67]. This is due to the fact that the grain in Roundwood is uninterrupted, while the grain in dimensional wood has been cut through in the milling process [70]. It was found that log-to-log joints use applied forms of joints that are accomplished by creating level cuts and are most often found in designing log cabin homes. Some of these applied forms can be seen in Figure 14.

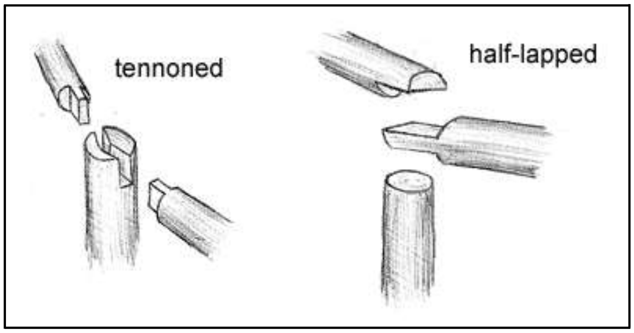


Figure 14: Joints Made Using Roundwood Log Members [72]

Methods of connecting members in a joint can be split into two categories: mechanical connections and adhesive bonding. Mechanical connections are characterized by using a fastener to penetrate members [73]. Dowel-type fasteners, including nails, lag screws, wood screws, and bolts are utilized by fully inserting the dowel into each member to prevent lateral movement. Bolts completely penetrate both members and are fastened by nuts and washers on each end. Bearing-type connectors such as split rings and shear plates are used for higher-strength connections as they are able to connect members together while distributing the load wider.

Adhesive bonding is characterized by using an adhesive to seal a joint between two members. The adhesive helps distribute the load stresses over a larger area [74]. The behavior of the adhesive bond can vary based on several factors, including chemistry, bond thickness, and curing time, as well as environmental factors such as changes in moisture and temperature.

Joints between two wooden members involve making cuts into each beam. Doing this increases the strength and security of the joint, but the cuts must be made with precision to ensure that the connection strength is maximized. An alternate connection method is by using a chemical adhesive, which bonds the two members together with a material such as wood glue or other sealant. More traditional connection types such as bolts or screws require less precision but demand both more tools and supplies in order to be built. When designing joints, it is important to keep the connection as strong as possible. Specifically regarding the Batipa Boardwalk, it is also vital to consider constructability and the tools available when selecting a connection type.

Analysis References

Load types, load calculations, and load combinations were identified through the *ASCE 7 Standard*. Given the Panamanian mangrove swamp nature, five original types of loads on the structure were initially considered: dead load (self-weight), live load (temporary occupancy), wind load (wind effects at low tide), fluid load (water effects at high tide), and earthquake load (seismic activity). Earthquake load was soon after disregarded since the structure is relatively small in a region with relatively minor seismic activity. Thus, dead load, live load, wind load, and fluid load were implemented into the load combination equations provided in the *ASCE 7 Standard*. It was determined that the dead load, live load, and fluid load could all be prepared and calculated using previous academic experience without a manual. However, wind load needed additional provisions, found in the *ASCE 7-10 Wind Loads: Guide to the Wind Load Provisions* [32]. Furthermore, since the fluid load is not a typical loading condition, the rules for how to apply it needed to be researched, which was found in the *ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures* [33]. Although no Panamanian references could be found for load combinations, the *ASCE 7 Standard* was deemed a suitable substitute since it is referenced frequently in IBC. The only regional limitation *ASCE 7* contained was that there were no base wind values for Panama, which are necessary to calculate wind load using the Wind Load Provisions. To adjust for this, regional wind speed data were researched. The regional wind speed implemented into wind load calculations was researched to be 115 kph (70 mph) [75].

To verify the strength of the Batipa Boardwalk, design strength equations for timber structures were identified in the *2018 National Design Specification (NDS) for Wood Construction*. It was developed by the American Wood Council with the intent to "be used in conjunction with competent engineering design, accurate fabrication, and adequate supervision of construction" [34]. It is used as an American National Standard for the design and analysis of softwood timbers. NDS is also implemented and referenced in the International Building Code (IBC) and thus was selected as a valid governing design specification manual.

The *2018 NDS Supplement* contains initial design strength values for typical American softwood materials, which are then adjusted through adjustment equations detailed in the NDS Specification [76]. The initial design value is multiplied by coefficients based on location, construction, material, and member sizing. A similar process is also done for typical mechanical connections. Acceptable dowel-type mechanical connections are outlined in the *2018 NDS Manual* [77]. The NDS Specification then assists in providing failure cases for acceptable dowel-type mechanical connections based on the size, length, and type of connection. Failure cases can then be used in design value adjustment equations similar to the material design value adjustment equations.

There are some limitations of NDS in the context of the Batipa Boardwalk. Since specifications are established to provide assistance in American softwood timber construction practices, it contains no design values to reference for Panamanian teak. As for connection types, it is important to note that the NDS Manual does not include equations to prove the structural competence of connections made with adhesive bonding [77]. All connections detailed in NDS are in reference to connections made on flat surfaces, as seen in Figure 15. Joints with rounded surfaces therefore may not be applicable to NDS equations supporting structural strength.

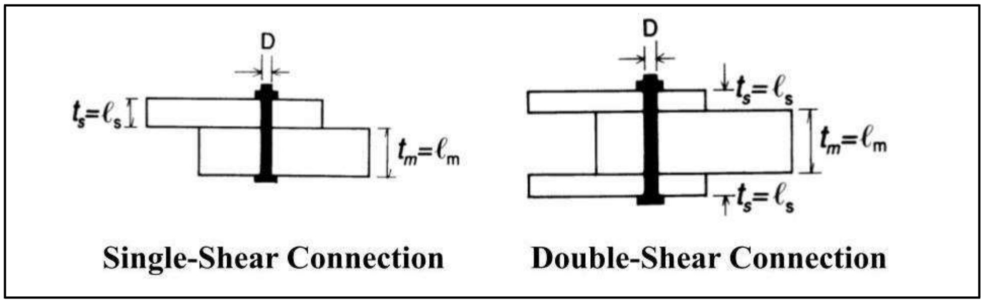


Figure 15: Typical NDS Dowel-Style Connection Setups [77]

In Objective 4, these limitations were acknowledged. In design, the limitations helped establish preferences in the final design. In analysis, the shortcomings of NDS were used to make the analysis process more conservative, allowing NDS to remain applicable.

4.3 Objective 3: Design, Build, and Test Batipa Boardwalk Prototypes

Prototype 1

Batipa employees on-site indicated that teak develops a natural coat of oil around 40 – 50 years into its growth, which helps the wood's resistance to water and sun (also confirmed through literature research in Objective 2). Since teak at Batipa is harvested in 20-year cycles, the available material does not have this coating. The sponsor also indicated that the teak for the Batipa Boardwalk would come from harvested wood that was unsuitable for sale, so a quantitative assessment of the available material was determined by the deflection test of Prototype 1. Figure 16 shows the typical wood logs available for the boardwalk.

Figure 16: Conditions of Teak Wood Available at Batipa

Once Prototype 1 was constructed, the deflection test was performed to determine the MOE or stiffness of the material. Testing was performed on each of the six teak planks with a measured unsupported length of 51.6 in (131 cm). A load of 130 lbf (578 N) was applied at the center of the span. Each plank deflected downwards and the results can be seen in Table 11.

Table 11: Deflection Test Results

Trial	Width, b (cm)	Thickness, h (cm)	Initial height from the ground (cm)	Final height from the ground (cm)	Δ (cm)
1	24.7	3.2	26.9	26.4	0.50
2	20.8	2.5	27.2	26.6	0.60
3	22.8	2.7	25.9	25.45	0.45
4	18.2	2.1	24.2	23.4	0.80
5	20.5	2.9	26.2	25.7	0.50
6	20.9	3.5	27.7	27.4	0.30
Avg	21.3	2.8	26.4	25.8	0.52

Key: 1 cm = 0.39 in

The average values for width, thickness, and deflection were used to determine the MOE. Table 12 shows the experimental MOE of the teak at Batipa to be 13.0 GPa (1,885,000 psi).

Table 12: Experimental Elasticity Calculations

Item	Variable		Value
Average Deflection	δ	(cm)	0.52
Average Load	P	(N)	578
Average Unsupported Length	L	(cm)	131
Average Width	b	(cm)	21.3
Average Thickness	h	(cm)	2.8
Moment of Inertia	I_x	(cm^4)	39.7
Experimental MOE	E	(GPa)	13.0

Key: 1 cm = 0.39 in; 1 N = 0.22 lbf; 1 GPa = 145,000 psi

Despite the initial concern for the material quality at Batipa, this value closely matches the average researched value (12.87 GPa – 1,870,000 psi) found in Objective 2. Therefore, it can be assumed that the short-rotation teak at Batipa may have similar properties to the researched short-rotation teak. The experimental 1,885,000 psi MOE and researched 0.56 average specific gravity were deemed suitable to be used in analysis calculations in Objective 4. The researched yielding stress values for long-rotation teak could also be considered qualitatively for comparing teak to softwood in Objective 4.

Prototype 2

Upon completing the site assessment, it was realized that Prototype 2 was not feasible. The connections at the joints of Prototype 2 were not constructible using the materials and tools available at BFS. The connections in the design consisted of large bolts, however, the local hardware stores did not have large enough bolts both in length and width or the drill bits required to assemble it. Additionally, the large girder diameter accounted for in the prototype design was not available from the lumber options at the Batipa Harvest Site.

The inability to build Prototype 2 did, however, provide a solid understanding of the materials, tools, and levels of precision that are achievable for BFS. A prototype or final design that is too specific requires specialized tools or includes materials that are not available on or around the site. Some materials, such as cinder blocks, screws, and nuts, can be purchased, but more specialized tools and materials are not practical. Additionally, to increase constructability, it is best to keep logs in their original states when possible and avoid additional cuts. The available material and constructability restrictions were realized with Prototype 2.

Prototype 3

Once Prototype 3 was constructed, it was concluded that several design elements needed alteration. Regarding tools and constructability, it was established that the number of significant figures used in design would have to be reduced. The tools at the Batipa Harvest Site are not as precise as accounted for in the prototype designs, so design dimensions were changed from three or four significant figures to a range for the final design.

In viewing the constructed prototype, it was requested by the sponsor that the boardwalk deck be increased from 3.3 ft (1 m) to 5 ft (1.5 m) wide to accommodate more pedestrian flexibility, including the ability for two people to comfortably pass each other. Also, gaps between planks were noted to be increased in the final design to prevent water from pooling up on the deck surface and prevent a tripping hazard.

For the girders, the rounded top and bottom of the logs will have been cut to make them flat while lying on their side. This will increase the surface area, make securing planks easier, and increase friction with the column, making the design more stable. Finally, many of the wood plates split during construction and had to be replaced, suggesting that a stronger material was needed for these locations. The plates securing each girder to the columns should be replaced with steel plates to increase the strength of these connections, which is critical to the overall success of the boardwalk.

4.4 Objective 4: Produce Final Batipa Boardwalk Design and Deliverables

Final Design

Using the knowledge developed from the prototypes and other objectives, a final design, largely resembling prototype 3 (at the request of the sponsor), was drafted. The girders were designed to be cut so that they have a square cross-section, minimizing the risk of them rolling and increasing the surface area available for connections. Deck planks with a thickness of 2 in (5 cm) were chosen instead of the initial 1 in (2.5 cm) used in the prototype to accommodate the longer plank length. Of the 5 ft (1.5 m), 4 ft were dedicated to the walking surface and 6 in (15 cm) were dedicated to the railing and girder connections on each side. The proposed width is in accordance with guidelines set by the Municipal Council of Panama on walkway width minimums [78]. A 2 in x 2 in (5 cm x 5 cm) base plate was chosen to connect the railing to the planks using screws with a diameter of ⅜" (0.95 cm). Lastly, stringers of the same dimensions as the deck planks were chosen to be screwed into the columns 3 in (7.6 cm) below the notches. Figures 17 and 18 show the final design section views and connections used respectively.

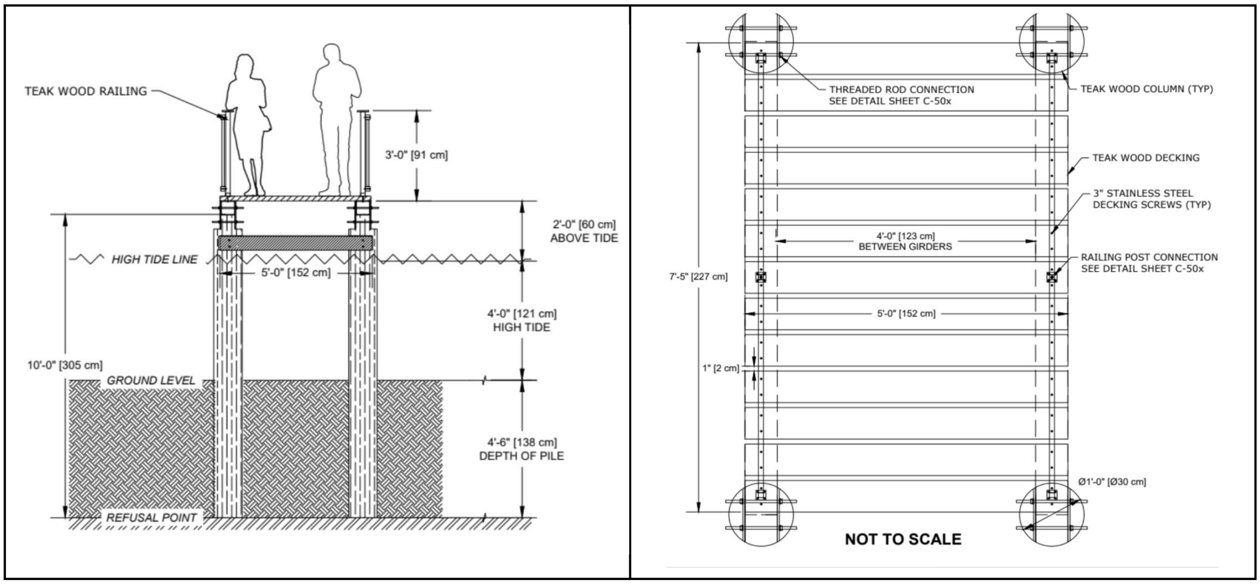


Figure 17: Final Design Section Views

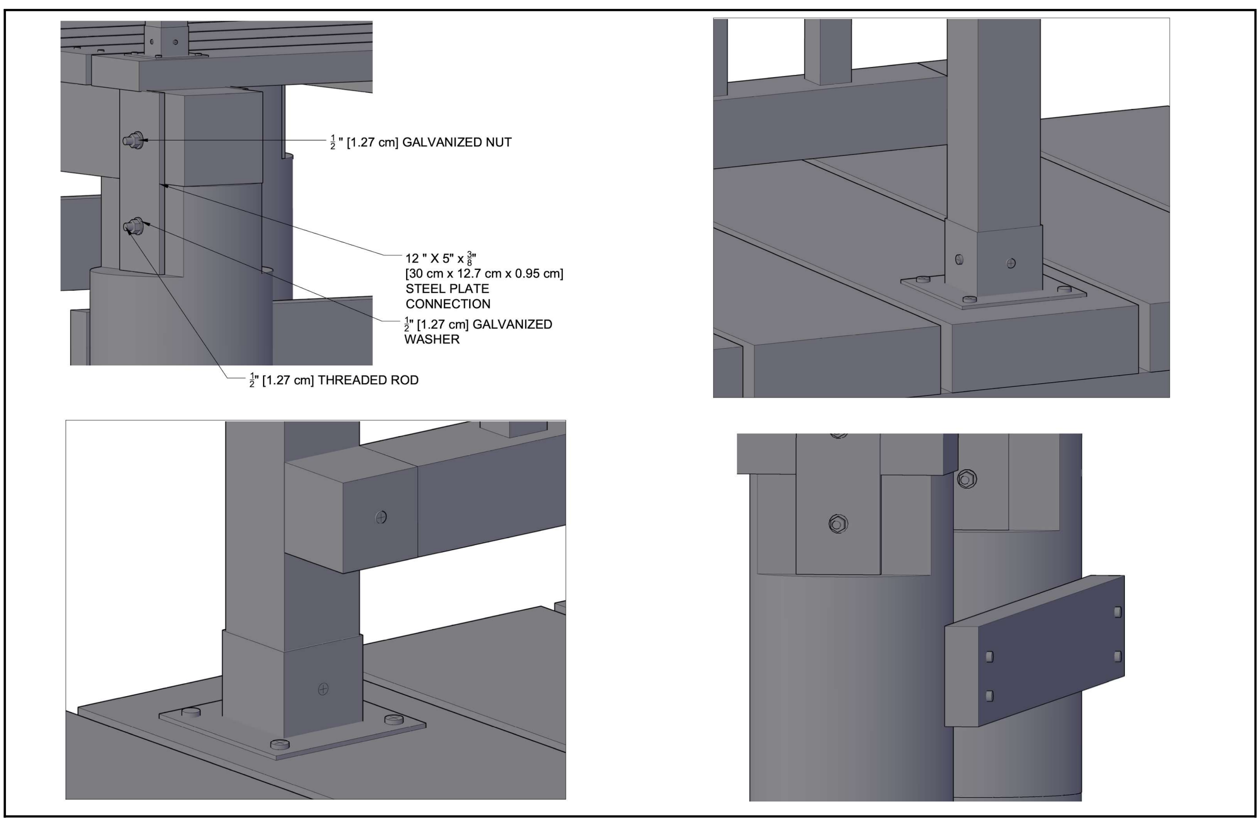


Figure 18: Batipa Boardwalk Connections

Due to the difficult terrain of the proposed site, readily available materials were chosen to cut down on the amount of transportation necessary. It must also be acknowledged that the environment created by the proposed site may negatively affect the boardwalk in the future. Since the naturally preserving oils present in aged teak were not present in the lumber available at Batipa, an external protective coating such as borates or disodium, mentioned earlier, was incorporated into the design.

Member and Connection Analysis

After creating the final design, the analysis was conducted to verify the structure's strength. Figure 19 shows the boardwalk design created in RISA-3D. To simplify the analysis, the RISA model only consisted of the girders, columns, and stringers

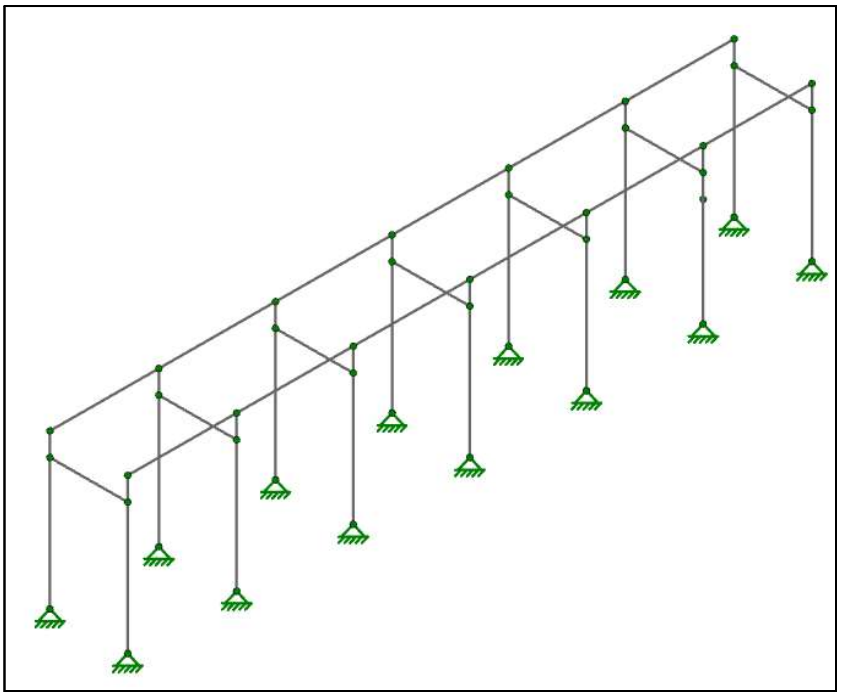


Figure 19: RISA Diagram of the Batipa Boardwalk

All the following calculations and loads were done for a 7.5 ft (2.3 m) section of the Batipa Boardwalk. Using the load type equations, dead loads, live loads, wind loads, and fluid loads were calculated. The total dead load was found to be 430 lbf (1.9 kN) per repeat unit. Table 13 shows the complete dead load calculations for one section.

Table 13: Dead Load Calculations

Item	Variable	Value	Units
Weight density of water	γ_w	62.4	lbf/ft^3
Specific Gravity of teak	G	0.56	lbf/ft^3
Density of teak	γ	34.9	lbf/ft^3
Plank volume	V_p	0.42	ft^3
Girder volume	V_g	1.88	ft^3
Column volume	V_c	0.79	ft^3
Plank weight	D_p	14.56	lbf
Girder weight	D_g	65.52	lbf
Column weight	D_c	27.44	lbf
Plank quantity	N_p	13	
Girder quantity	N_g	2	
Column quantity	N_c	4	
Railing System weight	D_h	30.17	lbf
Total Dead Load	D	430	lbf

Key: 1 lbf/ft^3 = 157.1 N/m^3; 1 ft^3 = 0.028 m^3; 1 lbf = 4.45 N

The live load was calculated to be 2,000 lbf (8.9 kN). This value was based on a maximum occupancy of 10 occupants with a conservative average weight of 200 lbf (90.7 kg) on each repeat unit. Table 14 summarizes the live load calculations.

Table 14: Live Load Calculations

Item	Variable	Value	Units
Weight per person	p	200	lbf/person
Total occupants on the boardwalk	n	10	persons
Total Live Load	L	2,000	lbf

Key: 1 lbf = 4.45 N

Using the *ASCE 7-10 Guide to Wind Load Previsions* and Panama wind speed data, the maximum wind load was calculated to be 6.13 lbf/ft^2 (293.5 N/m^2). Table 15 summarizes the variables used to calculate the wind load.

Table 15: Wind Load Calculations [32], [75]

Item	Variable	Value	Units
Exposure Category		B	
Exposure velocity pressure coefficient	K_z	0.57	
Topography coefficient	K_{zt}	1.0	
Directionality coefficient	K_d	0.85	
Basic wind speed	V	70	mph
Total Wind Load	W	6.13	lbf/ft^2

Key: 1 mph = 1.61 kph; 1 lbf/ft^2 = 47.88 N/m^2

The fluid load was calculated to be 250 lbf/ft^2 (11.97 kN/m^2) at its maximum depth. Table 16 shows the fluid load calculations.

Table 16: Fluid Load Calculations

Item	Variable	Value	Units
Maximum high tide height	h	4	ft
Weight density of water	γ_w	62.4	lbf/ft^3
Maximum Fluid Load	F	250	lbf/ft^2

Key: 1 ft = 0.30 m; 1 lbf/ft^3 = 157.09 N/m^3; 1 lbf/ft^2 = 47.88 N/m^2

Once these loads were calculated, load types were then applied to the RISA model. The dead load was applied as an equally distributed load to each respective member excluding the loads from the deck and railing system. Instead, the deck and railing system were added together (220 lbf – 980 N) and distributed as 15 lbf/ft (220 N/m) across each girder. Similarly, the live load was applied as 133.3 lbf/ft (1.95 kN/m), evenly distributed load across the length of each girder. The wind load was applied as a lateral pressure across the length of the boardwalk for low tide scenarios. The fluid load was added laterally on columns at heights submerged in water during high tide scenarios. Since columns are 1 ft (0.3 m) in diameter, the load was applied as a triangularly distributed load, starting at 0 lbf/ft at the high tide water level and ending at 250 lbf/ft (3.65 kN/m) at the end of each column. Figure 20 shows each loading type individually applied to the RISA model.

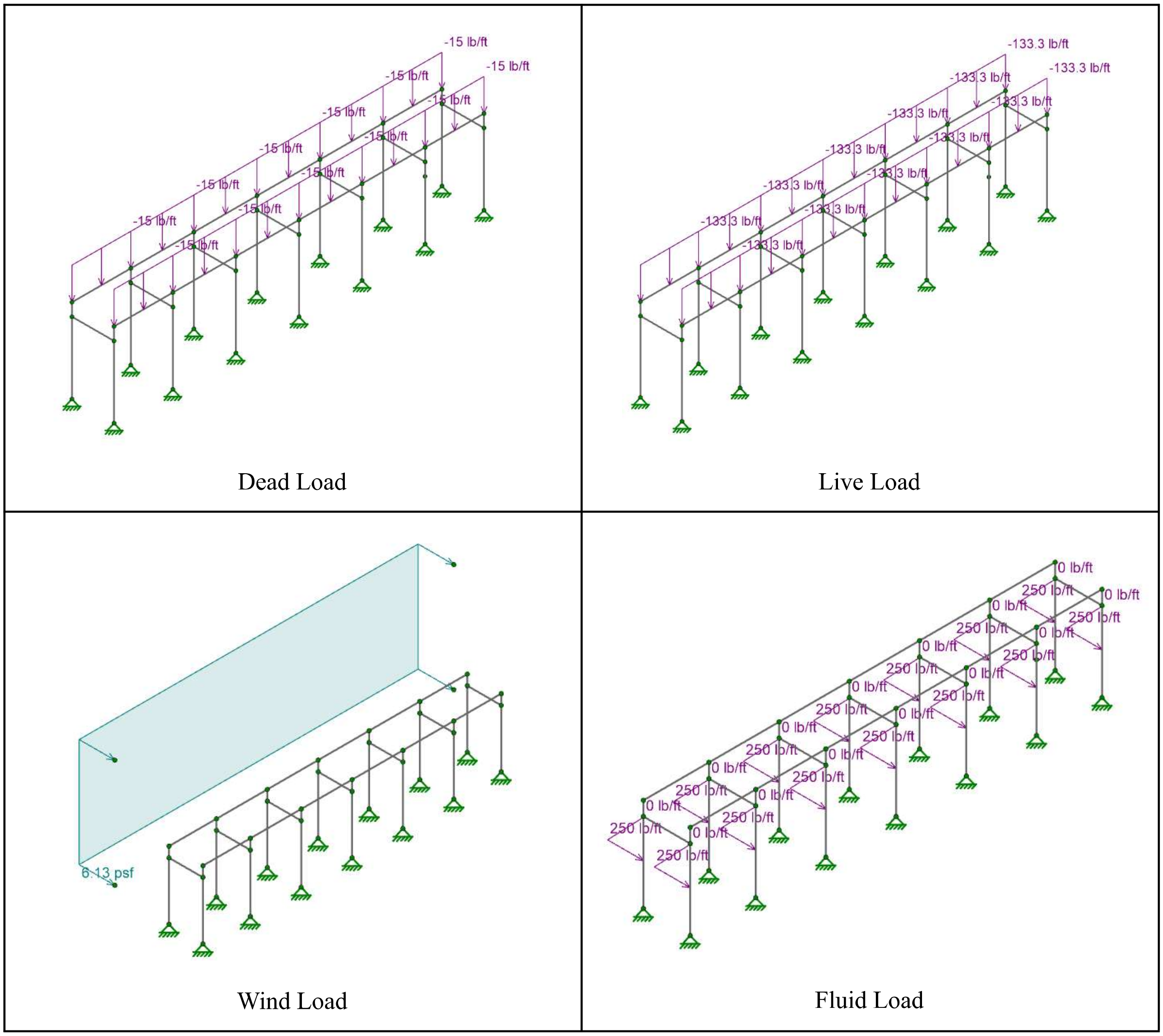


Figure 20: RISA Diagrams of Each Loading Type
Key: 1 lbf/ft = 14.59 N/m; 1 lbf/ft^2 = 47.88 N/m^2

After applying each load type, the ASCE 7-10 LRFD load combination equations were adjusted to only account for dead load, live load, wind load (at low tide), and fluid load (at high tide). The resulting seven governing load combination equations, shown in Table 17, were applied to the RISA model.

Table 17: Modified LRFD Load Combinations Applied to RISA Model [33]

Load Combinations Adjusted for Low Tide (no Fluid Load)	Load Combinations Adjusted for High Tide (no Wind Load)	Governing Load Combinations Applied to the RISA Model
1. 1.4D	1. 1.4D + 1.4F	1. 1.4D
2. 1.2D + 1.6L	2. 1.2D + 1.6L + 1.2F	2. 1.2D + 1.6L
3. 1.2D + L	3. 1.2D + L + 1.2F	3. 1.2D + 1.0W + L
4. 1.2D + 1.0W + L	4. 1.2D + L + 1.2F	4. 0.9D + 1.0W
5. 1.2D + L	5. 1.2D + L + 1.2F	5. 1.4D + 1.4F
6. 0.9D + 1.0W	6. 0.9D	6. 1.2D + 1.6L + 1.2F
7. 0.9D	7. 0.9D + 0.9F	7. 0.9D + 0.9F

The load combinations were then inputted into RISA and solved to compute the moments, axial forces, and shear forces present across the structure. Table 18 compiles the maximum forces and moments present across each girder, column, and stringer. Maximum bending stresses, tensile stresses, shear stresses, and compressive stresses were also calculated for their respective member type.

Table 18: RISA Model Maximum Forces and Stresses

Member Type	Max Moment, M (lbf-ft)	Max Axial, T (lbf)	Min Axial, C (lbf)	Max Shear, V (lbf)	Bending Stress, f_b (psi)	Tensile Stress, f_t (psi)	Compressive Stress, f_c (psi)	Shear Stress, f_v (psi)
Girder	1138.33	88.03	-	908.74	10.540	2.445	-	25.243
Column	4042.44	3537.27	1431.78	700.96	0.252	31.276	12.660	6.198
Stringer	4042.50	0.96	-	1623.94	0.009	0.080	-	0.347

Key: 1 lbf-ft = 1.36 N-m; 1 lbf = 4.45 N; 1 psi = 6.90 kPa

Douglas Fir-Larch No. 2 was selected as the softwood material used in the NDS design value adjustment equations. It has a lower MOE (1,600,000 psi – 11.0 GPa) than the determined MOE of Batipa's teak in Objective 3 (1,885,000 psi – 13.0 GPa), so Douglas Fir-Larch No. 2 is a weaker material susceptible to more deflection. Although no stress values were researched for short-rotation teak, the tensile, bending, and compressive stresses for long-rotation teak (10,310 psi, 8,660 psi, and 5,710 psi – 71.1 MPa, 59.7 MPa, and 39.4 MPa, respectively) are each significantly greater than the equivalents for Douglas Fir (575 psi, 900 psi, and 180 psi – 4.0 MPa, 6.2 MPa, and 1.2 MPa, respectively). For these reasons, the short-rotation teak at Batipa can be assumed to be stronger than Douglas Fir, adding an additional factor of safety to the calculations.

Using the established NDS LRFD design value adjustment equations, design bending, tensile, shear, and compressive stresses for each member type were calculated to be compared to the calculated maximum stresses. The calculations for each member are provided in Tables 19-21.

Table 19: NDS LRFD Design Value Adjustment Equations for Girders [34], [76]

Item		Initial Value (psi)		C_M	C_t	C_L	C_F	C_{Fu}	C_i	C_r	C_P	K_F	Φ	λ		Final Value (psi)
F_b'	=	875	×	1.00	1.00	1.00	1.00	1.00	0.80	1.15	-	2.54	0.85	0.60	=	1,040
F_t'	=	425	×	1.00	1.00	-	1.00	-	0.80	-	-	2.70	0.80	0.60	=	440
F_v'	=	170	×	1.00	1.00	-	-	-	0.80	-	-	2.88	0.75	0.60	=	175

Table 20: NDS LRFD Design Value Adjustment Equations for Columns [34], [76]

Item		Initial Value (psi)		C_M	C_t	C_L	C_F	C_{Fu}	C_i	C_r	C_P	K_F	Φ	λ		Final Value (psi)
F_b'	=	725	×	1.00	1.00	1.00	1.00	1.00	0.80	1.15	-	2.54	0.85	0.60	=	860
F_t'	=	475	×	1.00	1.00	-	1.00	-	0.80	-	-	2.70	0.80	0.60	=	490
F_v'	=	170	×	1.00	1.00	-	-	-	0.80	-	-	2.88	0.75	0.60	=	175
$F_{c\perp}'$	=	625	×	0.67	1.00	-	1.00	-	1.00	-	0.98	2.40	0.90	0.60	=	530

Table 21: NDS LRFD Design Value Adjustment Equations for Stringers [34], [76]

Item		Initial Value (psi)		C_M	C_t	C_L	C_F	C_{Fu}	C_i	C_r	C_P	K_F	Φ	λ		Final Value (psi)
F_b'	=	900	×	1.00	1.00	1.00	1.30	1.15	0.80	1.15	-	2.54	0.85	0.60	=	1,600
F_t'	=	575	×	1.00	1.00	-	1.30	-	0.80	-	-	2.70	0.80	0.60	=	775
F_v'	=	180	×	0.97	1.00	-	-	-	0.80	-	-	2.88	0.75	0.60	=	180

Key: 1 psi = 6.90 kPa

With maximum stress outputs and adjusted design values calculated for each member, the adequacy of the structure could be determined through comparison. Table 22 presents all of the maximum outputs, their respective adjusted design values, percentages of capacity used, and factors of safety.

Table 22: Comparison of Maximum Stresses and Design Strengths

Member	Output Stress (psi)		Adjusted Design Value (psi)		% Capacity	Factor of Safety
Girder	f_b	10.54	F_b'	1040	1.01%	99
Girder	f_t	2.45	F_t'	440	0.56%	180
Girder	f_v	25.24	F_v'	175	14.42%	7
Column	f_b	0.25	F_b'	860	0.03%	3415
Column	f_t	31.28	F_t'	490	6.38%	16
Column	f_c	12.66	$F_{c\perp}'$	530	2.39%	42
Column	f_v	6.20	F_v'	175	3.54%	28
Stringer	f_b	0.01	F_b'	1600	0.00%	179667
Stringer	f_t	0.08	F_t'	775	0.01%	9677
Stringer	f_v	0.35	F_v'	180	0.19%	519

Key: 1 psi = 6.90 kPa

Since every capacity is lower than 100%, each member can withstand the stresses if made using Douglas Fir-Larch No. 2. Additionally, since the teak at Batipa was proven to be stronger than Douglas-Fir, the designs will also work for teak.

The connection strength of the final design was also calculated. In the RISA model results, the largest lateral shear force was found to be 82.82 lbf (369 N), located on column-girder connection points at each of the corner columns. Connection calculations were therefore focused on this connection point. The final design uses two steel plates and two threaded rods to form a double-shear connection between girders and columns, so the connection design value was only considered for yield mode equations I_m, I_s, III_s, and IV, calculated below in Table 23. The lowest yield strength of the rods was calculated to be 465 lbf for each threaded rod (2.1 kN/rod).

Table 23: Calculations for Lowest Connection Design Value [34], [76]

Item	Variable	Value	Units
Diameter	D	0.5	in
Dowel Bending Yield Strength	F_{yb}	45,000	psi
Main member length	l_m	6	in
Side member length	l_s	0.375	in
Main member dowel bearing strength	F_{em}	6,250	psi
Side member dowel bearing strength	F_{es}	6,250	psi
Reduction Term (Yield Limits I_m & I_s)	R_d	5	
Reduction Term (Yield Limits III_s & I_V)	R_d	4	
F_{em}/F_{es}	R_e	1	
l_m/l_s	R_t	16	
Yield Limit III_s Constant	k_3	4.44	
Yield Mode I_m Design Strength	Z	3,750	lbf/rod
Yield Mode I_s Design Strength	Z	465	lbf/rod
Yield Mode III_s Design Strength	Z	865	lbf/rod
Yield Mode IV Design Strength	Z	1,210	lbf/rod
Weakest Design Strength	Z_{min}	465	lbf/rod

Key: 1 in = 2.54 cm; 1 psi = 6.90 kPa; 1 lbf = 4.45 N

The weakest design strength was then adjusted using LRFD adjustment factors. Computed in Table 24, the adjusted value was determined to be 400 lbf/rod (1.78 kN/rod).

Table 24: NDS LRFD Design Value Adjustment Equation for Connections

Item		Initial Value (lbf/rod)		C_M	C_t	C_g	C_{eg}	C_{di}	C_{tn}	K_F	Φ	λ		Final Value (lbf/rod)
Z_{min}'	=	465	×	1.00	1.00	1.00	0.67	1.00	1.00	3.32	0.65	0.60	=	400

Key: 1 lbf = 4.45 N

Since there are two threaded rods per connection point, the total adjusted design strength at a connection point is 800 lbf (3.56 kN). Applying the 82.82 lbf (369 N) maximum lateral shear force found in the RISA model therefore puts the connection design at 10.4% capacity for a factor of safety of 9.6. Therefore, connections are strong enough for the loading conditions. Because both the members and connections were calculated to be able to withstand anticipated loading, the Batipa Boardwalk design was proven to be structurally stable, and the analysis was complete.

5.0 Conclusion

In collaboration with OTU, the Batipa Boardwalk was designed to be constructed in the Mangrove Swamp of BFS. Edmundo Gonzalez, the coordinator of BFI and project sponsor liaison, identified the project goal and its parameters and provided assistance for site assessments and prototype testing. Using information obtained during the site assessment, literature research, and prototype testing, the final Batipa Boardwalk design was produced in the form of design drawings and supporting analysis calculations. The project deliverables were given to OTU to provide a design they can construct to enable accessible transportation to mangrove trees, allowing the institution to improve its efforts in conducting research and increasing ecotourism.

The work completed in this project benefits both the project sponsor and the undergraduate students involved. The long-term collaborative experience of conducting research, design, and analysis in a real-world engineering problem bolstered teamwork and engineering skills beneficial to undergraduate education in civil and environmental engineering. This project also fulfilled the requirements of WPI's design criteria for the Accreditation Board for Engineering and Technology (ABET).

Capstone Design Statement

The Major Qualifying Project (MQP) at Worcester Polytechnic Institute (WPI) is a research project degree requirement for students fulfilling their Bachelor's Degree. The MQP is a real-world, team-based project that demonstrates professional and technical learning outcomes in the student's major. To complete the MQP, students document their design process, complete an MQP report, and orally present the project's results. Since the project is within the department of the student's intended major, the MQP is used to fulfill the design requirement for the Accreditation Board for Engineering and Technology (ABET) accreditation [79].

The Batipa Boardwalk was designed to traverse a sensitive mangrove environment. To limit the disruptions to this delicate ecosystem, environmental factors including soil types, water, animals, and construction materials were carefully accounted for in the design. The Batipa Boardwalk was also designed to be safely and feasibly constructed. To verify the strength of the Batipa Boardwalk, loading equations were identified in the American Society of Civil Engineers (ASCE) *ASCE 7 Standard,* and compared to timber structure strength values identified using the *National Design Specification* (NDS) for Wood Construction. ASCE 7 is integrally used in American structural loading requirements, and NDS is an American National Standard for the design strength of softwood timbers. Both ASCE 7 and NDS are implemented into the International Building Code (IBC).

The *ASCE 7 Standard* details the factored loading combinations that the design strength of all American structures, components, and foundations must equal or exceed [33]. Equations are established independent of location and thus were applicable to the Mangrove Swamp with little adjustments. The *2018 NDS Supplement* provides design strength values for typical American softwood materials. NDS Specification then details how initial material values are adjusted based on factors dependent on the material, sizing, and location [76]. Acceptable dowel-type mechanical connections are also outlined in the *2018 NDS Manual* [77]. The NDS Specification assists in providing failure cases for acceptable dowel-type mechanical connections based on the size, length, and type of connection. Since NDS applies to American softwood timbers, it contains no design values to reference for Panamanian hardwood teak. To resolve this, Douglas Fir-Larch No. 2 was proven to be a weaker material than the available teak (including lower MOE, tensile, bending, and compressive stress values) and thus used in the NDS design value adjustment equations. The design was proved to work using Douglas Fir-Larch and therefore should also work for the teak the sponsor has available to build the structure.

Engineers must uphold principles of ethics including integrity and professionalism. When completing the project, the ASCE Code of Ethics was closely followed to ensure the health and welfare of the public and those involved with the project. Some of the fundamental principles of a professional career include creating a safe and resilient infrastructure, treating all persons with respect and equity, considering the current and anticipated needs of society, and utilizing knowledge and skills to enhance the quality of life for humanity [80]. All members of ASCE must commit to all ethical responsibilities established in the Code of Ethics. Throughout the project, professional standards were held at all times.

Professional Licensure Statement

The Batipa Boardwalk was designed by students who are not yet professionals. As such, all designs created in this report should be firstly reviewed by a Professional Engineer (PE), or the Panamanian equivalent of a licensed engineer, prior to construction or use. Doing so will increase the safety of potential users of the Batipa Boardwalk. It is recommended that a Professional Structural Engineer and a Professional Engineer with a specialty in Geotechnical Engineering both review the designs before building. This is important to make sure that the structural aspects, especially the joints and foundation - which are the two areas of the boardwalk that are most likely to fail, are reviewed by a professional prior to construction.

A PE license is the highest standard of competence in the field of engineering, and the highest rank an engineer can achieve [81]. A PE license is awarded to engineers after they have completed the following requirements:

- Completed a four-year degree at a college that is accredited by ABET
- Passed the Fundamentals of Engineering (FE) examination
- Completed four years of work in their field while under the supervision of a PE
- Passed the PE examination in their respective field [81].

Another component of being a PE is abiding by the Code of Ethics of the National Society of Professional Engineers (NSPE), which outlines personal rules for designing structures and maintaining professional relationships. This is done to ensure the safety of the public by avoiding inadequate work and corruption [82]. Violating these rules can result in the suspension or removal of a PE license. This Code of Ethics had six Fundamental Canons, which are the broadest and most important rules of conduct, which are:

1. Hold paramount the safety, health, and welfare of the public
2. Perform services only in areas of their competence
3. Issue public statements only in an objective and truthful manner
4. Act for each employer or client as faithful agents or trustees
5. Avoid deceptive acts
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession

Once an engineer has become a PE, they can create, sign, and seal documents such as designs, and construction drawings, and submit these records to public or private entities for approval. This rank is also important for job prospects as a licensed engineer can directly seal and submit their own work for further approval.

Bibliography

[1] "World Bank Climate Change Knowledge Portal," Climatology | Climate Change Knowledge Portal, https://climateknowledgeportal.worldbank.org/country/panama/climate-data-historical (accessed Sep. 8, 2023).

[2] K. Kathiresan, "Importance of Mangrove Ecosystem," International Journal of Marine Science, 2, 70-89, https://www.scirp.org/(S(lz5mqp453edsnp55rrgjct55))/reference/ReferencesPapers.aspx?ReferenceID=1676462 (accessed Sep. 8, 2023).

[3] J. Lai, W. Cheah, K. Palaniveloo, R. Suwa, and S. Sharma, "A systematic review of the physicochemical and microbial diversity of well-preserved, restored, and disturbed mangrove forests: What is known and what is the way forward?," MDPI, https://www.mdpi.com/1999-4907/13/12/216 0 (accessed Sep. 8, 2023).

[4] L. Guinessey, "Protecting mangroves in Panama to create a better climate future," Audubon, https://www.audubon.org/news/protecting-mangroves-panama-create-better-climate-future (accessed Oct. 5, 2023).

[5] R. L. Millett, B. L. Gordon, and G. Anguizola, "Panama," Encyclopædia Britannica, https://www.britannica.com/place/Panama (accessed Sep. 7, 2023).

[6] National Hurricane Center, https://www.nhc.noaa.gov/ (accessed Sep. 8, 2023).

[7] J. Baker, "Chiriqui," Embajada de Panama, http://embajadadepanama.org/pages/organizacion-territorial/provincia/chiriqui.php (accessed Sep. 8, 2023).

[8] R. J. Alfaro, "Datos Climáticos Históricos," Instituto de Meteorología e Hidrología de Panamá, https://www.imhpa.gob.pa/es/clima-historicos (accessed Sep. 8, 2023).

[9] "Panama Boundaries Locator," ArcGIS web application, https://si.maps.arcgis.com/apps/webappviewer/index.html?id=abb150e8b74f40bebc8eb13c6328739b (accessed Sep. 8, 2023).

[10] S. Chamberland-Fontaine, G. T. Estrada, S. Heckadon-Moreno, and G. M. Hickey, "Enhancing the sustainable management of mangrove forests: The case of Punta Galeta, Panama," Trees, Forests and People, https://www.sciencedirect.com/science/article/pii/S2666719322000814?via%3Dihub (accessed Oct. 5, 2023).

[11] S. Chamberland-Fontaine, S. Heckadon-Moreno, and G. M. Hickey, "Tangled roots and murky waters: Piecing together Panama's mangrove policy puzzle," Frontiers, https://www.frontiersin.org/articles/10.3389/ffgc.2022.818722/full (accessed Oct. 5, 2023).

[12] "Historia - Universidad Tecnológica Oteima," Universidad Tecnolgica OTEIMA, https://www.oteima.ac.pa/oteima/historia/ (accessed Sep. 8, 2023).

[13] 1 dictionary entries for 'boardwalk,'" Oxford English Dictionary, https://www.oed.com/search/dictionary/?scope=Entries&q=boardwalk&tl=true (accessed Oct. 5, 2023).
[14] K. S. Sealey, E. Andiroglu, J. Lamere, J. Sobczak, and P. Suraneni, "Multifunctional performance of coastal structures based on South Florida Coastal Environs," BioOne Complete, https://bioone.org/journals/journal-of-coastal-research/volume-37/issue-3/JCOASTRES-D-20-00068.1/Multifunctional-Performance-of-Coastal-Structures-Based-on-South-Florida-Coastal/10.2112/JCOASTRES-D-20-00068.1.short (accessed Sep. 8, 2023).
[15] G. K. Westbrook, N. C. Hardy, and R. P. Heath, "Structure and Tectonics of the Panama-Nazca Plate Boundary," GeoScienceWorld, https://pubs.geoscienceworld.org/gsa/books/book/441/chapter-abstract/3798927/Structure-and-tectonics-of-the-Panama-Nazca-plate?redirectedFrom=fulltext (accessed Sep. 8, 2023).
[16] "Earthquakes and Tsunamis," American Museum of Natural History, https://www.amnh.org/exhibitions/natures-fury-natural-disasters/earthquakes-and-tsunamis#:~:text=Tsunamis%20are%20caused%20by%20sudden,speed%20of%20a%20jet%20plane . (accessed Sep. 8, 2023).
[17] "Turbidity," U.S. Environmental Protection Agency, https://www.epa.gov/system/files/documents/2021-07/parameter-factsheet_turbidity.pdf (accessed Sep. 8, 2023).
[18] C. E. Lovelock, M. F. Adame, V. Bennion, M. Hayes, and R. Reef, "Sea Level and Turbidity Controls on Mangrove Soil Surface Elevation Change," Digital Commons, https://core.ac.uk/download/pdf/77949211.pdf (accessed Sep. 8, 2023).
[19] L. A. Uneke, P. P. Akpan, and L. L. Kormah, "Effect of Salinity in Civil Engineering Concrete Basement," International Journal of Engineering and Modern Technology, https://www.iiardjournals.org/get/IJEMT/VOL.%204%20NO.%202%202018/EFFECT%20OF%20SALINITY.pdf (accessed Sep. 8, 2023).
[20] G. T. Kirker, C. Brischke, L. Passarini, and S. L. Zelinka, "Salt Damage in Wood: Controlled Laboratory Exposures and Mechanical Property Measurements," United States Forest Service, https://www.fs.usda.gov/research/treesearch/59605 (accessed Sep. 8, 2023).
[21] "Tidal Creeks," OzCoasts, https://ozcoasts.org.au/conceptual-diagrams/science-models/geomorphic/tc/ (accessed Sep. 8, 2023).
[22] "Soil Atlas of Latin America and the Caribbean," Euroclima, https://edepot.wur.nl/484482 (accessed Sep. 8, 2023)
[23] "Soil Qualifiers," ISRIC, https://www.isric.org/sites/default/files/major_soils_of_the_world/annexes/qualifie.pdf (accessed Sep. 8, 2023).

[24] D. Heinz and C. Saavedra, “Analysis of the Relationship Between Landslides and Precipitation Events in Chiriquí Province, Panama,” Revista de Iniciación Científica, https://revistas.utp.ac.pa/index.php/ric/article/view/2237 (accessed Sep. 8, 2023).
[25] C. Nolan, “Why Hardwood Decking is a Great Option for Boardwalks,” Ipe Decking, https://www.mataverdedecking.com/blog/why-hardwood-decking-is-a-great-option-for-boardwalks#:~:text=Ipe%20Hardwood%20Decking%20for%20Boardwalks&text=Ipe%20decking%20offers%20high%20strength,resistance%20and%20it%20great%20looks . (accessed Sep. 8, 2023).
[26] A. Harte, “Introduction to Timber as an Engineering Material,” University of Galway, https://www.universityofgalway.ie/media/timberengineeringresearchgroup/Harte---2009---Introduction-to-timber-as-an-engineering-material.pdf (accessed Sep. 8, 2023).
[27] N. Engler, “ The Nature of Wood,” Wood Strength, https://workshopcompanion.com/KnowHow/Design/Nature_of_Wood/3_Wood_Strength/3_Wood_Strength.htm (accessed Oct. 5, 2023).
[28] E. Meier, “Wood and moisture,” The Wood Database, https://www.wood-database.com/wood-and-moisture/ (accessed Oct. 5, 2023).
[29] “Personal Protective Equipment - construction,” Occupational Safety and Health Administration, https://www.osha.gov/personal-protective-equipment/construction (accessed Oct. 5, 2023).
[30] “Commonly used statistics,” Occupational Safety and Health Administration, https://www.osha.gov/data/commonstats (accessed Oct. 5, 2023).
[31] R. C. Hibbeler, “Mechanics of Materials - 10th Edition,” Pearson, https://www.pearson.com/store/p/mechanics-of-materials/P200000003357/9780134321189 (accessed Oct. 5, 2023).
[32] K. C. Mehta and Wi. L. Coulbourne, “Wind Loads: Guide to the Wind Load Provisions of ASCE 7-10,” ASCE, https://ascelibrary.org/doi/book/10.1061/9780784412756 (accessed Oct. 6, 2023).
[33] American Society of Civil Engineers, “Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10,” ASCE, https://ascelibrary.org/doi/book/10.1061/9780784412916 (accessed Oct. 6, 2023).
[34] “2018 NDS,” American Wood Council, https://awc.org/publications/2018-nds/ (accessed Oct. 6, 2023).
[35] Admin, “Teak wood : Properties, characteristics & uses in detail,” Cameroon Timber Export Sarl - Selling Quality Logs in Douala, Cameroon, https://cameroontimberexport.com/teak-wood-properties-characteristics-uses/ (accessed Oct. 5, 2023).
[36] L. A. Pratiwi et al., “Characterization of thermally modified short and long rotation teaks and the effects on coatings performance,” Maderas. Ciencia y tecnología, https://www.scielo.cl/scielo.php?pid=S0718-221X2019000200209&script=sci_arttext&tlng=es (accessed Oct. 5, 2023).

[37] R. Martha et al., "Differences of technological properties on sapwood and heartwood of short rotation teak wood," Wood Material Science and Engineering, https://www.tandfonline.com/doi/abs/10.1080/17480272.2023.2221678 (accessed Oct. 5, 2023).
[38] D. E. Rizanti et al., "Comparison of teak wood properties according to forest management: Short versus long rotation - annals of forest science," BioMed Central, https://annforsci.biomedcentral.com/articles/10.1007/s13595-018-0716-8 (accessed Oct. 5, 2023).
[39] C. A. Schuh et al., "Microstructural Analysis to Understand the Strength of Teak Wood Using Experimental Methods," Materials Today Communications, https://www.sciencedirect.com/science/article/abs/pii/S2352492822009163#:~:text=This%20study%20shows%20that%20the,1%20mm%2Fmin%20loading%20rate. (accessed Sep. 8, 2023).
[40] J. Gerard, D. Guibal, S. Paradis, and J.-C. Cerre, "Tropical Timber Atlas," ITTO, https://www.itto.int/files/itto_project_db_input/3028/Technical/E-TMT-SDP-010-12-R1-M-Tropical%20Timber%20Atlas.pdf (accessed Oct. 5, 2023).
[41] A. Tusinski, "[PDF] the role of mangroves in the design of coastal dikes ...," Semantics Scholar, https://www.semanticscholar.org/paper/The-Role-of-Mangroves-in-the-Design-of-Coastal-and-Tusinski/7ff729f62412fceafe8595391adc5a88291858e5 (accessed Oct. 5, 2023).
[42] J. I. Perez, "Good News! Recovery of the Juan Diaz Mangroves," Smithsonian Tropical Research Institute, https://stri.si.edu/story/good-news#:~:text=The%20most%20common%20mangrove%20species,Mangle%20Salado%20(Avicennia%20bicolor) (accessed Oct. 5, 2023).
[43] M. D. Hossain and A. A. Nuruddin, "Soil and mangrove: A Review," Science Alert, https://scialert.net/fulltext/?doi=jest.2016.198.207#:~:text=Mangrove%20soils%20are%20of%20marine,as%20sandy%20or%20clayey%20types (accessed Sep. 21, 2023).
[44] K. R. T. Whelan, T. J. Smith, D. R. Cahoon, J. C. Lynch, and G. H. Anderson, "Groundwater Control of Mangrove Surface Elevation: Shrink and Swell Varies with Soil Depth," Estuaries, Volume 28 No.6, https://www.jstor.org/stable/3526950?seq=2 (accessed Sep. 21, 2023).
[45] O. Spaargen, "Acrisols, Alisols, Lixisols and Nitisols," Wageningen, https://esdac.jrc.ec.europa.eu/events/SummerSchool_2003/presentations/II_WRB/10Acri-Ali-Lixi-Nitisols2_OS.ppt (accessed Oct. 5, 2023).
[46] J. Lo, L. P. Quoi, and S. Visal, "Some preliminary observations on peat-forming mangroves in Botum Sakor, Cambodia," Global Environment Centre, http://mires-and-peat.net/media/map22/map_22_03.pdf (accessed Oct. 5, 2023).
[47] J. da Silva Andrade Neto, A. D. De la Torre, and A. P. Kircheim, "Effects of sulfates on the hydration of Portland Cement – A Review," Construction and Building Materials,

https://www.sciencedirect.com/science/article/pii/S0950061821001884#:~:text=Calcium%20sulfate%20is%20used%20in,and%20strength%20in%20cementitious%20materials (accessed Oct. 5, 2023).
[48] H. H. Bache, G. M. Idorn, P. Nepper-Christensen, and J. Nielsen, "Morphology of Calcium Hydroxide in Cement Paste," TRB, https://onlinepubs.trb.org/Onlinepubs/sr/sr90/90-014.pdf (accessed Oct. 5, 2023).
[49] M.-J. Kim, S. Kim, S. Shin, and G. Kim, "Production of high-purity mgso4 from seawater desalination brine," Desalination Volume 518 (15), https://www.sciencedirect.com/science/article/abs/pii/S0011916421003593 (accessed Oct. 5, 2023).
[50] "Concrete exposed to seawater – effects and preventions," The Constructor, https://theconstructor.org/concrete/concrete-seawater-effects-preventions/843/#:~:text=Effect%20of%20Seawater%20on%20Concrete%20Structures,-The%20constituents%20of&text=The%20magnesium%20sulfate%20present%20in,and%20forms%20calcium%20sulpho%20aluminate (accessed Oct. 5, 2023).
[51] S. Delacroix, T. J. Nystuen, E. Höglund, and A. L. King, "Biological impact of ocean alkalinity enhancement of magnesium hydroxide on marine microalgae using bioassays simulating ship-based dispersion," Biogeosciences Discussions, https://bg.copernicus.org/preprints/bg-2023-138/ (accessed Oct. 5, 2023).
[52] P. Lawson, M. Alviar-Agnew, and H. Agnew, "7.5: Neutralization," Chemistry LibreTexts, https://chem.libretexts.org/Bookshelves/Introductory_Chemistry/Chemistry_for_Changing_Times_(Hill_and_McCreary)/07%3A_Acids_and_Bases/7.05%3A_Neutralization (accessed Oct. 5, 2023).
[53] "Rust formula - introduction, chemical formula and equations," VEDANTU, https://www.vedantu.com/formula/rust-formula (accessed Oct. 5, 2023).
[54] X. Hou, L. Gao, Z. Cui, and J. Yin, "Corrosion and Protection of Metal in the Seawater Desalination," IOP Science, https://iopscience.iop.org/article/10.1088/1755-1315/108/2/022037/pdf (accessed Oct. 5, 2023).
[55] "Iron hydroxide (fe(oh)3)," National Center for Biotechnology Information. PubChem Compound Database, https://pubchem.ncbi.nlm.nih.gov/compound/Iron-hydroxide-_Fe_OH_3 (accessed Oct. 5, 2023).
[56] P. Cadmus, S. F. Brinkman, and M. K. May, "Chronic toxicity of ferric iron for North American aquatic organisms: Derivation of a chronic water quality criterion using single species and Mesocosm Data," Archives of environmental contamination and toxicology, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5893738/ (accessed Oct. 5, 2023).

[57] B. Rodriguez, “The effects of saltwater on Metals,” Sciencing, https://sciencing.com/effects-saltwater-metals-8632636.html (accessed Oct. 5, 2023).
[58] D. Ellis, “The Iron-Bacteria,” JSTOR, https://www.jstor.org/stable/43432329 (accessed Oct. 5, 2023).
[59] K. Alcott, “Wet rot - causes, identification & solution,” Allcott Associates, https://www.allcottassociates.co.uk/blog/wet-rot-causes-identification-solution/#:~:text=Wet%20rot%20is%20the%20natural,moisture%20content%20of%20around%2020%25. (accessed Oct. 5, 2023).
[60] P. T. Shien, H. N. Seneviratne, and D. S. A. Ismail, “A Study on Factors Influencing the Determination of Moisture Content of Fibrous Peat,” E-Journal of Civil Engineering Volume 2, file:///C:/Users/Sarah/Downloads/93-Article%20Text-196-1-10-20160428.pdf (accessed Oct. 5, 2023).
[61] J. J. Morrell, “Chapter 14 - Protection of Wood-Based Materials,” Science Direct, https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/B9781437734553000146 (accessed Oct. 5, 2023).
[62] T. Vaessen, C. Verwer, M. Demies, H. Kaliang, and P. J. van der Meer, “Comparison of Termite Assemblages Along a Landuse Gradient on Peat Areas in Sarawak, Malaysia,” JSTOR, https://www.jstor.org/stable/23616920 (accessed Oct. 5, 2023).
[63] “Overview of wood preservative chemicals | US EPA,” United States Environmental Protection Agency, https://www.epa.gov/ingredients-used-pesticide-products/overview-wood-preservative-chemicals (accessed Oct. 5, 2023).
[64] Michael, “How borates protect wood,” Perma, https://www.permachink.com/resources/how-borates-protect-wood (accessed Oct. 9, 2023).
[65] “Ethylene Glycol in Freshwater and Marine Water,” Austrailian Government Initiative, https://www.waterquality.gov.au/anz-guidelines/guideline-values/default/water-quality-toxicants/toxicants/ethylene-glycol-2000#:~:text=The%20aquatic%20toxicology%20of%20ethylene,a%20low%20log%20Kow. (accessed Oct. 9, 2023).
[66] A. Abdul-Wadoud Mahmod et al., “Construction of Buildings on Peat: Case Studies and Lessons Learned,” MATEC Web Conferences, https://www.matec-conferences.org/articles/matecconf/pdf/2016/10/matecconf_iconcees2016_03013.pdf (accessed Oct. 5, 2023).
[67] P. Wheaton, “Round Wood timber framing,” Round Wood Timber Framing: the Berm Shed Movie - HD Streaming (digital market at permies), https://permies.com/w/berm-shed (accessed Oct. 5, 2023).
[68] B. McCarley, “The advantages and disadvantages of different wood joints,” eHow UK, https://www.ehow.co.uk/list_6363133_advantages-different-wood-joints.html (accessed Oct. 5, 2023).

[69] “A woodworkers guide to woodwork,” A Woodworkers guide to Woodwork, http://www.woodworkbasics.com/ (accessed Oct. 5, 2023).
[70] A. Leaman, “Round Wood timber framing,” Lowimpact.org, https://www.lowimpact.org/categories/round-wood-timber-framing (accessed Oct. 5, 2023).
[71] D. Rigamonti, “Green Wood Timber,” Green wood timber - Designing Buildings, https://www.designingbuildings.co.uk/wiki/Green_wood_timber (accessed Oct. 5, 2023).
[72] J. Simon, “Timber frame,” A Low Impact Woodland Home, http://www.simondale.net/house/frame.htm (accessed Oct. 5, 2023).
[73] Task Committee on Fasteners of the Committee on Wood of the Structural Division, “Mechanical Connections in Wood Structures,” Iowa State , https://intrans.iastate.edu/app/uploads/2018/08/solti97c.pdf (accessed Oct. 5, 2023).
[74] Z. Ahmad, M. P. Ansell, and D. Smedley, IOP Conference Series, https://iopscience.iop.org/article/10.1088/1757-899X/17/1/012007/pdf (accessed Oct. 5, 2023).
[75] “Basic Wind Velocity For Panama,” Dlubal, https://www.dlubal.com/en/load-zones-for-snow-wind-earthquake/wind-rep.html#&center=8.254549819409274,-82.21876563620823&zoom=9&marker=8.29965812484463,-82.261174640876 (accessed Oct. 6, 2023).
[76] “2018 NDS Supplement,” American Wood Council, https://awc.org/publications/2018-nds-supplement/ (accessed Oct. 6, 2023).
[77] “Manual For Engineered Wood Construction,” American Wood Council, https://awc.org/wp-content/uploads/2022/01/AWC-2018-Manual-1810.pdf (accessed Oct. 6, 2023).
[78] H. C. C. P. Herrera, “Agreement No. 155,” Consejo Municipal de Panama, https://legalyjusticia.mupa.gob.pa/wp-content/uploads/2019/01/155-13-se-modifica-y-adiciona-el-articulo-49-50..pdf (accessed Oct. 9, 2023).
[79] “Major Qualifying Project,” Worcester Polytechnic Institute, https://www.wpi.edu/project-based-learning/project-based-education/major-qualifying-project (accessed Oct. 9, 2023).
[80] “Code of Ethics,” American Society of Civil Engineers, https://www.asce.org/career-growth/ethics/code-of-ethics (accessed Oct. 9, 2023).
[81] “Licensure,” National Society of Professional Engineers, https://www.nspe.org/resources/licensure (accessed Oct. 9, 2023).
[82] "Code of Ethics for Engineers,” National Society of Professional Engineers, https://www.nspe.org/resources/ethics/code-ethics#:~:text=Accordingly%2C%20the%20services%20provided%20by,highest%20principles%20of%20ethical%20conduct. (accessed Oct. 9, 2023).