A CUMULATIVE STUDY OF

BAMBOO HOUSING:
BUILDING WITH COMPOSITES FOR DIGNITY AND LONGEVITY

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To my family and friends,

Thank you for your love and support through this journey.

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I truly hope this thesis can be used as a building block for other students and faculty that wish to explore bamboo, and that they may find personal and professional inspiration from this wonderful material like I have.

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ABSTRACT

This mixed methods thesis provides a cumulative study of bamboo as a natural material and building product through the lenses of architectural and product design, engineering, manufacturing, agriculture, material science, environmental science, history, and culture. All case study work is based in the context of coastal Ecuador. The main goal of the thesis is to explore an identified need for a bamboo relief housing system that has the attributes of longevity and quality, but is also rapidly deployable via pre-fabrication. This exploration is performed with the methodology of an in-country applied product and process design, physical prototyping of elements and joints, mechanical performance testing, a case study house design, and a comparative cost analysis with an alternative bamboo relief home. Results of these methods include a successful on-site fabrication process for cross-laminated floor panels installed into culm-frame structure, adequate floor system bending data for design incorporation, and a cost-effective design proposal compared to bamboo disaster-relief precedence. This thesis has the potential to be built upon to the result of real-world environmental, economic, and social impact.

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GENERAL AUDIENCE ABSTRACT

This thesis addresses the use of bamboo in coastal Ecuador from the perspectives of architectural and product design, engineering, manufacturing, agriculture, material science, environmental science, history, and culture. Specifically focused on is the need for post-disaster bamboo housing that is factory-built, and therefore quickly deployable when needed, but also designed for durability and longevity, providing people with safe and dignified living conditions in times of severe need. It is concluded that the proposed system has merit, but will require further research and testing to prove its exact role in Ecuador and/or elsewhere. Ultimately, this work is important to solving greater global environmental issues such as increasing atmospheric CO_2, increasing natural disaster frequency and intensity, and increasing human population and the accompanying housing demand.

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NOTATION

Asper	*Dendrocalamus asper*
BDRG	Biodesign Research Group at Virginia Tech
Bd. Ft.	board feet
CCA	comparative cost analysis
CMU	concrete masonry unit
CLB	cross-laminated bamboo
GPa	gigapascal
GLB	glue-laminated beam
GLC	glue-laminated column
Guadua	*Guadua angustifolia "Kunth"*
LCA	life cycle assessment
LMB	lightly modified bamboo
MPa	megapascal
MOE	modulus of elasticity
MOR	modulus of rupture
Prefab	pre-fabricated
RAS	radial arm saw
RFI	Regeneration Field Institute
Tam Vong	*Dendrocalamus strictus*
Tre Gai	*Bambusa blumeana*

1. INTRODUCTION

1.1 PROBLEM

Bamboo has long been used in the global south as a material for temporary disaster relief dwellings due to its fast growth, low weight, and high strength properties. However, it is applications such as this that has contributed to the material's association with poverty and cheapness, and therefore its underutilization for permanent, high quality structures.

In a typical post-disaster scenario where masses of people are forced to vacate their homes, relief dwellings act as temporary shelter. Bamboo in these structures can be untreated and applied in ways that are uncharacteristic of proper bamboo design. Meanwhile, governments and social organizations scramble to provide long-term housing solutions that frequently results in inadequately designed concrete rectangles densely packed into urban limits. In rural regions, those affected resort to building their own temporary shelters, and often their new home as well. In best case scenarios where quality relief dwellings and long-term housing is provided, the transition period is still months of waiting. There is a clear need for a hybrid bamboo housing solution that is significantly quicker to construct and limits the amount of time spent in relief shelters, if not eliminates them altogether.

Ecuador, the setting of this case study proposal, is a country with significant and noticeable wealth disparity. In the impoverished communities where natural disasters have the most severe negative impacts, short-term relief shelters are commonly erected with whatever materials individuals own or find. This typically materializes into CMU blocks, bamboo poles, and tarps. Long-term affordable housing options are commonly reinforced concrete or CMU, although some companies and institutions like the Regeneration Field Institute (RFI) are implementing more bamboo housing in response to the 2016 earthquake. These bamboo homes are a step in the right direction, but they still take too long to construct, require many hours of skilled bamboo labor, and use significant amounts of concrete and cement for foundations and building envelopes. In this context, a better solution is needed to reduce these factors by providing standardized pre-fabricated bamboo elements that create more accessible factory jobs, constructed on-site in a matter of days and minimize the use of non-biomaterials. This system needs to be permanent, quality housing deployed at relief dwelling speeds.

1.2 PURPOSE

The ultimate purpose of this thesis is to address the fundamental environmental issues of our time through the built environment. Namely, increasing atmospheric carbon, increasing natural disaster frequency and intensity, and exponentially increasing global human population and the accompanying housing demand. These problems present a complex, interconnected web of unintended consequences. Additionally, the purpose is to explore the global underutilization of bamboo in the built environment and methods to re-market the material to successfully address the previously stated issues.

1.3 OBJECTIVES

This thesis is intended to address bamboo from a wide array of perspectives and methods. Firstly, an extensive background is presented to show the versatile importance of bamboo from the lens of history, culture, agriculture, material science, engineering, architectural and product design, environmental science, and current research. Particular focus is put on Ecuador, its local bamboo culture and disaster relief efforts.

Secondly, a case study house design is presented to demonstrate qualitative and technical details of an emerging technique of bamboo construction, lightly modified composites. Accompanied by cost comparisons to an alternative bamboo building method, physical prototyping, mechanical testing, and a product manufacturing case study, realistic feasibility and adoption conclusions can be made. This case study also provides a chance to display bamboo in a new light, and perhaps change some long-held negative perceptions in Ecuador.

Lastly, presented is an opportunity to address real global issues in an environmentally responsible manner; specifically, climate change via atmospheric carbon, global population growth and the subsequent housing demand, and increasing natural disaster intensity and the resulting destruction of economic livelihood.

2. BACKGROUND

2.1. DRIVING ISSUES

Climate change can be defined as a shift in climate patterns mainly caused by greenhouse gas (GHG) emissions from natural systems and human activity (Fawzy et al. 2020). These gases, most notably carbon dioxide, cause heat to be trapped in the atmosphere, causing global warming. It is projected that global temperatures will reach between 1.5ºC - 2ºC above pre-industrial levels by 2100 if current emission rates persist (Masson-Delmotte et al. 2021, Fawzy et al. 2020). Heavy focus has been placed on reducing GHG emissions and capturing existing atmospheric carbon in order to meet climate action goals for 2030. While reducing GHG emissions requires efforts that will hurt certain industries' bottom line, it can be successfully achieved in a number of ways. Carbon capturing, however, is a less understood science, and is frequently a financially hurtful endeavor for the companies and industries who tackle the issue (Hinkle 2021).

As a result of climate change, extreme weather events are occurring at an alarming rate and intensity. In 2018, the world encountered 315 cases of climate-related natural disasters, affecting 68.5 million people (Fawzy et al. 2020). Earthquakes, hurricanes, landslides, typhoons, tornados, and more natural disasters are all decimating communities and countries to an extent that is unprecedented over centuries to thousands of years (Masson-Delmotte et al. 2021). It can take decades to fully recover from the effects of these events, in which time more disasters exponentially continue to strike. Developing tropical nations, like many bamboo countries, are even more vulnerable to these natural disasters due to financial limitations. While addressing disaster preparedness in all facets of society is more important than ever, these practices do not address the root cause of climate change.

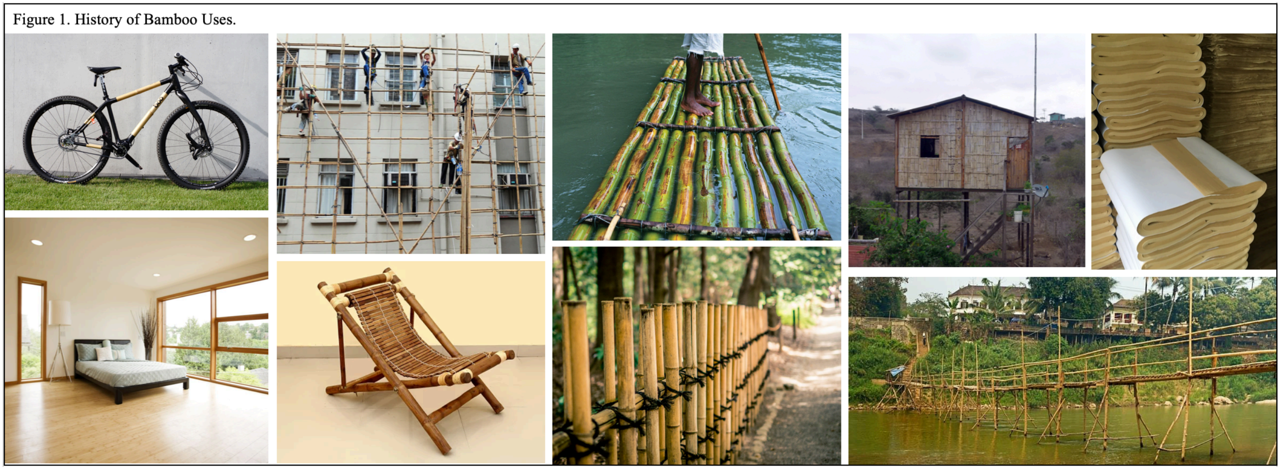
Compounding the difficulty to address climate change is the exponentially increasing global population, expected to reach 8.5 billion by 2030 and 9.7 billion by 2050 (UN 2022). While the reasons for this growth are extensive, the resulting factor most important to this study is the corresponding growth in global housing demand. In order to keep up with such a demand will require an abrupt change from the status quo materials and methods of construction. Materials such as concrete and steel require the extraction of virgin resources that are diminishing, and a renewable resource like timber still requires as little as 20-30 years to reach maturity, and is a much less established industry in the global south where population growth is the most prevalent.

All of these problems have common factors. First, they all are interrelated where the effects of one directly serves as the input for another. Given this fact, it's more complicated to truly solve the underlying causes of one without addressing them all. Secondly, they all have the potential to be addressed by bamboo. Unfortunately, bamboo is globally underutilized, due mainly to the untrue stigma that bamboo is "poor man's timber," or a poor performing material that is only used when other materials are inaccessible. Part of this is due to the lack of a lucrative market in most bamboo regions outside of China, resulting in limited research funding and educational understanding. It is also partly due to historical uses having a prehistoric vernacular. The next section discusses exactly how bamboo can help contribute to solutions for these research driving issues.

2.2. BAMBOO AND THE BUILT ENVIRONMENT

Bamboo is the fastest-growing flowering perennial grass and is considered one of the world's most important tree species, playing an important role in human life in terms of meeting economic, ecological, and social needs (Mustafa et al. 2021). Some of the earliest documented human uses of bamboo dates back 7,000 years ago, when the Chinese used bamboo to construct treehouses. Since then, bamboo has been used to create paper, furniture, hardwood flooring, planes, boats, bicycle frames, scaffolding, bridges, houses, pipes, fences, clothing, biofuel and much more (Linvill, 2009). It's even used as an ingredient in many traditional culinary dishes, such as ceviche in Ecuador. Figure 1 shows bamboo's wide array of uses throughout history and current.

Figure 1. History of Bamboo Uses.



Bamboo has many attributes that make it such a versatile and inherently valuable material. From a construction perspective, characteristics such as renewability, carbon storage capacity, mechanical properties parallel to grain, cost, and durability are why bamboo should be revered as a building material, particularly in regions where it is naturally located. These attributes also present bamboo as a great candidate to address the major environmental and social issues discussed in the previous section.

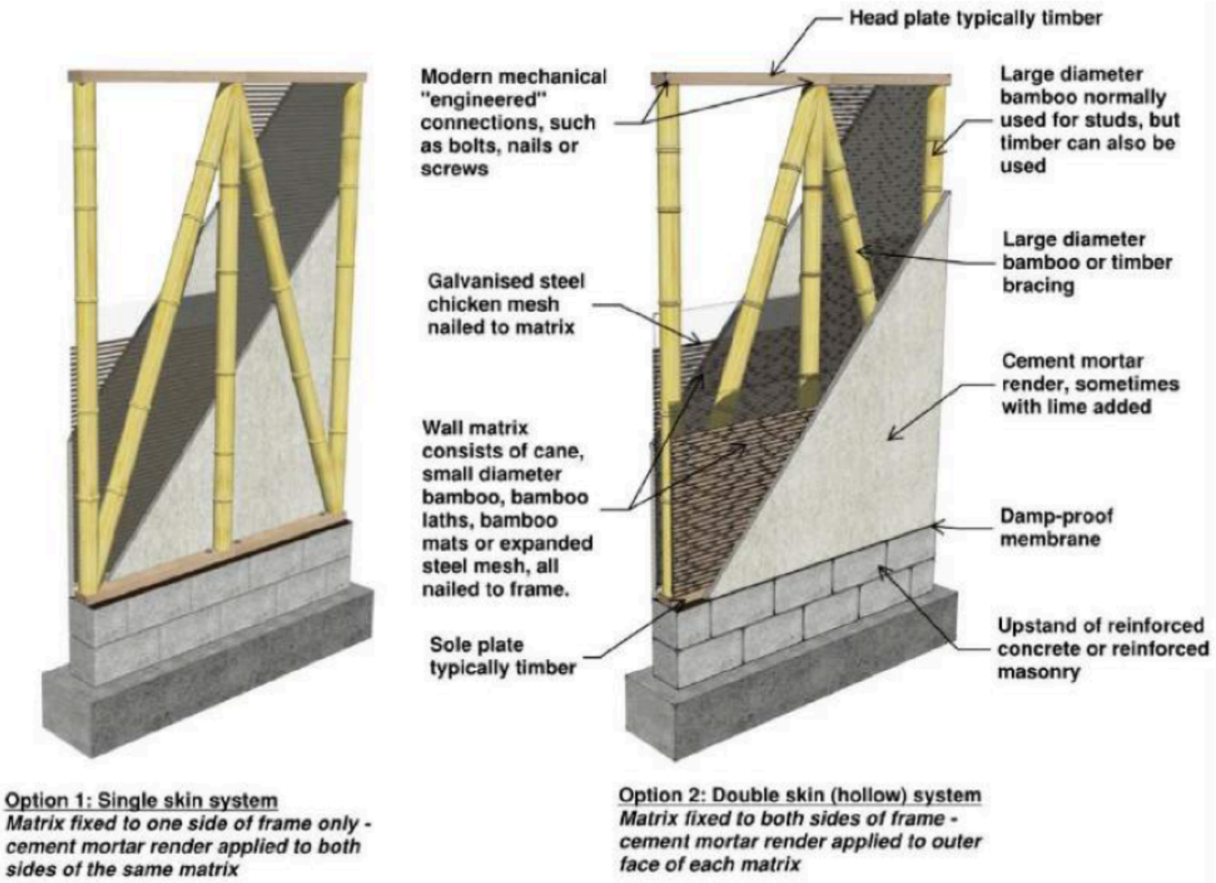
While there is some debate amongst the bamboo community regarding the growth timeline to reach full maturity, it’s evident that this specification varies from species to species, and even from plant to plant. Typically, it takes several years for the rhizome, or underground root structure, to fully mature from a seedling, at which point culms will begin to shoot vertically. The outside diameter of the culm is consistent from the moment the culm breaks the soil. On average, culms will require 6-10 years, in addition to the rhizome development time, to fully mature in terms of wall thickness, density, and height. *Guadua angustifolia,* the thesis species of focus, reaches full maturity around 4-5 years (Schröder 2021 (2). Even when considering the longest case scenario for achieving full bamboo maturity, about 15 years, that is still at least half the time tropical hardwoods require to fully mature. This characteristic of rapid renewability offers a greater opportunity to meet short-term climate goals.

Bamboo, like all plants, extracts carbon from the atmosphere as an input for photosynthesis. In our efforts to sequester carbon from the atmosphere, it is imperative we utilize these capabilities of wood-based materials. As a note, bamboo is technically wood, since it shares the same basic chemical fiber composition as tree wood (i.e. cellulose, hemicellulose, and lignin). However, given the UN forestry sequestration goal to remove 5 gigatons of carbon a year by 2030, trees don't have the same short-term capabilities as bamboo. In addition to bamboo's fast growth rates and short annual harvest cycle, it can sequester more carbon per hectare and is more effective at retaining stored carbon through harvest than wood (Hinkle et al. 2019). Unlike the common wood practice of clear-cutting, mature bamboo culms are selectively cut when properly managed, leaving young stems intact. As long as the rhizome is alive, new stems will shoot every year, creating a continuous carbon farm (Schröder 2021 (1)). The last step for creating a long-term carbon sink is the transformation of bamboo into durable building products, and designing structures that further protect these products. Despite these direct carbon comparisons with wood, it should also be noted that the goal is not to completely replace wood with bamboo, but use bamboo composites to replace heavy concrete use common in alternative bamboo building methods. Wood has an important role to play in long-term carbon sequestration if managed properly.

Bamboo is an anisotropic material, just like wood, meaning it has different properties in the longitudinal, transverse, and radial directions. It contains cellulose fibers in the longitudinal direction, which are strong, stiff, and make up the majority of the bamboo's structure. It contains lignin in the transverse direction, which is soft and brittle. For these reasons, bamboo is strong in all forces that are applied parallel to the grain, but weak and prone to crushing against any forces perpendicular to the grain. Bamboo is mechanically most notable for its high strength to weight ratio, with a tensile strength almost equal to steel and a compressive strength almost double that of concrete, on a per weight ratio basis (Yadav, 2021). This is not to say bamboo should be engineered and designed like these other materials, but rather that it is far more capable than typically represented. While it certainly isn't a perfect material, bamboo has many great mechanical attributes that make it an obvious choice to composite, nullifying any individual detrimental qualities within the performance of a group.

Bamboo's high strength to weight ratio implies that is a lightweight building material, relative to alternative materials like steel, concrete, and heavy timber. This attribute of low weight, in addition to flexibility, make bamboo a high performing material in seismic and wind conditions, conditions that are establishing the demand for relief housing in the first place. By building post-disaster structures in bamboo, communities can begin towards slowing the cyclical nature of post-disaster restart. For example, in 1999, Colombia experienced a magnitude 6.4 earthquake that resulted in 300,000 people being made homeless. After the event, it was evident that modern masonry and reinforced concrete structures suffered devastating damage and often collapsed, while bahareque bamboo style housing fared much better (Trujillo, 2007). While reinforced concrete structures can perform well in seismic conditions, they often don't due to poor construction quality. Bahareque is a bamboo construction technique originated in Colombia, and consists of a whole culm bamboo frame that is sheathed with bamboo strips or mats and then troweled over with cement, as shown in Figure 2. This system performs very well in high wind and seismic zones because the elements behave compositely with the foundation slab, and therefore create a simple and continuous load path through the structure (Kaminski et al., 2016).

Figure 2. Well-designed engineered bahareque housing: wall system (Kaminski et al., 2016)



Despite common misconceptions, bamboo structures have been shown to last for upwards of a century, displaying high durability even without preservative treatment and proper design considerations. A study by Zambrano et al. 2023 examined vernacular bamboo dwellings in the coastal province of Manabí, and a survey of 309 houses concluded that 67% were 11-40 years old, 14 % were 41-50 years old, and the remaining 19% were 51-100 years old. Examples of non-treated, poorly-designed houses that have lasted decades are shown in more detail in the next section, specific to Ecuador. If a bamboo house that is constructed without much planning, most often due to limited finances, resources, or time, can last for decades, then it’s reasonable to wonder how long a bamboo house that is constructed with strategic planning can last for.

While there are several ways to preserve bamboo for building, the most common, and most expensive, modern method is a boric acid treatment. For this method, bamboo is placed in a liquid borate bath, ideally within hours of harvest, and left to soak for several days. In order to obtain maximum absorption in the internodes, holes are punched through the nodes from the ends of the culm. It is traditionally believed that it is not mechanically crucial to have the nodes intact, hence why this method is extremely common. Alternatively, small holes could be drilled into each internode from the exterior of the culm, leaving the nodes solidly intact. This treatment process can also be sped up by using a hot solution, but requires additional energy and resources. Once the submersion treatment is complete, the culms will be left to air dry for several days to several weeks. Ultimately, what the borate solution is doing is driving the sugars and starches out of the bamboo, leaving nothing for insects and fungi to feed on, and therefore lowering the chances of infestation and decay.

In addition to preservative treatment is strategic and “proper” design of a structure. Bamboo architects will often say that a bamboo structure needs “botas y un sombrero,” or “boots and a hat.” Boots refer to a foundation or footings that elevate the bamboo away from the soil, and the hat referring to a large roof with steep pitch and adequate overhangs. Both of these design considerations are an effort keep water and sunlight off of the bamboo, because similar to wood, water and UV are the leading causes of premature rot and decay. (Shmulsky & Jones 2019).

Bamboo construction methodology generally falls onto a spectrum. This spectrum ranges from vernacular construction to engineered composite construction (see Figure 3). These two groups are also sometimes referred to as "bamboo engineering" and "engineered bamboo," respectively.

Figure 3. Bamboo Construction Methodology Spectrum.

The main benefit of vernacular construction is the ability to beautifully, and often ornamentally, display bamboo in its natural morphological state. Attributes of this building method are no building envelope, raised foundational connections, and large roof overhangs. However, this method requires highly skilled bamboo maestros, and typically results in up to 40% waste of the harvested culms due to specific diameter and straightness requirements throughout a structure.

Across the spectrum, engineered composite construction has the ability to create highly standardized building products, and therefore more modern structures with a complete building envelope. The downside of this building method is that these heavily modified composites, such as scrimber bamboo, require intensive processing and adhesives to change the bamboo from its natural, round and hollow state into a rectangular, dense product. This requires large capital investment, and perhaps is treating bamboo too much like wood, an industry that has undergone research and development five times longer than the modern bamboo industry.

"Lightly Modified" bamboo is a concept first introduced to literature by Trujillo et al. 2013, adding that this nascent form of using bamboo reinforces its sustainable credentials. The Biodesign Research Group (BDRG) at Virginia Tech has established a bamboo processing method for use in composite fabrication that also fits this lightly modified description. This method entails putting two parallel faces on the bamboo, creating a form just like a 2-sided cant from lumber manufacturing. This provides gluing surface for compositing layers of bamboo together, using a simple, affordable, and replicable sawing method. In a way, these lightly modified composites fill a need along the bamboo construction spectrum; dimensionally and mechanically standardized building units that retain much of the bamboo's natural morphology and thus require significantly less manufacturing processes and adhesive than their heavily modified counterparts. Lightly modified specifics will be discussed in more detail in a later section.

This section provides a summary of important bamboo background relevant to the thesis problems. It's clear that bamboo's characteristics of renewability, carbon storage potential, high strength to weight ratio, and durability are all vital to quickly meeting housing demand in a method that is environmentally responsible and beneficial, and structurally safe for the inhabitants. The next section provides background into the case study region of coastal Ecuador in order to provide context to the problem and proposed design solutions.

2.3. ECUADOR AND DISASTER RELIEF

2.3.1. Geography and Climate

Ecuador has a unique geographic composition. The Andes transverse the country from north to south, creating three dominant regions: the coastal zone in the west, the mountainous central zone, and the eastern lowlands which form part of the Amazon basin. Across the 270,000 km^2 that Ecuador occupies, the elevation varies as much as 6 km, making the Andes a literal climate divide within the country (Emck 2007). While the highly elevated mountainous zone has a relatively dry and temperate climate, the coastal west and lowland east are tropical and characterized by their dry (July-December) and wet (January-June) seasons. Ecuador's most economically important native bamboo species, *Guadua angustifolia* "Kunth", only grows in these tropical regions (Hornaday 2022). Additionally, the western zone is where almost all Ecuadorian bamboo commerce is operated, with the eastern Amazonian region being much too remote. This area is largely natural growth consisting of hundreds of unstudied species. For this thesis, the focus is on the eastern coastal region where commercial plantations and bamboo houses are the most common.

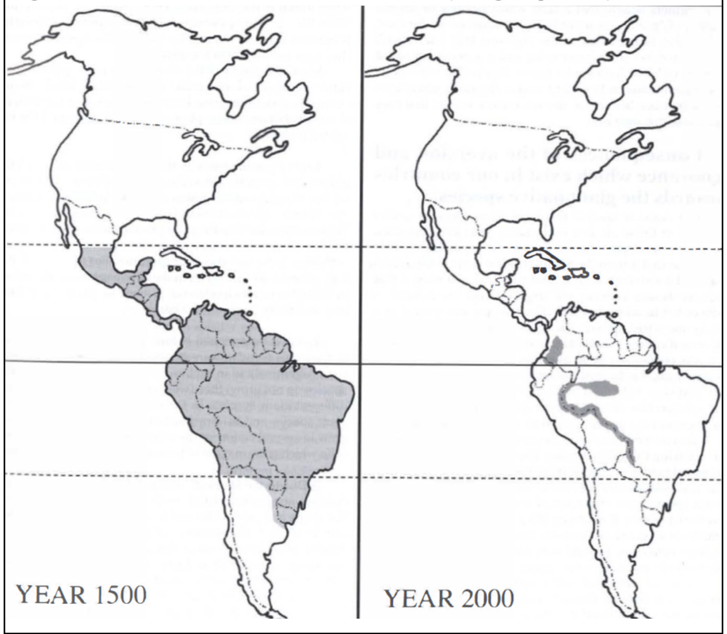

Figure 4. Ecuador topography map.

2.3.2. Native Bamboo Species

As stated in the previous section, the most economically relevant native Ecuadorian bamboo that is commercially harvested for construction is *Guadua angustifolia* "Kunth" (Guadua, for short, though there are many other species from the Guadua genus). *G. angustifolia*, and many of the giant timber species from the Guadua genus, have a long and important history in not only Ecuador, but South America, Central America, and Mexico. Figure 6 shows 500 years of Guadua's astonishing destruction across these regions caused by centuries of Spanish colonialism. Deliberate burning of massive bamboo forests was done by the Spaniards to establish their cattle farms, but also as a way to eliminate Native culture and display ultimate conquest (Hidalgo Lopez 2003). More recently, in the 19th and 20th centuries, the United States has been behind much of the continued Guadua forest destruction, first for banana plantations and later for cattle upon the encouragement of U.S. president Dwight D. Eisenhower (Hidalgo Lopez 2003). During this time, no Latin American governments were opposed to this development, expect for Colombia, whose Institute of Natural Resources established regulations forbidding the cutting of bamboo without permission. These regulations are still in effect today, hence why Colombia now is the leader in Guadua forest cover in Latin America. Meanwhile, Ecuador has seen some benefits from sharing an ecosystem with Colombia, and while bamboo cover remains proportionally small, the supply still heavily outweighs demand. Ultimately, cultural perception issues plague Ecuador, a country with a plentiful supply of bamboo but a lacking market (Hornaday 2022).

Figure 5. *Guadua angustifolia.*

Figure 6. 500 Years of Destruction of the Genus Guadua. (Hidalgo Lopez 2003)



Guadua angustifolia is considered to be the strongest bamboo in the world, and the most important bamboo in the Americas, rivaling the importance of Moso (*Phyllostachys edulis*) in Asia (Schröder 2021 (2)). Fully developed Guadua culms average a height, diameter, and wall thickness of 15-25 m, 9-14 cm, and 1.3 cm, respectively (Schröder 2022, Hidalgo Lopez 2003). According to common literary terminology, Guadua would be classified as “Very Thin Walled” (Hauptman et al. 2023, Judziewicz et al. 1999). This presents challenges regarding light modification with two parallel faces, as it’s difficult to not cut through the culm wall. However, recent thought by the BDRG questions whether this is structurally relevant, just as long as all the nodes remain intact. Correal and Arbeláez 2010 analyzed *G. angustifolia’s* mechanical properties relevant to age and position along the culm (bottom, middle, top, shown in Figure 7). It should be noted that the

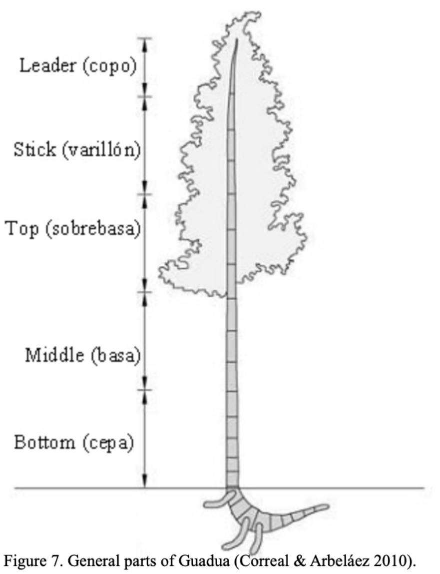


Figure 7. General parts of Guadua (Correal & Arbeláez 2010).

Leader, Stick, and even Top segments are commonly not used for any construction purposes due to taper, small diameter, and thin walls. Correal and Arbeláez 2010 concluded that between 3 and 4 years is the mature age of Guadua in terms of density and mechanical properties. Additionally, mechanical properties were maximized in the Top samples, due to the higher fiber density in the Top segment, a conclusion corroborated by findings from Hidalgo Lopez 2003. The average data of highest performing samples (3-4 years of age from the Top segment) is as follows: Density- 745 g/m^3, Compression strength- 38.6 MPa, Compression modulus E- 17.6 GPa, Shear strength- 7.75 MPa, Bending MOE- 17.3 GPa, and Bending MOR- 101.3 MPa (Correal and Arbeláez 2010). This data outperforms that of *bambusa bluemeana*, a Vietnamese thick-walled species, studied by the BDRG and proven to adequately perform in composite floor systems.

Another common construction species in Ecuador is *Dendrocalamus asper,* also known as Giant Bamboo. This species has become local to Ecuador, but is actually native to Southeast Asia, having been introduced to Latin America in the last 50 years. Although *D. asper* has proven to be a profitable commodity in the Ecuadorian bamboo trade, with several plantations in the Eastern foothills focusing solely on it, it doesn't come close to the natural abundance and familiarity that has been established with Guadua.

2.3.3. Architectural History

Ecuador has a rich, but yet somewhat disheartening culture of architecture due to the combined influences of native tribes, the Incan empire, and Spanish colonialism. The natives were considered to be expert bamboo builders, and an example of a common coastal bamboo and timber house is shown in Figure 8. As seen, they would typically build their homes significantly elevated off the ground due to floods in the rainy season and dangerous animals of the jungles (Hidalgo Lopez 2003). The roof structures are steeply pitched to promote water runoff away from natural fiber covering, which also helps with passive cooling on the interior. The siding was a mosaic of weaved bamboo strips, the earliest versions of bamboo compositing in Ecuador. The other images from Figure 8 show 20th century bamboo homes. While many of the basic design principles are the same, the most noticeable difference is the advancement in sheathing, now a flattened bamboo mat referred to as esterilla. To make esterilla, first a single cut is made through the entire depth of the wall, along the length of the culm. Then numerous shallower cuts are made again along the entire length, and finally the culm can basically be rolled open flat. While it's a product with many imperfections and openings, it's a basic, affordable, and fast method for turning round culm bamboo into flat, unitized products. Additionally, in all of these bamboo homes there are specific uses for wood, like around fenestrations and for connective blocking. This concept will come up again during the case study design discussion. Another important architectural typology from native influence is the coastal area's "housing of three spaces," (Zambrano 2023) which separates living and kitchen quarters by a small hallway, therefore isolating potential cooking fires from other parts of the house. Bamboo housing technology in Ecuador hasn't changed much since the mid to late 20th century, being mostly confined to rural regions, due to large scale adoption of reinforced concrete construction in major population areas.

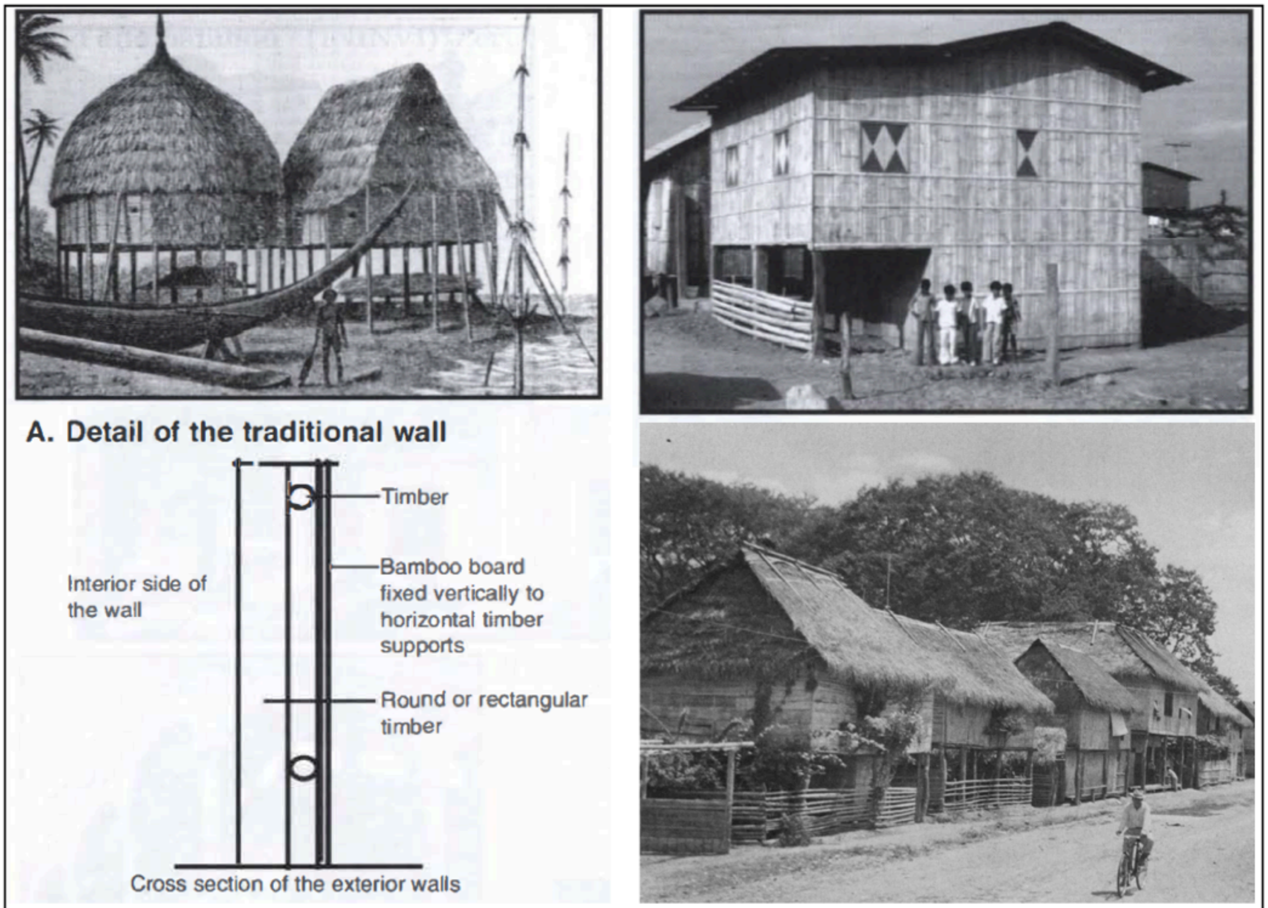


Figure 8. Historical bamboo houses of Ecuador. *(top left) 16th century typical bamboo and timber house of the coast. (top right) Typical architecture still found in a few towns. (bottom left) Traditional wall detail. (bottom right) Stilt supported guadua houses with palm-thatched roofs.* (Hidalgo Lopez 2003, Parsons 1991)

Figure 9. Spanish architectural influence in Quito, Ecuador.

When the Spanish arrived in Ecuador in the 16th century, they began to develop consolidated cities to promote urban centrality (Zambrano 2023). The outskirts of these cities were left to natives and their traditional houses, while city centers gathered the dominant institutions of Church and State, and lots within the cities were distributed in this order of hierarchy: Spaniards, their descendants, and then natives (Zambrano 2023). In their development efforts, the Spanish implemented the use of materials and methods that were culturally familiar to them: lime, clay, and iron nails (Zambrano 2023). Over time, these materials influenced smaller cities and towns outside of the major populations hubs of Quito, Guayaquil, and Cuenca. Additionally, these major city outskirts only continued to expand, and traditional native homes were replaced with concrete houses. Characteristics of Spanish architecture can be seen in Figure 9, highlighted by ornate facades, small balconies, vibrant colors, and barrel tile roofing. City centers like this in Quito are distinguished by central extravagant churches, government buildings, and stone plazas, which are wrapped by tight alleys and densely packed multi-story housing units. While these historic areas are certainly beautifully detailed, they also symbolize colonial oppression and the erased history of native culture.

2.3.4. Current Affordable Housing Tendencies

Today, vernacular bamboo and timber houses are not valued as cultural heritage, since much of the native cultural values have been diluted through generations of Spanish influence (Zambrano 2023). Bamboo construction, in particular, has been almost exclusively left for those in extreme poverty and rural geographical locations. Due to this association with low quality in Ecuador, market demand is low, and given the abundant supply capabilities, the market is saturated. Many farmers have forgone bamboo all together and transitioned to crops with more predictable supply chains. What this all boils down to is not a problem of supply and demand, but of infrastructure. Ecuador lacks an organized bamboo industry, which can't benefit from economies of scale, and therefore can't compete with China's prices (Hornaday 2022). In order to globally compete, Ecuador's goals are to establish increased U.S. investment and purchasing, and to educate the importance of bamboo within the domestic industry.

Given the state of the bamboo industry, much of the affordable housing projects, many in urban outskirts, are constructed with reinforced concrete or CMU. Advantages of masonry construction in Ecuador are standardization of the building units, fire performance, and cheaper labor. Masonry skills are more widely understood, whereas bamboo building skills are more of a specialty. Some disadvantages are that masonry construction doesn't adapt to hot and humid climates very well, and therefore provides minimal thermal comfort to inhabitants without the installation of mechanical ventilation (Hernández et al. 2019). Additionally, concrete and cement contain high embodied energy and are non-renewable, making them materials that should be used only where necessary for performance, given the global climate. An example of an affordable housing neighborhood project in Quito is presented in Figure 10. This particular project was done in collaboration with USAID, as well as other private and public domestic organizations, in hopes to install change across many facets of infrastructure. One notable developmental decision made was the reduction of lot sizes, which resulted in an additional 2,000 homes being built. This decision has the benefit of providing more people with housing, but also sacrifices standards for housing and infrastructure through densification (Vidal & Goyes 2016). Neighborhoods like this have become commonplace in the country's large urban centers.

Figure 10. Urban Housing. *(top left)* The Solanda Housing Project, Quito, Ecuador (Vidal & Goyes 2015). *(top right and bottom)* Hillside communities outside of Quito (Photo Credits: Jonas Hauptman).

In more rural regions towards the coast, informal bamboo and CMU construction is the common method for affordable housing. Informal structures refer to those built by the residents, typically people without any education or training regarding building, engineering, or architecture. They simply can't afford anything professionally built, doing so themselves out of sheer necessity. This concept of informal architecture is actually similar to vernacular architecture, since embedded in the meaning of vernacular architecture is the fact that qualifying structures are not built with architects or designers, just craftspeople and or experts of a given material and methodology. The presence of material expertise is not always common in modern times, however. This, coupled with the fact that building codes in rural regions, and with bamboo construction in particular, isn't always firmly enforced, can make these homes and shelters dangerous for inhabitants. Figures 11 and 12 shows opposite ends of this idea. The bottom right image of Figure 11 shows the improper side, an elevated timber, bamboo, and brick house that benefits from the lack of building regulations because it was able to be built without interference or questioning. Figure 12 shows the more positive side, a bamboo hostel at Los Arboleros Farm built by professional bamboo architects and builders, and showcases bamboo's ornamental visual capabilities. Also, displayed in Figure 11 are more examples of rural and small-town bamboo homes. The difference between proper and improper bamboo design methods is apparent in the visual quality of each home. The top left house has large overhangs, is slightly elevated from the ground, and has treated esterilla sheathing. Compare this to the elevated, but insufficient overhang and non-treated sheathing homes of the bottom row. While likely older than the first example, the bamboo has weathered to a greyish tone due to UV and moisture exposure. The middle house features a light cement finish, which has even begun to crumble away from UV and improper application. The top right example sits completely flush with the soil. While it looks to be withstanding the weather conditions well, most likely due to proper overhang length, it is only a matter of time before the bamboo within 1-foot of the ground begins to decay. As mentioned previously, despite improper design, many examples of bamboo homes such as these will still last up to 100 years. As will be discussed in the next section, a national Ecuadorian bamboo code has been implemented since the devastating earthquake of 2016, although the event also highlighted some of the benefits of straying from the proper due process in disaster times.

Figure 11. Rural Housing.


Figure 12. RFI headquarters at Los Arboleros Farm.

2.3.5. 2016 Earthquake and Relief Strategies

In 2016, a magnitude 7.8 earthquake destroyed 35,000 homes along the Pacific coast of Ecuador, leaving more than 140,000 people without permanent housing (Witte 2019). Several industries, economies, and communities still have yet to fully recover from this event, seven years later. Despite the tragic nature of this event, it was also an important moment in Ecuador's history for bamboo. After the events of the earthquake, it was immediately observed how well existing bamboo homes performed. Then, as communities began to rebuild, bamboo was the only material that was readily available to provide shelter at a large-scale. Ultimately, this event led to a reevaluation of bamboo and the creation of an Ecuadorian bamboo building code. Universities and industries began taking initiatives to tackle challenges within bamboo construction methodology, and the leaders of this effort continue to rebrand and reutilize the stigmatized material (Witte 2019).

In their rebuild efforts, the Ecuadorian government, global NGO's and non-profits, and local companies and communities alike employed many strategies. The government was heavily focused on a top-down approach for resettlements, part of a larger plan including subsidies for in-situ reconstruction (Testori et al. 2021). This method went against much of the advice from international cooperation and academia, and has been criticized by many Ecuadorians. While many groups stagnated in the due process of redevelopment, other groups, like RFI, and communities simply just started building back. Ultimately, this method was not scrutinized by the government because quick progress was being made at providing shelter. RFI, in collaboration with many architects, bamboo farmers and maestros, and local organizations played a huge role for the coastal Manabí Province. An example of the destruction caused to masonry homes by the earthquake is presented in Figure 13a, accompanied by a permanent bamboo relief home they built for a local woman in Figure 13b. The house in Figure 13b is a bahareque style bamboo home, and is an influence for the alternative housing system model used in the comparative cost analysis.

Figure 13. 2016 Earthquake in the Manabí Province. (a) Destruction to masonry home. (b) RFI bamboo relief home.

Figure 14. Shigeru Ban Temporary Structure, Philippines.

In contrast to RFI's permanent approach to housing solutions, many groups were focused on the short-term, temporary need. One example of this approach was the work of Etex company, Skinco Colombia, and local authorities. Working together to raise money, Skinco donated 120 of their Moduplak modular housing packs, which consist of a wood frame, corrugated fiber cement roofing and fiber cement board sheathing. While this is commendable charitable work, they don't utilize their countries most abundant and renewable resource. Section 2.4 gives more background on lightly modified bamboo, which could provide opportunities for a modular pack design like this to exchange the wood frame for one of bamboo

Outside of Ecuador, there are countless global methods for relief housing. One notable architect who has been involved with such designs since the turn of the century is Shigeru Ban. His relief dwellings are most notable for their usage of recycled, reused, and/or refurbished materials. Cardboard, bamboo, bricks collected from destroyed buildings, plastic crates, and shipping containers are just some of the materials and products Ban has incorporated into his designs. He also swings back and forth between temporary relief structures and their permanent counterparts, adapting to the unique needs of the different communities he is serving. Ban's structures that incorporate bamboo typically do so with splits or woven strips for permeable wall sheathing, and these dwellings fall into the category of temporary. Figure 14 shows an example of one of his bamboo and paper temporary relief dwellings in the Philippines, with the resourceful use of plastic crates for a foundation.

2.4. LIGHTLY MODIFIED BAMBOO

As previously mentioned, LMB was first coined in literature by Trujillo et al. 2013. While initially introduced with much broader meaning, this section will focus on the specific research that has been explored and developed at Virginia Tech for the past 5 years. Hauptman et al. 2023 outlined much of the current strategy being utilized to achieve light modification, specifically parallel facing, for use in composites such as cross-laminated floor and walls panels, laminated beams, and laminated columns. The methodology and underlying logic is relevant to the technologies and designs explored in this thesis.

The goal of lightly modifying bamboo from this perspective is to create standardized building products with bamboo, and do so in a way that preserves biomass, mechanical properties, and morphology. In other words, obtaining standardization via low waste processing and alteration of the bamboo that not only maintains but utilizes its inherent biological structure and correlated mechanical strengths. The current answer to these parameters is a parallel faced culm, as shown in Figure 15a. This method provides two glue surfaces for compositing while retaining as much cross-sectional area as possible and keeping all nodes intact. Hauptman et al. 2019 performed a study comparing the bending moments of *dendrocalamus strictus* culms with differing cross-sectional profiles (different amounts of modification). The study concluded that while removing material from the cross-section did reduce the strength of the pole, the faced samples maintained strength properties comparable to standard structural members in wood and steel. It was further concluded that the parallel two-faces profile was the right balance between adequate bending strength and faces for compositing. The drawback is that these elemental shapes cannot provide lamination between a single layer, displayed in Figure 15b. Despite this, the authors believe total composite action can still be obtained with the right adhesives and secondary connections.

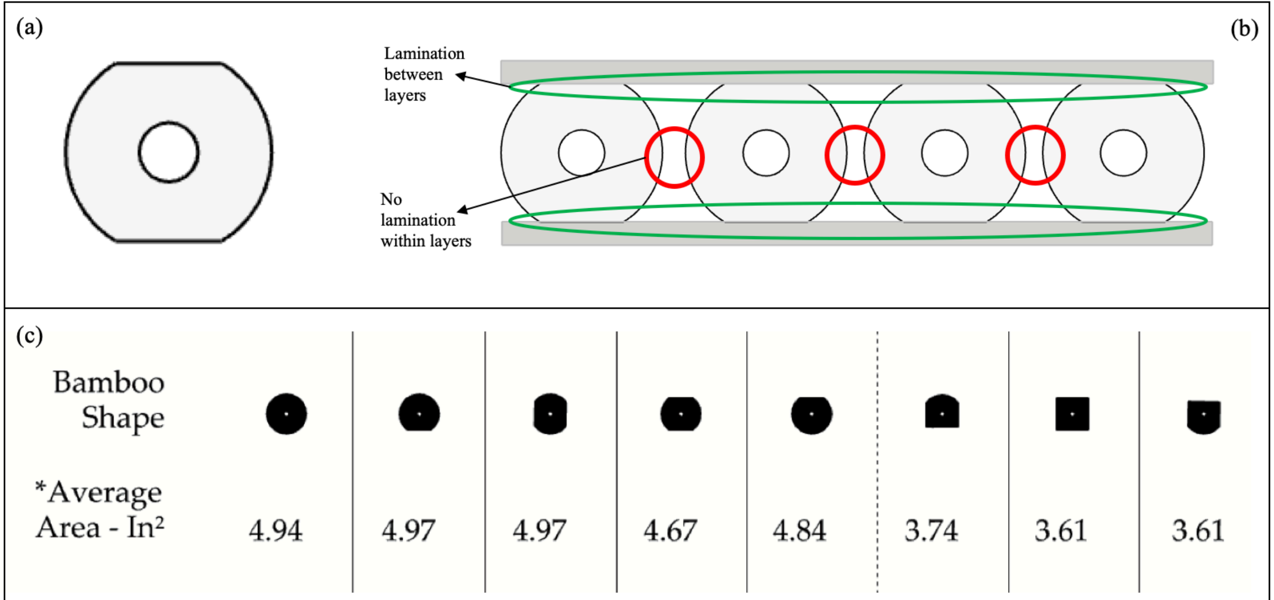
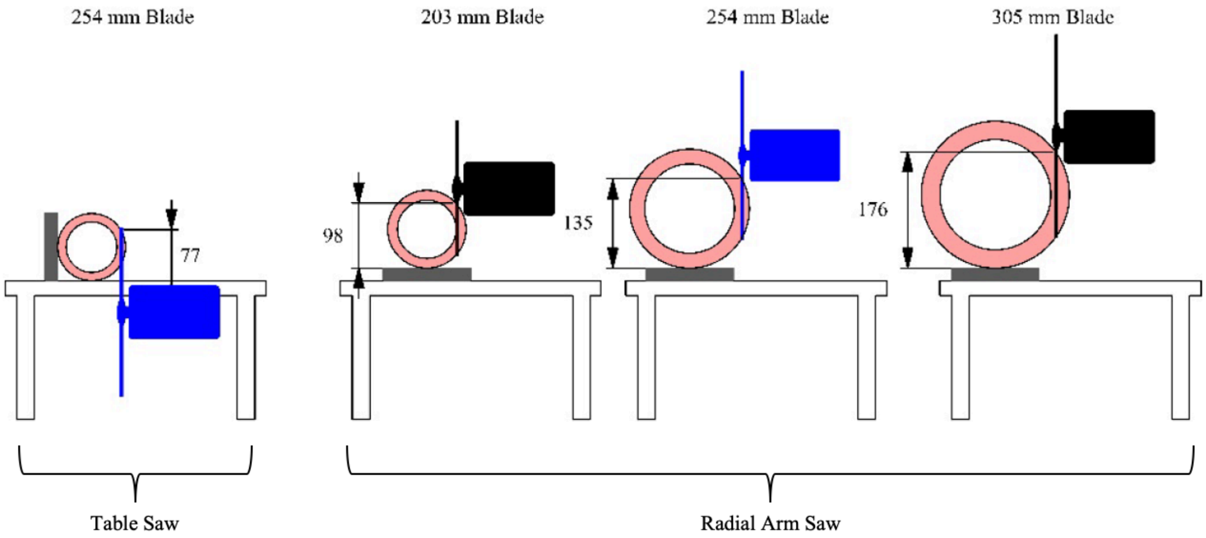


Figure 15. Lightly Modified Bamboo. (a) Parallel faced culm. (b) Laminations within cross-laminated panel composite. (c) Samples with differing modifications from Hauptman et al. 2019.

Before processing, Hauptman et al. 2023 suggest a series of "binning" steps, a methodology of organizing bamboo from one species based on diameter and wall thickness. Each bin is then designated a final part depth, assigning each final depth to a certain structural element. For example, the bottom of each culm will result in the thickest final parts, each of which would be assigned to a particular layer of a panel. The top of each culm, due to taper, will result in the thinnest final part, and may be used in a laminated beam. Ultimately, this minimizes waste and utilizes every part of a harvested culm length that would be discarded in traditional full-culm construction.

In order to obtain two parallel faces on a bamboo culm, Hauptman et al. 2023 suggest a radial arm saw (RAS). This once mainstream saw is versatile, capable of ripping, cross-cutting, mitering, and many more operations. Figure 16 shows the advantage the RAS has over a table saw in terms of its ability to cut larger species of bamboo in one pass. In addition, it has advantages in the categories of speed, cost, and capacity.

Figure 16. Comparison between table saw and RAS cutting depth capacity. Hauptman et al. 2023.



3. METHODOLGY

The methods utilized in this thesis are mixed of both qualitative and quantitative strategies. The specific methodology steps are listed below:

1. *Ecuador: Applied Product and Process Design.* On-site technical development of lightly modified bamboo processing is explored at Regeneration Field Institute (RFI) in Ricuarte, Chone, Ecuador. Three 1 m x 4.5 m, *dendrocalamus asper,* cross-laminated composite floor panels are manufactured for a small bamboo structure to examine on-site production feasibility and cultural reaction to the products.

2. *Physical Prototyping.* Structural members, parts of members, and joints from the house designs are fabricated and analyzed to determine feasibility and efficiency of the materials and processes involved. Performed at the Research and Demonstration Facility at Virginia Tech.

3. *Mechanical Testing.* Three-point and four-point bend testing is applied to calculate performance data (MOE and MOR) of glue-laminated beams, a bamboo truss, and cross-laminated panels. The data is then used to inform structural design choices. Performed at the Brooks Forest Products Center at Virginia Tech.

4. *Case Study House Design.* Using the background research on Ecuador and lightly modified bamboo, as well as data and results from the other methods, an elevated single story bamboo home is designed to demonstrate the system's aesthetic and technical attributes within a cultural context.

5. *Comparative Cost Analysis.* The Ecuadorian house design is cost compared with a permanent bamboo relief home of equal area. Cost data can further display the realistic chances for adoption of this bamboo house system in Ecuador.

Methods 1-3, and 5 will serve as a feedback loop to improve the case study house design from initial ideation to a robust plan that considers the plantation growth and harvest, product manufacturing, labor, structural integrity, economics, and culture.

4. RESULTS AND DISCUSSION

4.1. ECUADOR: APPLIED PRODUCT AND PROCESS DESIGN

The goals of the field development in Ecuador were 1) test feasibility of on-site lightly modified manufacturing methods, 2) fabricate composite cross-laminated panels for use in a floor system, and 3) design and build a small structure that utilizes the floor panels.

The processing set up was based on methodology from Hauptman et al. 2023, with the primary step of parallel facing via radial arm saw (RAS). For the full procedure for pole sorting and ripping to achieve light modification, refer to Hauptman et al. 2023. This procedure can be thought of as the basic building block for what could be taught to local factory workers.

Unfortunately for this test, the U.S. bought RAS, in addition to many other smaller tools, encountered shipping problems and did not make it on location in Ecuador. Given the situation, other power tool alternatives were considered, and ultimately chosen for the operation was a table saw that belonged to a local wood craftsman (maestro). Thinking back to Figure 16, the table saw presents challenges to achieving a full cut depth for larger diameter species, a solution to which was needed. Despite this challenge, the circumstances became an opportunity to examine lightly modifying without the proper prescribed tool setup. Additionally, due to a lack of Guadua supply (of diameter >10cm) on short notice, and RFI having already ordered about 20 culms of *dendrocalamus asper* ("Asper" for short), the Asper was used for these panels. Asper has similar mechanical properties to Guadua, and differs slightly in morphology, with Asper having a larger diameter range and slightly thicker walls. Since this analysis is regarding processing methods and a proof of concept structure, the small difference between the species is not relevant to making conclusions. The conclusions drawn here can be combined with understanding from Guadua processing performed in Blacksburg, which is analyzed in the next section.

Four panels were fabricated in total; one 1m x 2m test panel, and three 1.5m x 4.5m for the final structure. All of the panels have the same layout consisting of a core layer running longitudinal to the long panel axis, and two exterior latilla layers at opposing 22.5 degree angles. The test panel served to answer questions concerning the table saw ripping method effectiveness, glue reliability, and panel pressing method.

The test panel, shown in Figure 19, proved successful enough to continue with the full-scale iterations. Several adaptions to the original process were needed to get to this conclusion. First, in order to maximize the cut capacity of the table saw, a 40cm blade was used and set at the maximum upwards travel. This provided about 15cm of cutting depth capacity, considering the arbor nut prevents the blade from lifting exactly halfway above the table saw throat plate. Additionally, a low-profile plywood channel was used for work holding. With both factors accounted for, the final cut depth capacity was about 13cm. Figure 17 shows the range of bamboo diameters these parameters allowed for proper ripping, as well as a section view of the bamboo holding jig. Given the Asper stock available, it was determined that a final faced pole width of 11cm would allow utilization of majority of the stock, therefore the holding channel was made 11cm wide. This channel was fed into a track set up on the table saw so that the edge of the jig would sit right up against the blade. One side of the pole would be ripped, the jig flipped, and then other side. Although Figure 17 shows the allowable diameter range being 11.4cm to 12.7cm, upwards of 14cm still worked in terms of blade height, but would cut through the culm wall. Further studies are needed to determine the performance effects of cutting through the wall, but it is reasonable to assume that for use in composites it may be negligible. If true, the binning and ripping process would become less tedious and allow for a larger diameter range to be incorporated into any particular product, meaning less waste. Given this thought, the actual allowable diameter range is about 11.4cm to 14cm. Diameters above 14 encounter issues with blade height and not completing the cut, and diameters below 11.4 receive insufficient faces or none at all. Figure 18 shows a picture of the on-site ripping setup. Once the ripping was completed, a hand planer removed any kerf left by the saw for a flush glue surface. This was done evenly to all of the core layer poles to keep a consistent thickness, slightly under 11cm.

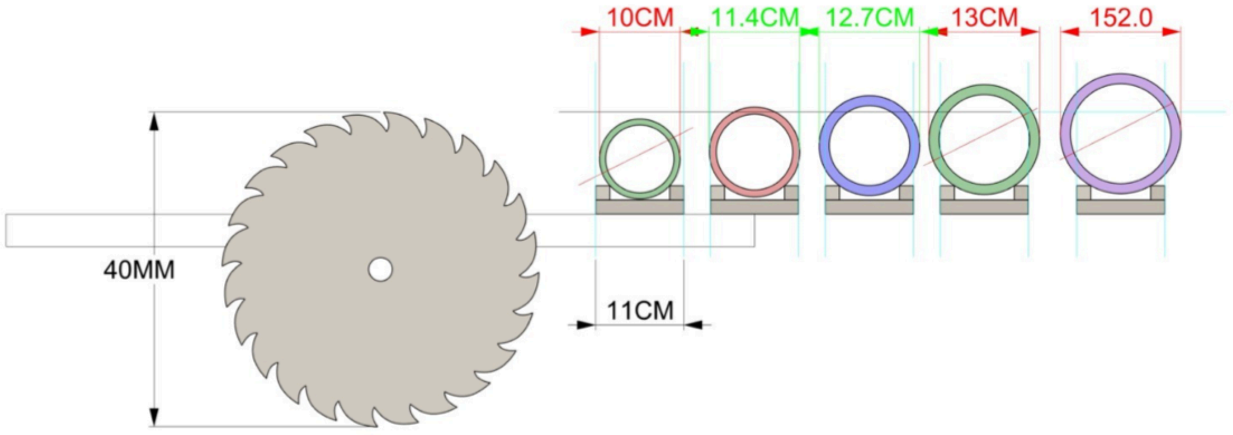


Figure 17. Diameter range for successful parallel facing with given parameters.

Figure 18. Ripping Setup.

Next, the latillas were produced using common methods stated previously in the Background section. While the methods are somewhat commonplace in bamboo countries, it was a new hands-on experience for the researchers, having fabricated Guadua latillas just once, using much different methods. Before beginning the fabrication, culms were selected based solely on sufficient wall thickness (>1cm). Diameter was not a factor. First, the round culms would be ripped into strips with the table saw, as seen in Figure 20. The blade would be set at a height just tall enough to go through the wall and into a portion of the node diaphragm. On average, each culm produced six 10cm wide strips. With a small portion of the nodes still intact, the strips would be separated and the large chunks of node sliced off with a machete. Once the strip was as smooth as possible on the interior, concave side, this side would be placed against the table saw fence and fed through the saw. The goal of this was to remove just the node bumps from the exterior side, so when the interior was ripped to the final thickness, the strip would feed smoothly and produce an equal thickness along the length. Therefore, the last step was to rip the interior to a final latilla thickness of 8mm. Given a limited time frame, the focus of latilla processing was speed over quality, unlike the core elements. The final thicknesses of the several hundred latillas produced ranged from 6mm to 10mm. This was also due to a table saw not being the best tool for this job, and the limited work holding options available. A planer would give this operation more reliable results and allow many strips to be processed in a single pass. Regardless, due to the nature of the final structure, an inconsistent lathe layer was okay, and provided considerations for the finished flooring that may not have been realized otherwise. One such consideration for the finished floor was poured concrete on top of burlap fabric.

Figure 19. Panels. (*top left)* 2'x6' test panel. (*top right)* Full-scale 1m x 4.5m panels. (*bottom left)* All three panels installed in structure. (*bottom right) Panels stacked on press mechanism.*

Once all the finished panel elements had been produced, the compositing process began. In previous test panels made at the Research and Demonstration Facility (RDF) at Virginia Tech, Titebond wood glue was the primary adhesive used. Common wood glue, or polyvinyl acetate (PVA), typically fully sets in 24-72 hours under warm and dry conditions. However, in extremely humid conditions, such as coastal Ecuador in June, this timeframe significantly lengthens. This was a major issue due to time constraints, so the test panel was closely examined to determine the PVA's behavior. Alternative adhesives were considered, such as polyurethane-based options which require moisture to cure, but due to limited availability and higher environmental footprint, PVA was used. After being clamped for 24 hours, the test panel was removed. While some of the glue was still wet, the panel held its structure. After sitting in a covered open air space for a week, the PVA had hardened. It's difficult to know if it had attained full strength without mechanically testing, but students successfully jumped on the panel while it was propped-up on supports, providing confidence the final panels would remain intact and continue to set over the next several days to weeks.

Lastly, the panel press used was a simple idea consisting of a hardwood table, threaded rod, and plywood dividers. Shown in Figures 19 and 20, the panel elements were actually fitted around the threaded rods, which were spaced 25 cm on center in four rows along the length of the table. First, the bottom lathe layer was placed. Glue was then applied to one side of the core poles and they were placed on top of the bottom lathe. Next, glue was applied to top of the core poles, and the top lathe layer was placed. A layer of 1-inch foam was placed on top of the whole panel, and the plywood top placed last. Nuts with washers tightened the plywood top down to the table frame. The foam provided an evenly dispersed loading, even more important given the aforementioned disparity in the latilla thicknesses. Once the panel was clamped for at least 24 hours and then removed, the overhanging latillas were trimmed with a circular saw, providing straight edges at the desired panel width.

Once it was understood the full-scale panels would work, this same process incurred again the full-scale. However, at the scale of 1.5m x 4.5m, other considerations were required. In terms of ripping parallel faces, it becomes much more challenging as the bamboo increases in length, primarily due to taper and curvature. Asper, like Guadua, is relatively straight and has minimal taper, relative to most other woody bamboo species. Through trial and error, it was determined 3m was the maximum length that could achieve a consistent face in a single rip. Therefore, the core layer of the 4.5m long poles was segmented together with 3m and 1.5m poles. These two poles were butted together, and the joints were staggered throughout the core layer. Hindered by limited stock, the cumulative 4.5m poles were spaced approximately 30cm on center. In order to close the panel ends, half meter blocking was used between the primary members. Ideally, this floor system would have a core layer that is fully nested together. If spacing is necessary, it should be no more than 12” on center. The full-scale panels were glued together all at once in a stack using the same concept described previously, this time adding plywood and foam dividers between each panel. They were removed after 24 hours, and while they remained intact, the glue was still wet in many places. To be cautious, pin nails were applied with a pneumatic nail gun as a secondary fastener. Once completed, each panel weighed likely around 300lbs. They were moderately easy to transport from the fabrication area up to the structure site with about ten people.

The penultimate structure came to fruition through collaboration with two local Ecuadorian architects, RFI founder Lucas Oshun, RFI’s bamboo maestros, and VT undergraduate students. The concept was an isolated place for bird observation, meditation, sketching, or other calming desires. The site chosen overlooks the vast and diverse forests of Los Arboleros Farm. The

Figure 20. Processes. (*top left)* Installation of panels into the structure. (*top right)* Ripping round culms into strips for lathe. (*middle left)* Panel layout during gluing process. (*middle right)* Glue and top lathe applied to panel. (*bottom)* Panel transportation across the farm.

structure can be divided into two schools of bamboo thought: a traditional bamboo frame and the lightly modified composite floor system. Emphasis was placed on pushing the limits as safely as possible, so a cantilever design was proposed that leads the inhabitant towards the amazing views beyond, while also providing space below for hammocks and other leisurely activities.

The structure, shown in Figure 21, is tied to the ground using Algorrobo (reclaimed from 100-year-old houses destroyed in an earthquake) piles driven one meter below the site grade. Towards the cantilever side the terrain starts to slope down to a steep hill, so longer stumps were used on these two supports. The bamboo columns connected to these footings extend all the way up to the roof. The four spaced culms that make up the hollow column are connected to short blocking culms right above the footings, and these short pieces are what allow for the main structural connection to the footing. These pieces are filled with cement, which holds threaded rod that extends down into the footing, a common traditional detail for pier foundations. Moving upwards, the columns accept two beams into their hollow space, which support the floor panels. These beams, and every other bamboo-to-bamboo joint in the structure, are connected with threaded rod, nuts, and washers. This is also a common detail, and allows compression forces to bear on the outside of the culms. This method is structurally reliable, common practice among bamboo designers and builders, although aesthetically questionable. Nails or screws for whole culm bamboo connections should be used with caution due to bamboo’s tendency to split along the grain, which makes fastener withdrawal and loosening likely over time. Threaded rod connections have to be pre-drilled, which helps reduce splitting. These connections are also what holds the panels in place. Certain latillas were intentionally left out during the glue up so threaded rods could be inserted and the nuts tightened both between panels as well as to the exterior rim beams that extend beyond the cantilever. The type of finish flooring to be installed for this system also dictates whether the panels can be connected to the support beams below in this manner. With the previously suggested concrete floor, connecting to the beams below is allowable, since the threaded rod and nut sitting above the surface of the floor will be poured over. Moving up again, the floor beams are repeated to support the roof structure, and the walls are fitted with triangular supports to resist shear forces. The wall exteriors are cement fiber board and the roof is corrugated metal. Since the entirety of the whole culm frame is not the main focus of this study, it won't be covered in more detail.

Once fully installed, the floor panels had at most 1cm of deflection in the least supported area, halfway between the support beams. While this is still almost 20 times the allowable deflection of a floor system given a certain span according to the IBC, it was difficult to identify the cause between the panels and the support beams, the latter of which were deflecting even more. If rather than a two-culm support beam, perhaps it should be three or four, or should utilize a lightly modified glue-laminated beam. Mechanical beam testing is the future of this work and will be discussed in the next section. Another certain cause for the deflection issue is the core layer spacing, leaving the latillas to span a greater distance without support, giving the perception of added panel deflection. While admittedly not a perfect installation of the composite floor system, the problems are identified and solvable.

Overall, the on-site application of lightly modified processing and product installation proved insightful and encouraging. With the absence of the previously proven tools and equipment, lightly modified products and building systems can still be created and constructed. Given the important underlying goal of making this technology accessible, this experience shows how basic tools may still deliver added benefit to bamboo and the environment just as a state of the art workshop or factory can. More imagery regarding this proof of concept structure can be found in Appendix B.

Figure 21.Structure. *(top left)* Night View. *(top right)* Group of students sitting on the cantilever. *(bottom left)* Side View. *(bottom right)* 1-20 scale model.

Figure 22. Cross-Laminated Composite Panel- Bench Installation (Photo Credit: Tony Lin).

Many physical prototypes including panels, beams, trusses, structures, and connection details have been fabricated using a mix of Vietnamese and South American bamboos from the inventory at the Research and Demonstration Facility at Virginia Tech. These prototypes serve to inform across the areas of structural performance, manufacturing methodology, architectural design, or simply to publicly promote bamboo. Regardless of the end goal, physically prototyping at a 1:1 scale offers invaluable information for material studies. While majority of the prototyping discussed in this section is Vietnamese Tam Vong or Tre Gai, important conclusions can still be made that can then be related to Guadua. Equally important, is to recognize and compare processing methodology and output in this section with the that from the on-site tests in Ecuador.

Figure 22 shows an architectural bench installation designed and built in collaboration with Keith Hack and VT undergraduate students. This prototype served to promote bamboo across the local community and beyond, as well as provided an opportunity to further understand and test panel system connections. Composed of five panels, each has a Tre Gai core layer and Tam Vong lathe layers. The smaller bench panels are 3-layers of intentionally spaced Tam Vong. The installation contains a parallel edge-to-edge connection, 90-degree butt joint, and notch and slot joints for the top panel and benches, respectively. The benches are also supported from beneath with laminated Tam Vong joists and are captured in the slot with a plywood inlay. The most important connection to further examine from this installation is the edge-to-edge connection, which translates directly to floor system designs.

Figure 23 shows two methods that were examined for internally splicing two panels together edge-to-edge. Both methods involve using a metal splice between the panels that is then fastened to each side using through bolts. The first method utilizes a chainsaw mortiser to cut a thin slot into either panel, which then receives a piece of flat bar steel. The second method uses a round splice such as aluminum conduit, steel pipe, wood dowel, or even milled bamboo. These holes can be created using a hole saw and centering jig. For this installation, the hole saw method was used with aluminum conduit, due to perceived higher availability across the globe of aluminum conduit than steel. Internal splicing was also the preferred method, as opposed to external splicing, considering fire safety. External splicing can increase the chances of fire spread from one panel to the next in the early stages of a fire. More testing on internal vs external connections is needed. In addition, more examination is needed into the necessity of panel-to-panel connections in floor systems, rather than just panel to sub-frame connections. Panel-to-panel is perhaps more necessary in wall conditions that lack additional support, which falls outside of the scope of this thesis and house design.

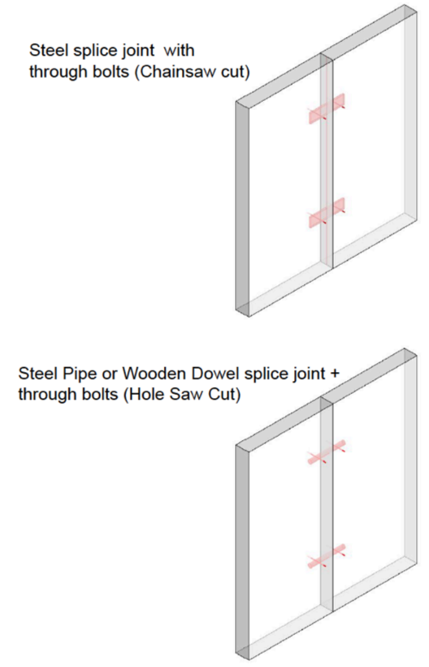


Figure 23. Edge-to-Edge Internal Splices.

A 2’x6’ test panel made of Guadua (core layer and lathe layer) was fabricated as part of a broader catalog of test panels to be tested in 3-point bending for floor applications. Shown in Figure 24, this panel is a good example of a tightly nested core layer, in stark contrast to the Asper panels from Ecuador. Additionally, the latillas were processed much differently. To obtain the initial strips, the culm was split using a hatchet carefully hammered down the grain. Next, groups of 15-20 strips were hot glued to a plywood sheet and fed through a planer as a group. This provides a much more reliable final thickness, although the finish is still inconsistent because the latillas only were planed on one side. The exterior of the strips was intentionally left natural in order to utilize the skin for resisting tension forces in the bottom face. The testing results are discussed in the next section. From a processing perspective, Guadua ripped much smoother than the Vietnamese species. Proportionally to the diameters, it has a much thinner wall than Tam Vong and Tre Gai, which as previously stated, amplifies the effects of curvature on the final face quality. However, over six feet, the Guadua stock was almost perfectly straight, and the final faces were high quality.

Also, displayed in Figure 24 is a Tam Vong lightly modified floor truss and a connection detail between a foundational column and subfloor beam. The truss was developed in conjunction with a study into glue laminated beams (GLB). The beams, which will be discussed more in the next section, are meant to compliment the panel studies with the goal of trying to understand how the two products relate in a single building system. The truss consists of two equal halves that were laminated together. Each half consists of laminated top and bottom plates, and web members that are pocketed into these plates. Each half is laminated with PVA, and the two halves are joined with Liquid Nails expanding construction adhesive and screws. The pockets that the web members sit in were created using hand tools for one half, and a CNC for the other. While the hand tool method was time consuming, it’s a much more accessible means of production than a CNC. However, it presents the question of whether pockets are necessary at all. The top and bottom chords could be planed square, or at least with 3 faces, making connection of the web more straight forward. The main purpose of this truss was to explore bamboo’s possibilities as a modern building material. While bamboo whole culm trusses are commonplace, they have the same drawbacks as the traditional building system. It’s explorations such as this that may have the power to rebrand bamboo.

Lastly, the connection detail displays bamboo's ability to create strong and contemporary joints. Load can pass through the joint via a bearing relationship between the beam and column, and the column can be pre-fabricated with a slot to accept the beam. The column was fabricated by facing the individual poles and laminating each stack of six. The middle stack was made shorter than the outside stacks by a factor of the beam depth. Then the connection faces were planed just enough to get a flat surface on 50% of the face, and the column was then clamped together. The beam underwent similar minimal facing, and then was inserted into the column and held in with threaded rods and nuts. The main concern with this design is trying to fit an irregular beam into multiple slots across long distances, which may likely require some manipulation on site. Because of the connecting rods however, the beam does not have to be form-fitting, and by leaving some tolerance, this problem could be reduced. The extra facing exposed to the exterior can also be problematic when used in unventilated areas in the sub-floor, despite the borate treatment. Additional finishes should be further studied in these applications. Lastly noted, is the incorrect placement of the threaded rod. Having two or more fasteners in a line along the grain can amplify splitting tendencies of the bamboo. Just two connection points in a horizontal line will work sufficiently in this joint, since the main forces are applied to the bearing surface between elements.

Despite many of these prototypes being Vietnamese species, the conclusions of bamboo processing challenges are still relevant. For example, the same connection detail could work very well in Guadua given the species more general uniformity. Similarly, the same truss design in Guadua would result in a 12-inch deep truss, and would be severe overdesign for any small structure, although interesting to explore in multi-story construction. Ultimately, many of the process and system design principles explored in this section influence design choices in the proposed relief structure.

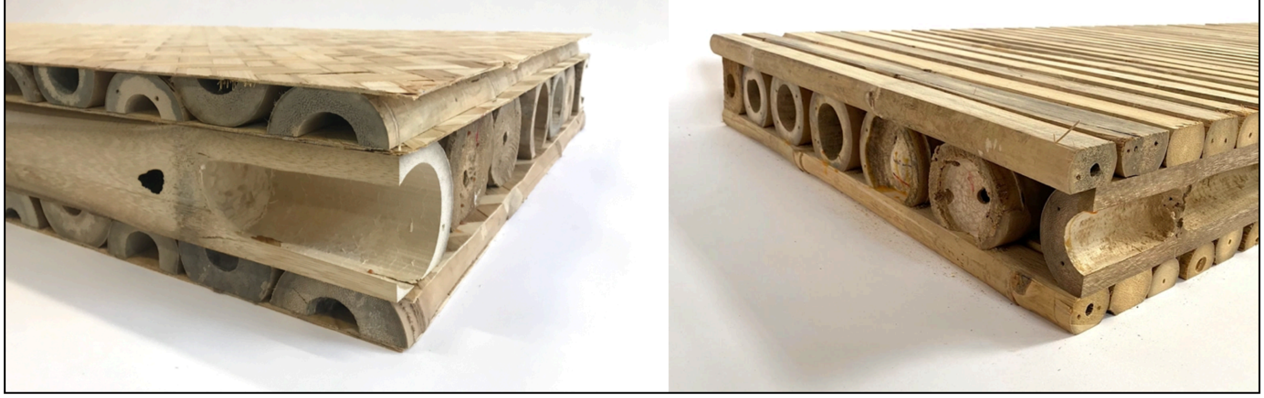
Figure 24. Prototypes from RDF. (*top left) G. angustifolia* 2’x6’ panel. (*top right)* Column to beam connection. (*middle) Dendrocalamus strictus* truss. (*bottom)* Truss side view showing the two halves.

4.3. MECHANICAL TESTING

The primary testing performed for this thesis is 3- and 4-point bend tests for floor elements (panels, beams, and a truss). A supplementary adhesive shear capacity study was also performed. No testing has been performed regarding shear walls.

The first set of prototyping and testing undertaken was for cross-laminated panels. The first samples consisted of three lamination layers of Tre Gai, with each testing different culm alterations and orientations. One example of the first generation of panels is shown in Figure 25, where the lathe layer is split culms and a woven bamboo mat serves as an interlayer for glue contact between each lamination. The other samples from this generation experimented with turning the core and lathe 90-degrees, as well as standing the core upright. The panel shown in Figure 25 performed the best of the three, and it was concluded this was because of the core layer running with the longitudinal axis of the panel, and each pole acted like a beam. Moving forward to the second generation, the core was consistently kept running along the long axis. For these iterations, the woven interlayer was eliminated due to splintering failure during testing and failure to serve its intended purpose as the adhesive substrate. Also, the lathe was converted from split Tre Gai to parallel faced Tam Vong. The two panels of the second generation, one of which is also shown in Figure 25, varied in the lathe layers. One was oriented 90-degrees to the core, and the other had offsetting 45-degree orientations. Between these two, the offsetting 45-degree panel (or 45IB-0TG as shown in Figure 26) performed better in terms of maximum bending load failure and stiffness. Other iterations included in Figure 26 are a Tam Vong-Tre Gai mix panel using an algae adhesive instead of wood glue, and a bamboo stud wall with OSB and gypsum sheathing on opposing sides. The final conclusion from these tests however, was that in a floor panel, the core layer should run with the length of the panel, and the lathe layers should be at opposing 45-degree angles to the core.

Figure 25. Cross-Laminated Test Panels. (*left*) 1st Generation. (*right*) 2nd Generation.



Based on this knowledge, a third-generation panel was fabricated using Guadua, as described in the previous section. Seen in Figure 26 (45SpG-0G), this panel was initially on pace with the strongest and stiffest two panels, but had a total failure at about 9000lbs of load and 1-inch of deflection. The sample deformed so greatly that the testing machine reached its maximum travel of five inches. This failure can be attributed primarily to two factors. First, the edge core poles were mostly cut through the culm wall, and the central node collapsed during failure, hence why the panel deformed so greatly. Unlike Tre Gai, Guadua has a smaller diameter-to-wall thickness ratio, meaning once some of the wall is sacrificed, it is more prone to crushing, especially when load is applied to the weaker orientation of perpendicular to grain. This reinforces the importance of strategically placing the thickest walled and best faced poles on the edges, regardless of species. Secondly, lathe strips on the tension face began to fall off during the testing. The strips showed no signs of bamboo failure, which indicates glue failure. Given the success of the PVA in previous tests, this could indicate poor glue application, or perhaps Guadua's greater resistance to adhesive absorption. Given Guadua's similar density to Tre Gai and lower density than Tam Vong, poor glue application seems a more likely cause. For reference, Guadua has an internode density of 526 g/km^3 , Tre Gai of 570 g/km^3 , and Tam Vong of 643 g/km^3 (Semple et al. 2015, Salzer et al. 2018, Ahmed and Kamke 2005).

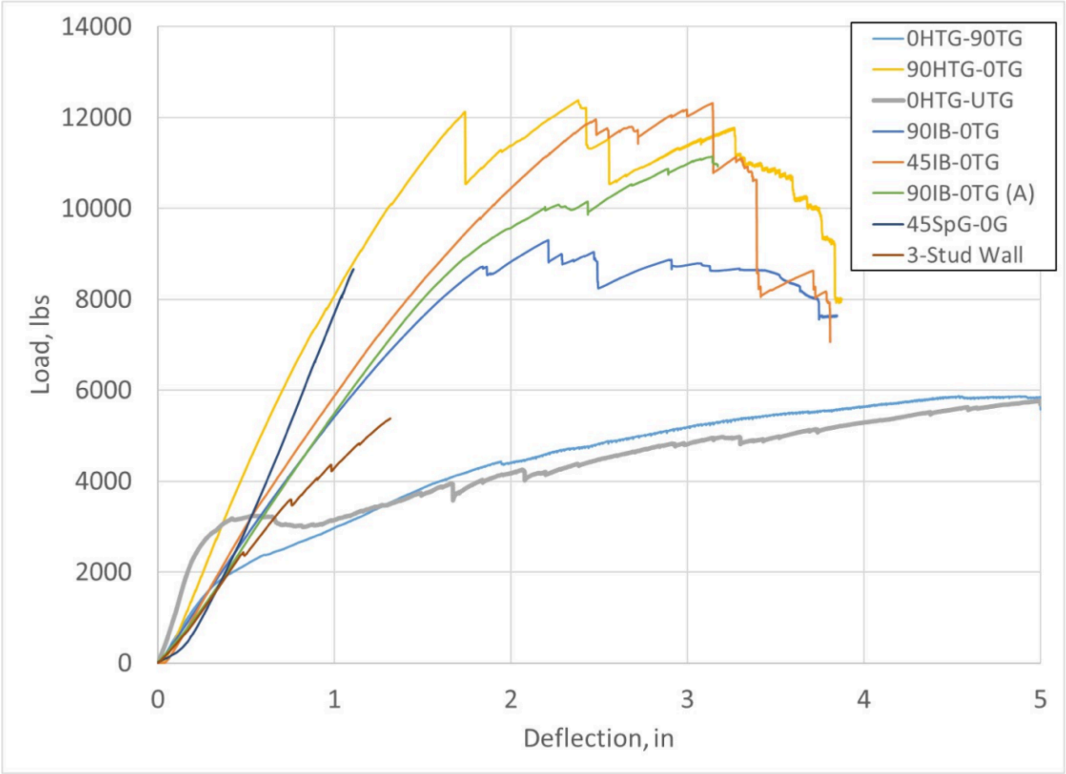
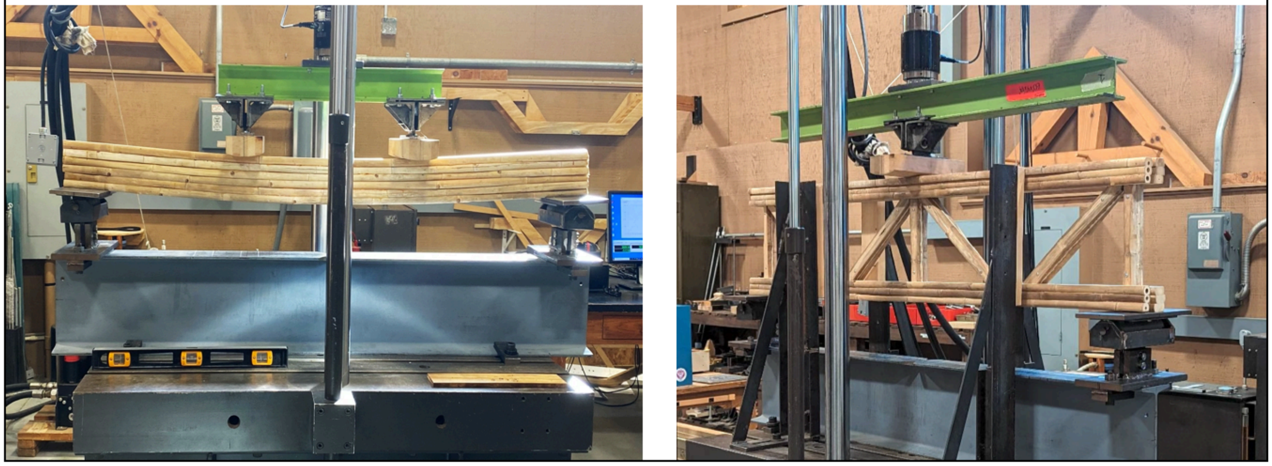


Figure 26. Load-Deflection Curves of 3-Point Bend Tests for Different 2'x6' Cross-Laminated Panels.

In correlation with the panel testing data, the simple span limit of a Guadua CLB panel was calculated for design purposes. Given a 3.5-in final core layer width, and assuming minimal composite action between all three laminations (displayed from testing results), the allowable simple span limit was determined to be 12-ft, or 3.5m. The addition of supports to create continuous spans and increasing beam depth can increase limit, but for the purposes of a single-story home, this limit allows enough flexibility for design considerations. The full calculations are found in Appendix C.

The other branch of mechanical testing for this thesis was laminated beams. To date, only one beam has been tested according to the ISO standard for softwood joists. The beam was 6 layers of lightly modified Tam Vong, pressed together with PVA. The beam is approximately the same dimensions as a 2x6 (actual dimension 1.5” x 5.5”). Although not the intended final comparison, the use of dimensional lumber data provided an easy initial look as to whether these beams were worth pursuing. Like previously mentioned, beams are a clear product to explore as a supplement to the floor panels. The goal is to understand how the two products could possibly work together in the same system, or whether they are distinctly different systems. This sample tested very well, showing the stiffness equivalent to a 2x6 SPF no.2 grade. Stiffness is the limiting factor for floor systems, in bamboo particularly. A single culm is plenty strong enough to carry the average combined live and dead load of 50 psf, as shown in previous single pole testing by the BDRG. However, the allowable deflection limit is a serious design safety concern, and a single culm is too malleable. The stiffness result of the GLB showed the concept was worth pursuing across a large sample size. Currently, a study of beams is in progress, testing a combination of varying beam depths, layer continuity, and connection type in 4-point bending.

Figure 27. Mechanical Testing. *(left)* 4-point bend test on laminated *dendrocalamus strictus* beam. *(right)* 4-point bend test on *dendrocalamus strictus* floor truss.



In addition to the beam, the truss discussed in the previous section was tested in 3-point bending. Ultimately, it failed at 2,100 lbs and 3/8-in of deflection. Equated across the area of the top chord, the truss failed at approximately 2000 psf. This shows adequate structural performance capacity given the standard live and dead design load total of 50 psf. This test has flaws however, given the fact that the truss was primarily made as a fabrication test, not with testing criteria in mind. The main issue is that the ratio between element depth and length doesn't make sense. For a 16" deep truss such as this one, it should be tested at a length of 12-16' to truly simulate a floor system. Additionally, a single-point load is also not an accurate representation of floor loadings. Regardless of these issues, this test shows that a lightly modified truss could potentially have merit. Further exploration is needed to draw accurate mechanical property conclusions.

Lastly, a supplemental experiment was performed to compare three different adhesive's shear capacity on Tam Vong. The three adhesives tested include 2-part epoxy, expanding construction adhesive, and PVA. The study also explored the effects of applied textures on the glue adhesion. The samples, shown in Figure 28, were sheared together using a vice clamp. The distance traveled by the clamp to reach failure was used to make conclusions about the shear strength.

The first part of this study tested a smooth face connection. Each adhesive had three samples. It was decisively clear from these results that Titebond PVA was the best performing adhesive between the three. Interestingly enough, Titebond's manufacturing claim for psi capacity is the lowest of the three. However, given Tam Vong's high density and bamboo's generally thick cell walls in comparison to wood, the low viscosity Titebond was able to penetrate the bamboo better than the others. This was reinforced by the nature of the epoxy and construction adhesive failures, the former of which was too brittle and the latter of which too soft. Only with the PVA was bamboo failure detected, which is a positive sign in an adhesive test.

Figure 28. Test specimens for adhesive shear test. *(left)* 2-part epoxy samples. *(right)* Expanding construction adhesive samples. *(not featured)* PVA wood glue samples.

The second part of this test aimed to answer whether a textured bamboo face would provide different results, particularly for the adhesives that failed to penetrate the bamboo before. Two methods for texturing were used: waffle cuts and drilled holes (see Figure 29). The waffle cuts were about 1/16” deep, and the drilled holes were about 1/8” deep. This test showed that all three adhesives performed similarly with the waffle cut texture as they did with a smooth texture. With the hole texture, the PVA and epoxy both outperformed their previous smooth texture samples. The construction adhesive showed no change in performance with either textures, meaning it was either too viscous to penetrate, or still not hard enough to prevent shear.

Based on these results, it was concluded to never use Liquid Nails expanding construction adhesive as the primary fastener with a dense bamboo. It is allowable to use it for the expanding qualities as long as something else is serving the duties of primary fastener, just as was done with the for the Tam Vong truss. 2-part epoxy can be used with the addition of texture, preferably drilled holes, which will create a mechanical connection to make up for the lack of a chemical connection. However, it is brittle and probably should be avoided in high seismic zones. Lastly, PVA or common wood glue, is the best adhesive for dense bamboo out of these three options. It performs well with a smooth machined face, but will also benefit from the addition of drilled holes as well. Not only this, but PVA is the most globally affordable and accessible adhesive between these three options.

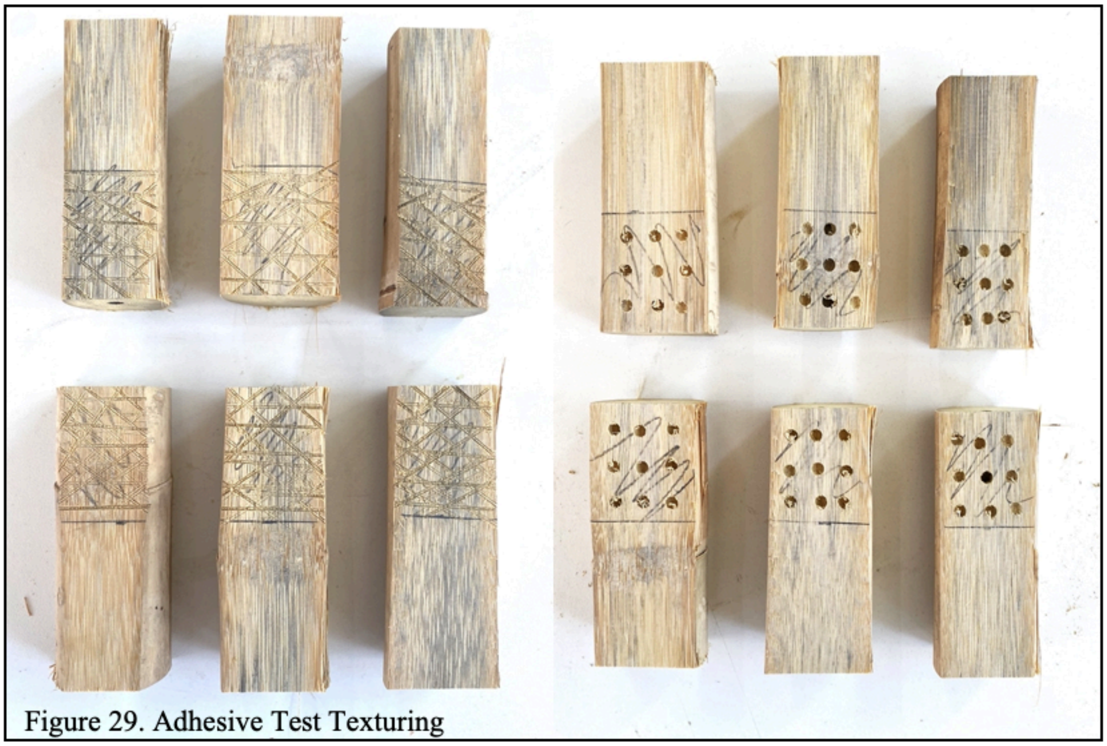


Figure 29. Adhesive Test Texturing

While this testing is limited to floor systems and adhesives, it provides a good basis from which to work from moving forward. Although shear wall testing is an important aspect of further development, it’s much more vital to multi-story construction, not single story relief dwellings. It is arguably more important to understand the abilities and limitations of a floor system that is raised off the ground, such as with the proposed design for this thesis. The walls are lightweight, yet strong enough to carry the roof dead load, and will be able to resist wind shear with the cement board sheathing. Ultimately, this testing provided sufficient design insight, which will be reflected in the next section.

4.4. CASE STUDY HOUSE DESIGN

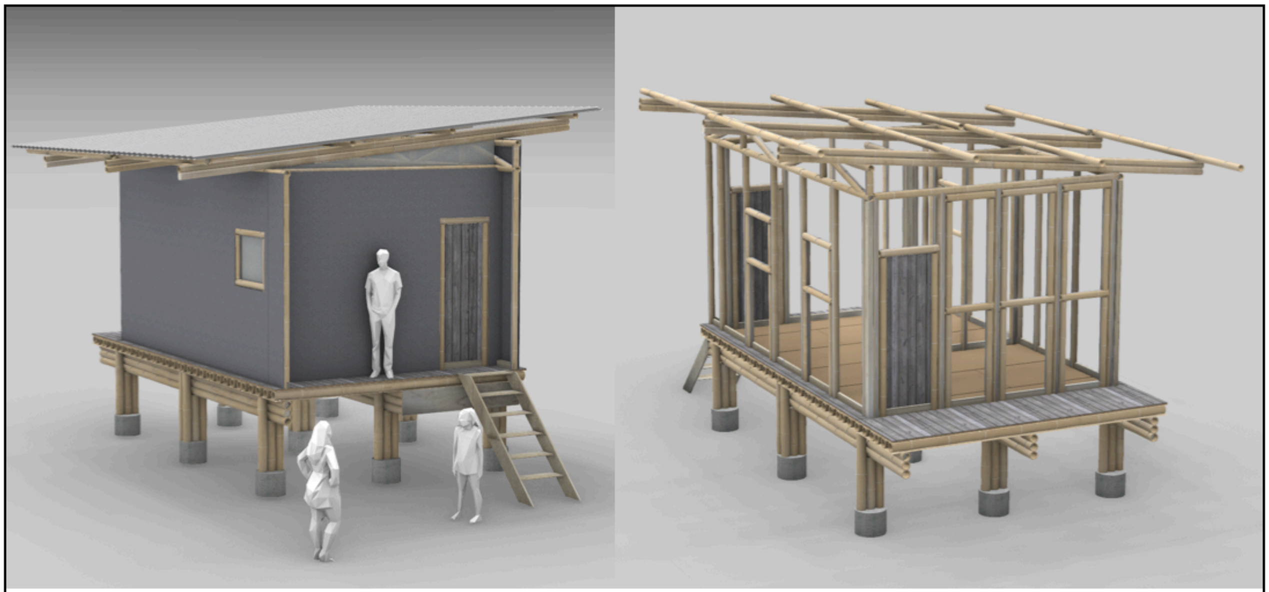


Figure 30. Case Study House Design. (shown both with and without the fiber cement board sheathing)

This section discusses the final house design proposed for bamboo permanent relief housing. The discussion progresses from the foundation to the roof. For the complete list of plans and drawings, refer to Appendix A.

The structure is tied to the ground with nine concrete footings. In total, the footings require just over one cubic meter of concrete. The total height of each footing is one-meter, with about two-thirds of this height buried, leaving about 33 cm, or one foot, above the ground to remove the bamboo columns away from direct soil moisture contact. These footings can be precast or poured on-site, and despite the overarching goal of prefabrication for this project, on-site molds are preferred to minimize additional transportation and labor costs. Off of the footings are glue-laminated stilts or columns, composed of three-pole segments. These columns connect to the footings using a traditional bamboo method consisting of a two-sided j-hook anchoring bolt, which is first cast into the concrete during the footing pouring process. The columns are then placed on top so that the anchor is fed into the hollow center. During the prefabrication process, workers should make sure no nodes are present in the bottom half of these poles, knocking any nodes out if necessary. This is not structurally relevant since this volume will be reinforced with cement in the final joint. Once in place, a hole should be carefully drilled perpendicular to the grain and in line with the j-hook sticking out of the footing. A threaded rod is then fed through the eye of the hook and tightened on either side with a nut and washer. Finally, a hole saw removes about a 2-inch disk of material on the bottom internode, containing the anchor-threaded rod connection, and the hole is used to fill this void with cement. Once filled, the circular cut-off is set back into place. This combination of cement infill and mechanical fasteners ensures a dual line of defense against severe uplift forces. In this design, the two outside poles of each column receive this connection, meaning there are 24 anchor points in total.

At the top of the columns, the middle pole of each group is shorter than the other two by a factor of the beam depth above. This provides a non-subtractive fabrication method for creating a notch for the beams to sit flush with the top of the columns. The beams are bolted together with the columns in the center pole of the three-layer beam. Only one connection is warranted, as more can increase the likelihood of splitting down the length of the columns, and because force transfer is occurring on the bearing surface below the beam. The extensions of the outside column poles simply serve to secure the beam in position, and therefore the threaded rods experience minimal shear or withdrawal forces. The columns in the middle of the structure are doubled up, containing six-pole segments. These columns are fabricated as two separate columns, exactly the same as the other six, and are then bolted together where they meet with round surface. This thicker column is necessary because the floor beam above is actually two beams, and the butt joint between the two occurs in between the doubled column. This provides sufficient bearing length for each beam edge, which would not be possible with a single column. Additionally, the beams are not continuous along the entire length of the structure due to the previously described processing limitation of three meters.

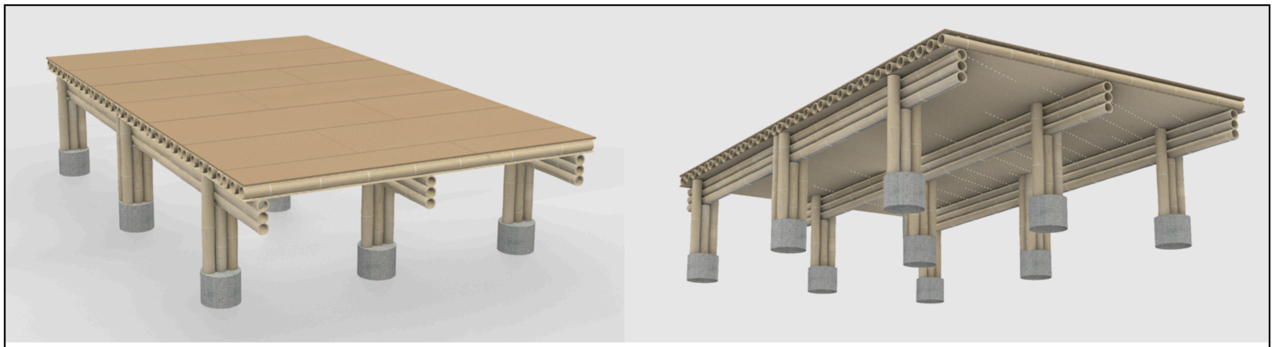


Figure 31. Floor System.

Above the beams, the floor system is composed of the cross-laminated panels, with a parallel faced core layer and two exterior latilla layers at opposing 45-degree angles. The panels run parallel with the short side of the structure, three meters in total. While these panels are capable of spanning this distance from a strength perspective (based on results from the bird observation structure, 3-point bending data, and span calculations), the deflection is still a limiting factor, hence why despite being structural panels, they are not single span. Across the new span of 1.5m, these panels are slightly overdesigned, but very sturdy. The panels are attached to the substructure via threaded rod, which is part of long tie-down connection that goes from the wall knife plate, through the panels, and down to the bottom of the floor beams. It's important that the threaded rod penetrates a core culm in the panels and doesn't fall between. This is simple since the core layers in this design are a tightly nested layout and the core structure is highly visible along the length of the house. This open nature of the panel cross-section is a long-term issue however, creating a habitat likely to attract animals, insects, and moisture. Figure 32 shows the proper finishing methods to completely enclose the ends of each panel. The method includes a cement plaster finish to seal the culms and wood blocking for the in-between spaces. The cement is typically applied after installation, and should really be used on any culm end that is towards the edge of the structure or subject to moisture exposure. The blocking is ideally installed during prefab, and can be glued and nailed in before pressing. In addition, plywood sheets are pressed as the top layer of each panel.

Figure 32. Enclosed panel finishes.

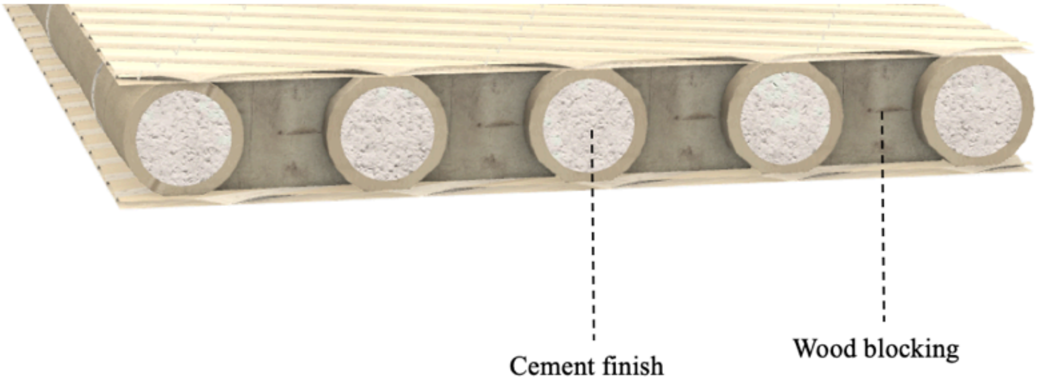


Figure 33 shows the prefab walls both with and without window screens and exterior fiber cement board sheathing. The former of which is the proposed method for pre-fabrication so that on site all that is required of the carpenters and maestros is to stand the walls up and secure the knife plate tie-down. The outside corners are also fixed with a timber 4x4 post, which comes attached to one of the two walls that make up the corner joint. They attach to the bamboo frame via wood screws through the bamboo and into the wood. By fastening the connection in this direction and not vice-versa, the chances of screw withdrawal are much lower.

Every element of the bamboo frame is parallel faced. The faces are oriented directly towards the interior and exterior, creating a flat face for sheathing connections. Flush connections between frame and envelope elements are uncommon in traditional bamboo design, making this system's workability far simpler, and minimizing waste typically associated with filtering straight culms for whole culm stud walls. Around fenestrations the faces are turned towards the openings, again creating the opportunity for a better seal. This does, however, eliminate the ability to glue-laminate connections in the frame, along with the size of each wall module being too large for any affordable glue press. For those reasons, the frame is primarily threaded rod connections. The top plate of the frame sits into the studs with fish mouth joints, and the two elements are tightened with a tie down strap and anchor through bolt. The top plate of the west wall (as detailed in Appendix A) is a truss. The structural purpose of the truss is to create roof pitch, but it also provides a unique aesthetic that contributes to the ideas of innovation and rebranding previously discussed.

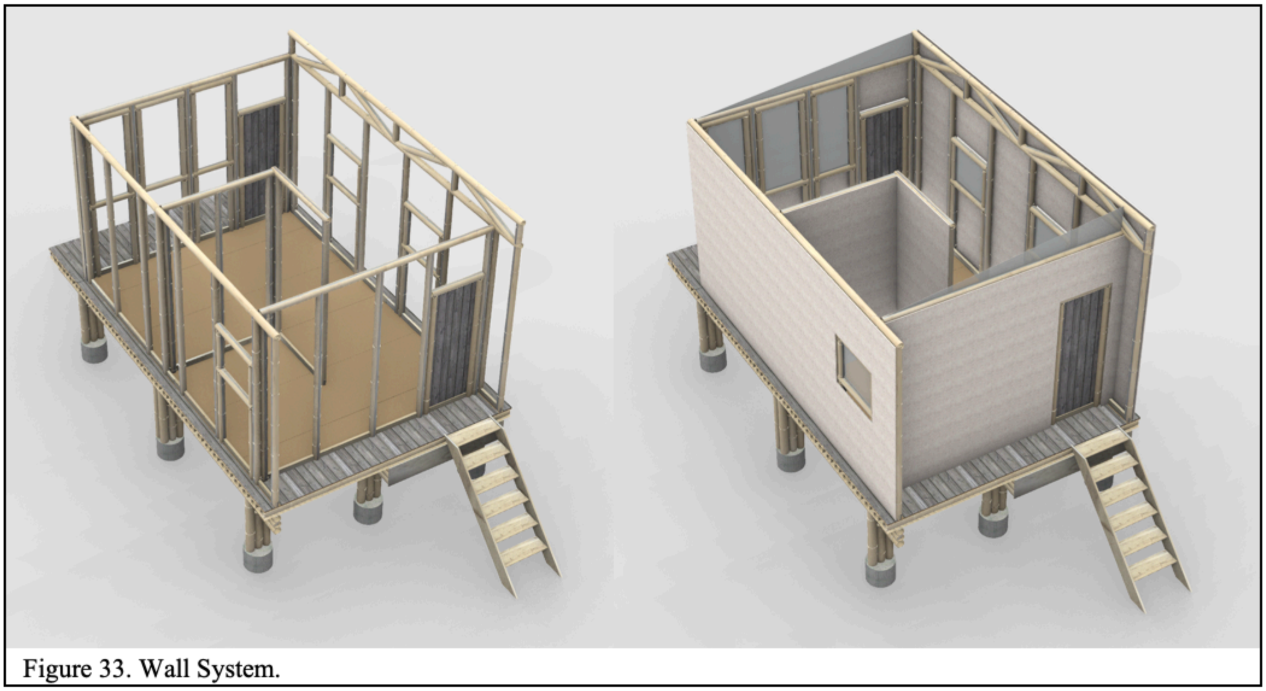
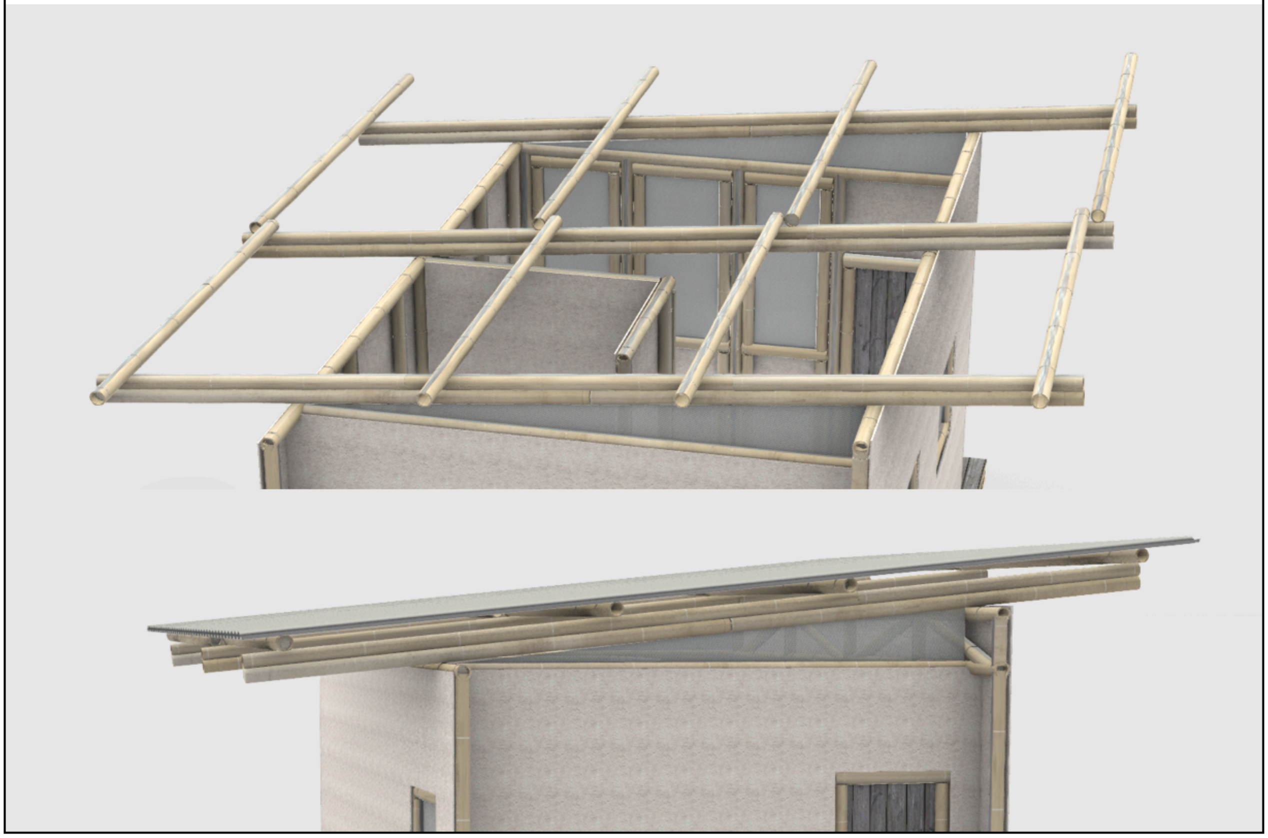


Figure 33. Wall System.

The roof system is rather simple, yet unique in that it is the only element of the design that is not pre-fabricated. This is due to the size of the framing members as well as the importance of proper roof covering installation. The 2-layer laminated rafters shown in Figure 34 will be pressed in a factory, as well as the purlins will be faced. However, installing the corrugated metal roof and then transporting to site as one piece is too large for any flatbed truck, and risks damage. It is crucial to properly install the roof with overlaps that are consistent in one direction and don't leak. This is easier done on site where a carpenter can properly manage and move the materials. Tie-down straps with anchor through bolts are again used to connect the rafters to the wall top plates and/or studs. Threaded rod connections then attach the rafters and purlins. Lastly, the metal roof sheathing sections are attached to the purlins via specialty screws with rubber washers.

Figure 34. Roof Structure.



This design can be viewed as a first generation, and so many aspects can use improvement. From an engineering perspective, it meets the criteria for a safe structure, but potentially is materially inefficient, having an overpoweringly strong floor system for a lightweight wall and roof design. Conversely, the more bamboo that can be stacked into durable building products, the more carbon sequestered, the more the goal of combatting climate change is met. From an interior design perspective, this house is raw, minimal, and truthful. Well-designed, exposed bamboo could help the material's image, or could create undesirable living conditions. This was an intentional design decision, focused on keeping costs and build time low, and provide resident freedom to design their own interior. However, this isn't suitable everywhere. Referring back to the Ecuadorian historical idea of "design of three spaces," fire safety in relation to the kitchen can be brought into question. Ultimately for this design, the floor and walls of the kitchen should have fiber cement board finish, and a partition added as you enter the space. A follow up study into utilities is also an essential next step. The Appendix A layout plan details a compost toilet, shower, sinks, and stove as all essential appliances. Getting up onto the utility grid in rural regions Ecuador can be difficult, so rain water collection and solar lights are resourceful investments. The next steps would be to take this "structure" and turn it into a livable home. It is essential that relief dwelling with the intentions of being permanent doesn't lose sight on the long-term picture.

Other notable limitations and omissions that should be addressed include the following. This design does not account for the common cultural practice of vertical additions, and given this it is not recommended inhabitants do so. The design also does not explicitly show egress means for anyone with disabilities, although it is proposed that a pre-fab ramp is designed for requested circumstances.

Figure 35. CCA Structures

The cost analysis presented compares the proposed LMB prefab building system to a representation of bamboo structures built in response to the 2016 earthquake in Ecuador. The alternative structure is a permanent dwelling, same as the proposed system. Both houses have an area of 25.2m^2 (interior and exterior space combined), and approximately the same interior volume. All calculations for material amount were done using information extracted from the 3-D models shown in Figure 35. Details such as roof overhang length, door and window material, interior partitions, and utilities and appliances have been held constant. This comparison focuses strictly on total material and labor costs affiliated with the principle building elements. Other costs such as transportation and resident personal finishes are difficult to accurately account for without a highly specific one-to-one life cycle assessment. Material and labor cost analysis provides an initial insight into the proposed system's fiscal feasibility.

The alternative structure for this comparison is similar to the bahareque style of bamboo construction described in section 2.2. This method is similar to bahareque because it is built on a concrete slab and encloses the round culm frame with cement mortar. It would most closely resemble the single-skin system, which leaves the frame exposed to the exterior of the building. Often any cross-bracing in the frame will be uniquely applied because of this visibility, as represented in the Figure 35. From a structural perspective, this indicates that the bamboo matrix is attached on the interior of the frame, allowing the cement to be applied from the exterior, between the culms. This leaves a bamboo matrix finish on the interior, which can also be coated with cement or left as is. The roof sheathing is also corrugated metal panels but wood is used for the roof purlins instead of LMB.

Material and Labor Costs

G. angustifolia	**Cost (USD)**
Treated	8.5
Untreated	2.75
Cost for 6m length, 9-13cm diameter	
Additional Materials	**Cost (USD)**
Structural plywood (4'x8'x18mm)	40
Cement Sheets (4'x8'x6mm)	27
Concrete (per m^3)	280
Painted Metal Roofing (1m x 6m)	35
Teak (per bdft)	4
Cement Plaster (per sq. ft.)	3.5
Labor	**Avg. Daily Wage (USD)**
Bamboo Maestro	45
Basic Factory Laborer	25
Mason	32.5
Carpenter/Cabinet Maker	38

Table 1. Material & Labor Cost Per Unit

Lightly Modified Pre-Fab Structure

Material (unit)	***Amount***	***Cost (USD)***
Bamboo (6m treated culms)	32	272
Lumber (BDFT)	370	1480
Plywood Sheets (120cmx240cmx18mm)	9	360
Concrete (m^3)	1.2	336
Cement Sheets (120cmx240cmx6mm)	19	513
Corrugated Metal Roofing (6mx1m)	7	245
Hardware	N/A	300
Window Screens (120cmx300cm roll)	1	20
Miscellaneous	N/A	200
Labor (# of workers)	***Days***	***Cost (USD)***
Factory (4)	6	600
Bamboo Maestro (2)	4	360
Carpenter (1)	4	152
Mason (1)	1	32.5
	Total Cost	**4870.50**

Table 2. Proposed Design Costs

Typical Bamboo Relief Structure

Material (unit)	***Amount***	***Cost (USD)***
Bamboo (6m treated culms)	56	476
Lumber (BDFT)	148	592
Concrete (m^3)	3.3	924
Cement Plaster (ft^2)	500	1750
Corrugated Metal Roofing (6mx1m)	10	350
Hardware	N/A	300
Window Screens (120cmx300cm roll)	1	20
Miscellaneous	N/A	200
Labor (# of workers)	***Days***	***Cost (USD)***
Mason (2)	7	455
Bamboo Maestro (2)	14	1260
Carpenter (1)	3	114
	Total Cost	**6441**

Table 3. Typical Design Costs

The results of the CCA are presented in Tables 2 and 3. Shown is a 1,343.00 USD difference between the structure's material and labor costs, in favor of the proposed LMB prefab system. It was determined the proposed system requires 14 days of labor between fabrication and installation, while the standard system requires 24 days for just on-site build.

The costs and wages in Figure 1 were determined through personal communication with Ecuadorian bamboo maestros, Lucas Oshun from RFI, and an Asper plantation manager from north of Santo Domingo. Guadua costs for construction are always based on 6m lengths, and the price is constant regardless of culm diameter. The difference in price between treated and untreated bamboo is over three-fold due to the cost of borate. Further research should be done to determine potential utilization of untreated bamboo in particular details to reduce costs.

Lumber is a particularly difficult cost to predict due to the lack of a formal industry in Ecuador, even though the material is naturally abundant. The country meets its needs mostly on domestic sources, importing on rare occasions. Many carpenters source their own wood personally, while it is also possible to purchase dimensional lumber in urban centers. Common species naturally found in Ecuador include Balsa, Ipe, Teak, Radiata Pine, Mahogany, White Oak, Red Oak. and Walnut, to name a few. Of these, Radiata Pine and Teak make the most sense for lower grade construction use because of their balance between structural capacities, cost, and visual value. Teak is the proposed species at $4 per linear board foot. Additionally, opportunities for repurposing waste that is abundant during post-natural disasters is difficult to quantify and price, but a highly-recommended method to be resourceful and divert the carbon in that wood from being released back into the atmosphere via burning or landfill.

The factory labor specifications for the proposed design were deduced based on experience fabricating composite bamboo systems. Typically, in a laboratory setting with two people ripping culms, a 2m part would take 2-3 minutes. In a factory setting with one or two dual-blade RASs and 4-5 workers for ripping and loading/unloading bamboo on the work holding jig, this time drops to 30-45 seconds. At that rate, and given the fact that processing lengths would be 3m based on the structure design, the entire bamboo for one house could be processed in a matter of a few hours. The six days specified is primarily tied into glue set time for panels and joint assembly of the wall system. Depending on factory specifics, this timeline could likely be shorter.

In comparing the costs of the structures, it's important to identify critical data contributing a high percentage of costs to the total. In the LM prefab structure, lumber is the most expensive material, due to its extensive use for decking. Even though the case was made for bamboo's superior short-term carbon sequestration advantages over timber, in a use such as decking, bamboo lacks the durable product development technologies of tropical hardwoods. Additionally, to reemphasize, the main objective is displacing concrete, and bamboo and wood both have a role in doing so. In the alternative structure, heavy concrete and cement use hikes up the cost, as does the 2-week timeline for bamboo labor. The high labor cost for traditional bamboo building methods was touched on in the introduction, and noted as a reason for pre-fabrication and standardized bamboo unit necessity. The results here tend to reinforce this idea of lowering costs via transition to factory labor. The promotion of factory labor will also create more accessible jobs for people without expert level bamboo skill. By economically fostering to the communities, local resilience can be improved to help with post-disaster struggles.

Although transportation was intentionally dismissed from the comparison, it is worth noting that prefab bamboo systems contain one extra transportation route once a factory is involved. The overall effect of this truth is unclear however, since locational factors of the plantation, treatment facility, and construction site vary. Additional cost assumptions were made for hardware (ie. threaded rod, nuts, and screws) and a miscellaneous $200 was added for good measure.

While limited by some data points, this CCA shows the proposed design's significant material and labor cost advantage to a traditional bamboo alternative. This holds true under the scope of main structure and envelope material, all utilities and appliances held constant.

5. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

This work contains certain limitations acknowledged by the author, which are discussed here in the same order as the methodology. These limitations directly influence the future of this work.

The applied process design in Ecuador is limited in its desired results by the inability to test the proposed RAS light modification procedure from Hauptman et al 2023. While pivoting to a table saw method provided important conclusions, the proposed method should be tested on-site in a bamboo country for future work.

The physical prototyping and mechanical testing done at Virginia Tech is limited by scale. More members, joints, and full-scale structures should be built and tested to further analyze processing efficiencies and to provide statistically significant mechanical performance results.

The case study design is limited to structural and building envelope components, meaning further work should be done to explore utilities, primarily water and electricity, both for on- and off-grid reliance. Also, a formal qualitative social study regarding cultural livability needs is essential for effective deployment of the proposed system.

The comparative cost analysis is limited by life cycle scope and an incomplete structure outfitting, as described above. A case study life cycle comparison should be performed between these two structures that accounts for exact cost and carbon emission tracking from bamboo harvest through building completion. This study should select specific building, plantation, and factory sites, and cover transportation as well.

As mentioned earlier in this thesis, a large-scale study is currently in progress studying laminated beams for floor systems. Based on the results of this study (expected by the end of 2023), and using the previous studies about cross-laminated floor panels, a determination should be made regarding how these elements should primarily relate- in a single building system or separate. This will further inform the use of lightly modified bamboo at the scale of mid-rise construction, which may be able to act as a housing solution for urban expansion.

Additional specific work that is crucial to moving this research along is the use of wood and bamboo dowels for compositing, and the effect of ripped face area on composite performance.

6. CONCLUSIONS

Explored in this thesis is an alternative method for bamboo relief housing systems; one that has the attributes of longevity and durability, but is also rapidly deployable via light modification and pre-fabrication. In the context of coastal Ecuador, many conclusion can be made.

First, this type of pre-fab system doesn't necessarily require high capital investments for factory space or power tools. Basic tools such as a table saw, hand planer, chisels, and machetes can achieve standardized bamboo products with a high enough degree of fidelity for the intended use. It also has the potential to provide a boost to an otherwise struggling economic market, and potentially alter the mass thinking of bamboo as "poor man's timber."

Lightly modified composites have also shown to be capable of meeting not only structural requirements for 1-2 story housing, but perhaps up to 6-7 mid-rise construction. This could provide opportunities to address healthy housing needs in both rural and urban communities. This system is also cheaper compared to the bahareque style of bamboo building in terms of labor and primary structural material costs, mainly due to the elimination of significant concrete use and more efficient labor solutions.

Perhaps most importantly, is there is a sense of excitement in the Ecuadorian and Latin American bamboo communities regarding innovative solutions to modernize bamboo construction in a sustainable way.

Lastly, shown is the massive potential of woody bamboo in the global south as a key resource in the great environmental confrontations of our time. It sequesters and stores carbon on plantations, through harvest, and into durable building products. It is rapidly renewable, yet a durable and strong material that can meet increasing housing demand in a safe and responsible manner. It can perform well in natural disaster events and also help to prevent their increasing frequency and intensity. It can provide economic resilience and slow the cycle of post-disaster restart. In order to allow bamboo to serve this multitude of services that are so deeply needed in our time, we, as humans, and specifically those of us in bamboo countries, need to grow, harvest, design, build, and teach bamboo responsibly and true to the naturally eccentric material it is.

The design proposed in this thesis is the most thorough exploration of lightly modified bamboo at the scale of single-story housing to-date. Considerations of agriculture, culture, history, manufacturing, engineering, material science, environmental science, and economics have all been accounted for to some extent in the final product and architectural designs. Mixed methodologies of in-country process deployment, physical prototyping, mechanical testing, and comparative cost analyses have been employed along with extensive background research into the project context, providing a cumulative look into the criteria for realistic deployment of permanent bamboo disaster relief housing. Still, this thesis can be viewed as just the start of research and projects with much greater capacity for significant real-world impact.

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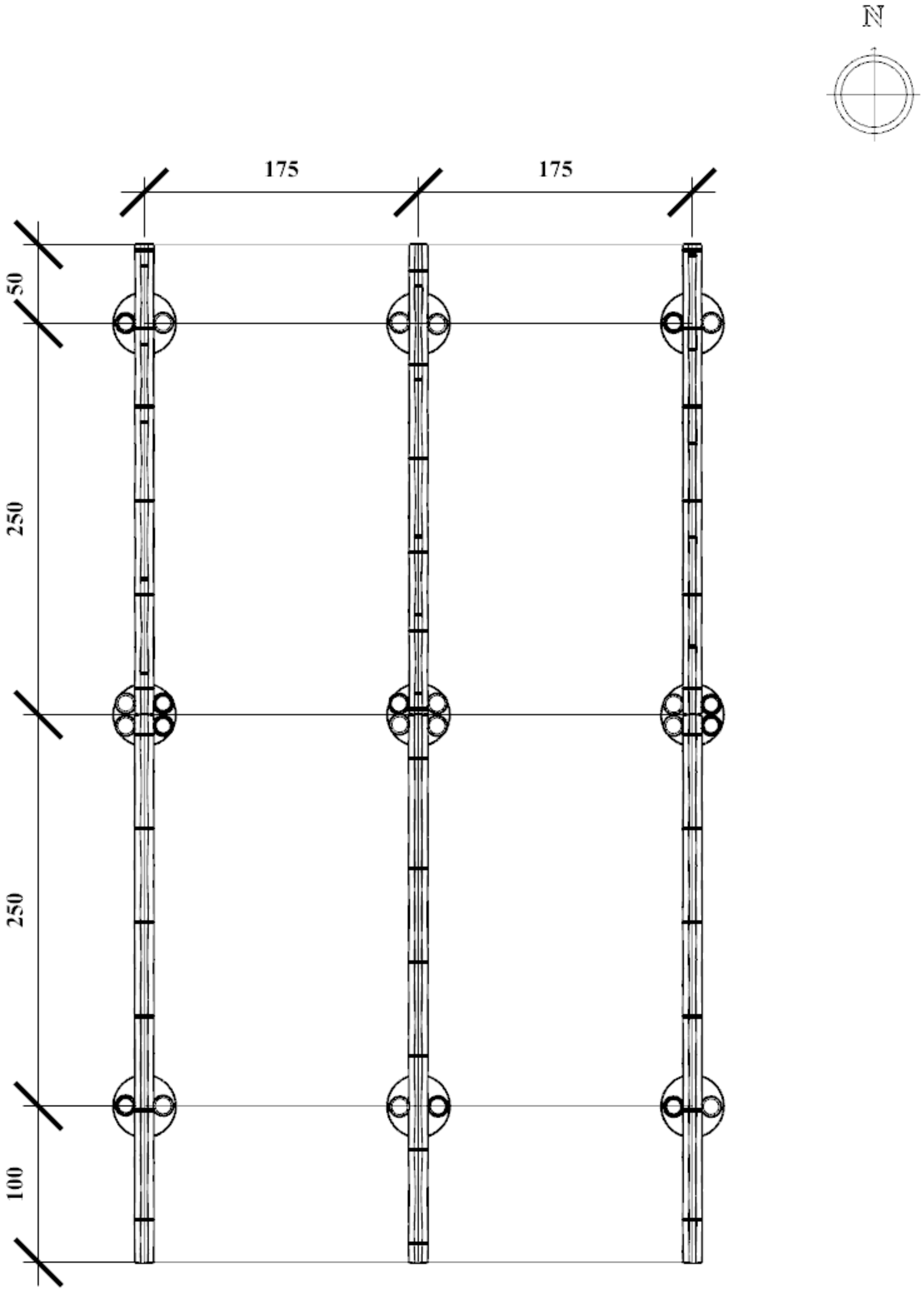
APPENDIX A

DESIGN BOOKLET

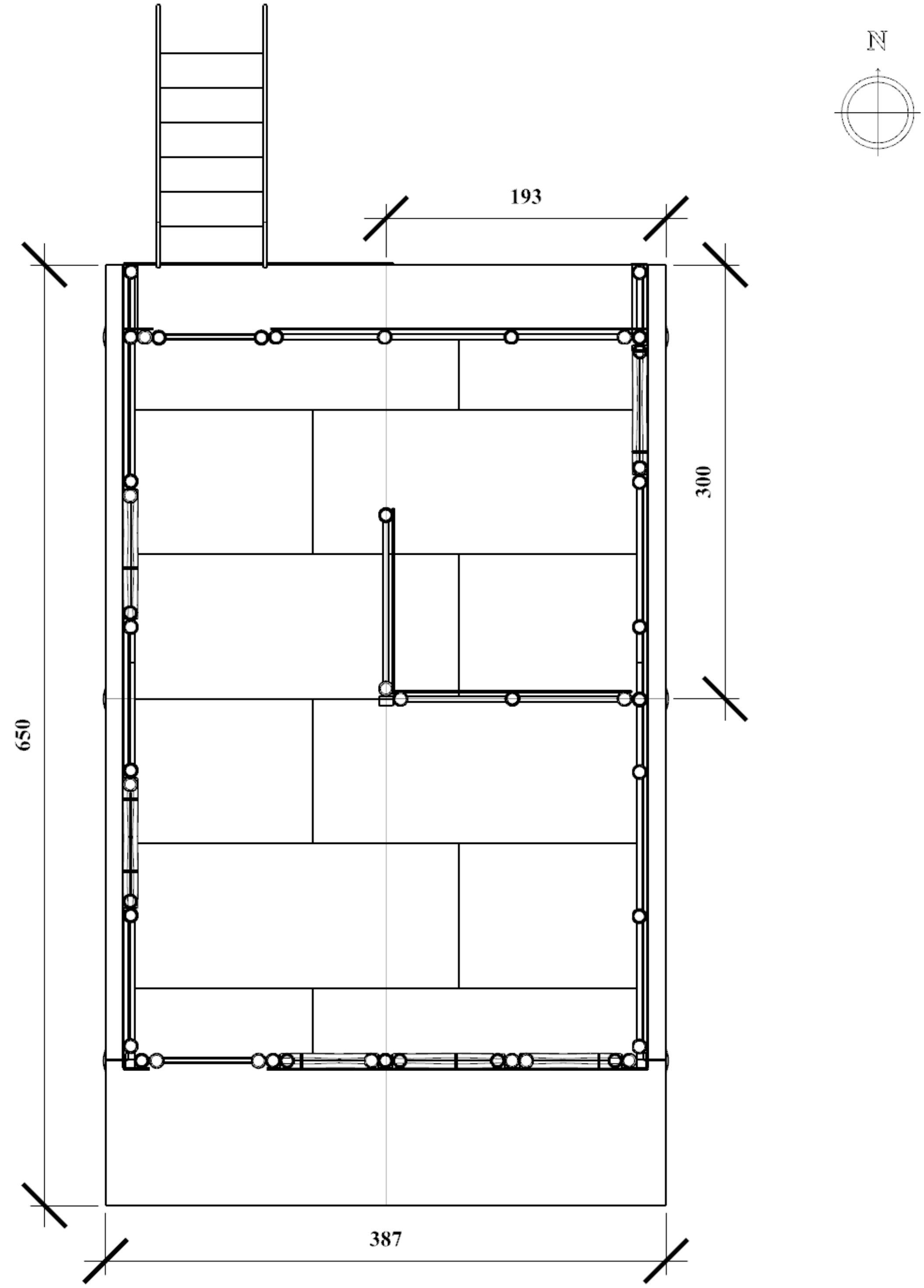
This Appendix features all additional output relating to the proposed LMB design for a pre-fabricated relief dwelling in Ecuador. It is broken into five categories: Renders, Plans/Sections/Elevations, Pre-Fabrication, Structural Details, and Community Plan. Visual representations and brief analyses are contained.

a. Renders

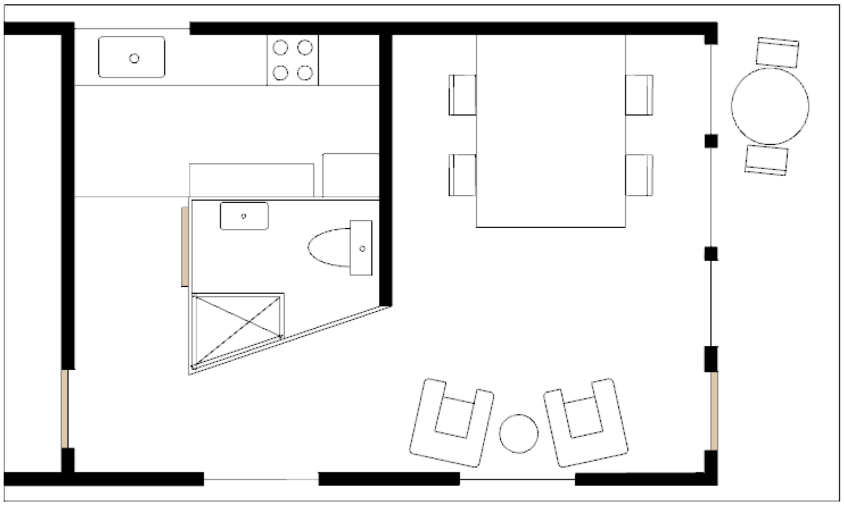
b. Plans, Sections, and Elevations

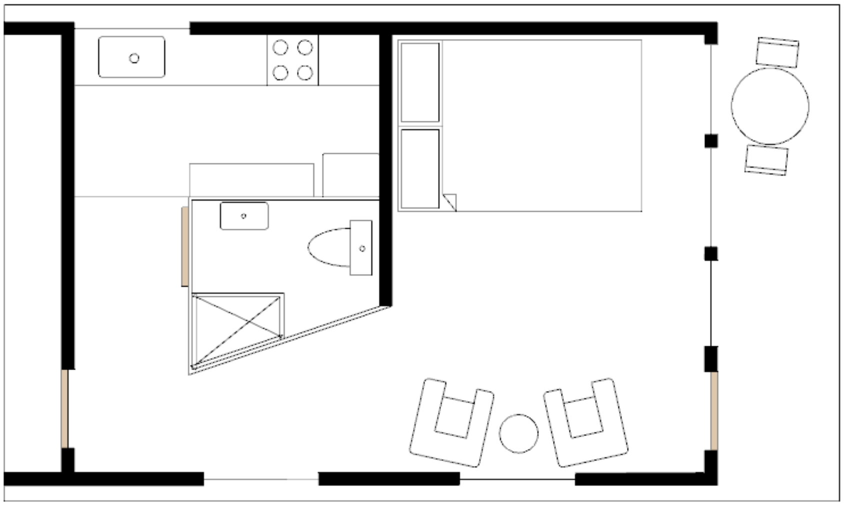


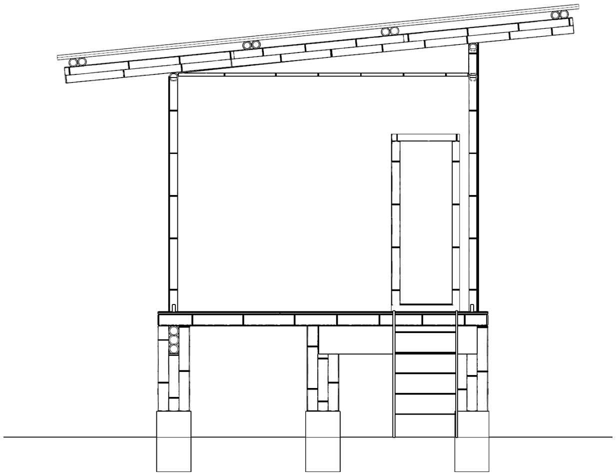
Sub-Structure Plan



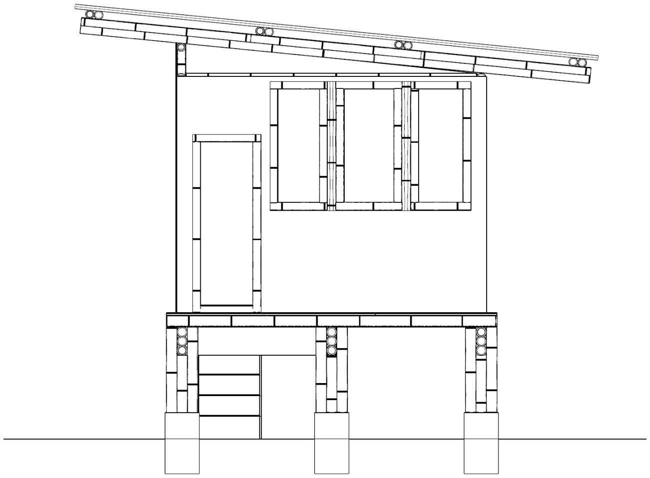
Main Structure Plan



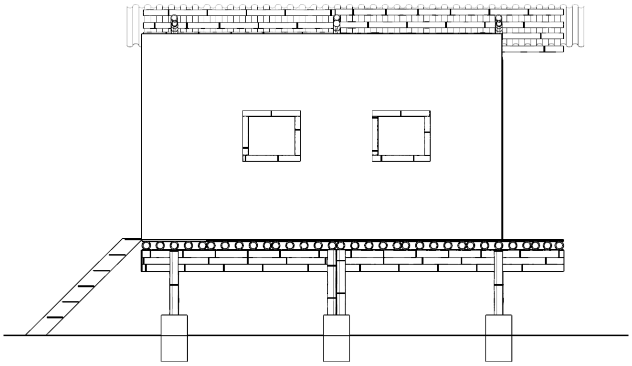




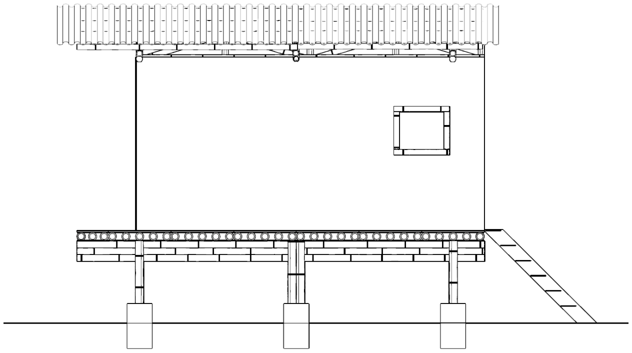
North Elevation



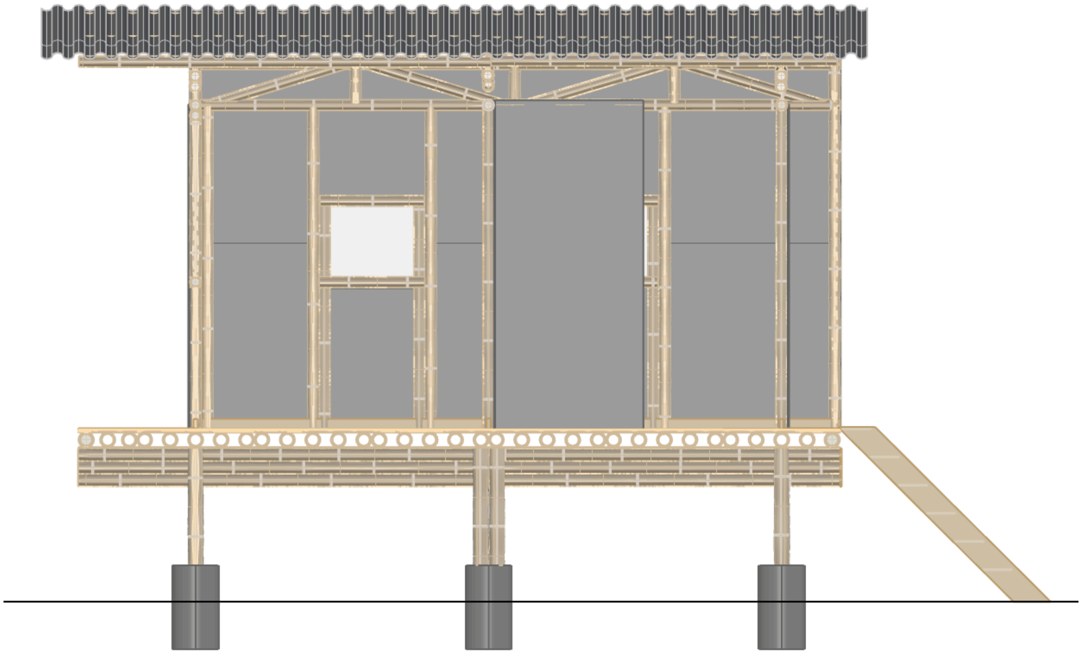
South Elevation



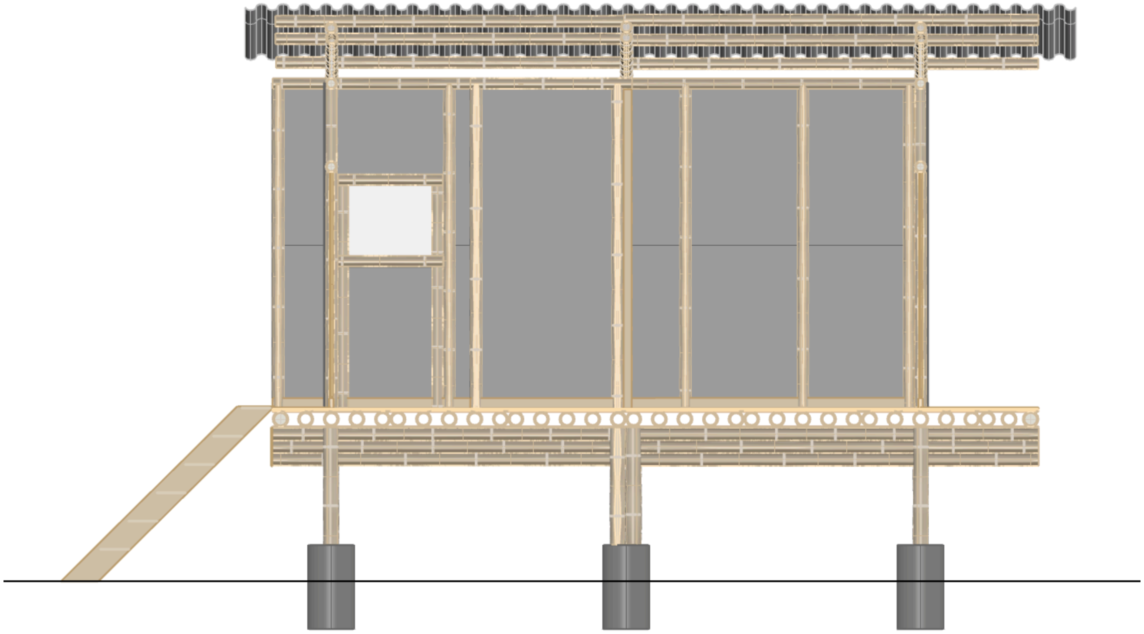
West Elevation



East Elevation

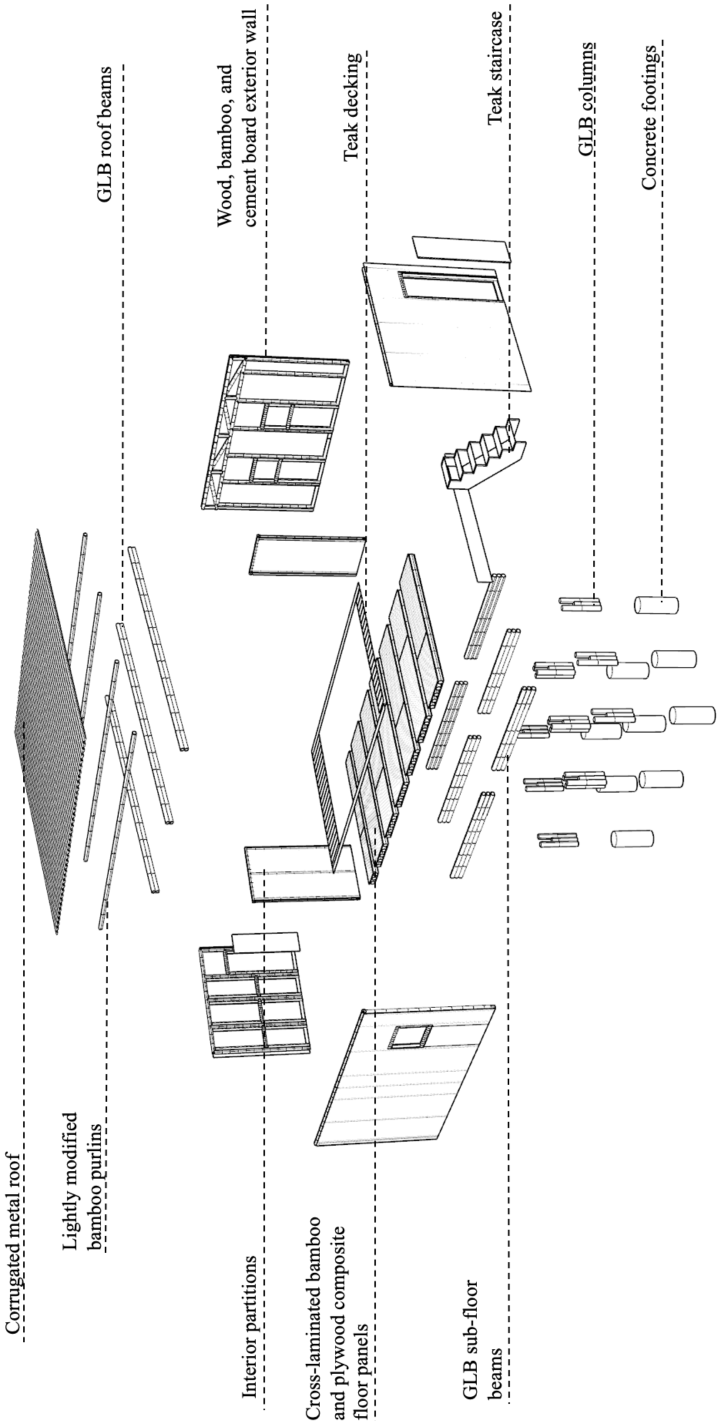


East Section



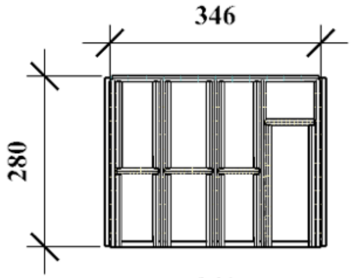
West Section

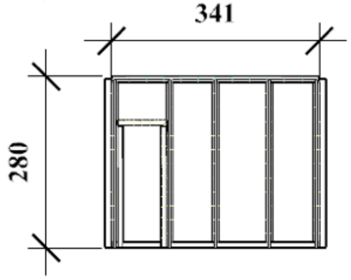
c. Pre-Fabrication

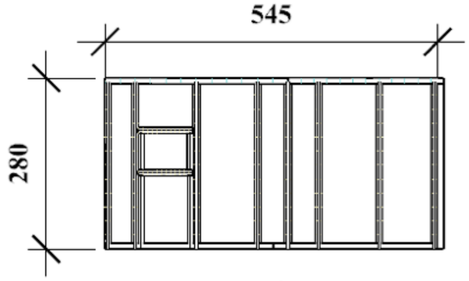


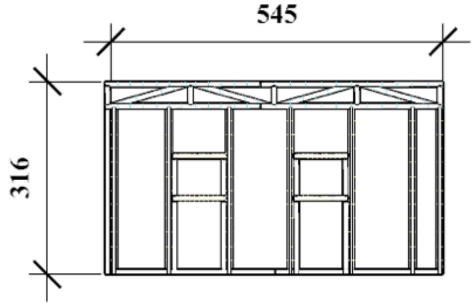
Exploded Prefab Model

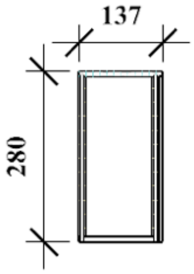
Walls

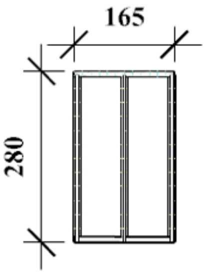




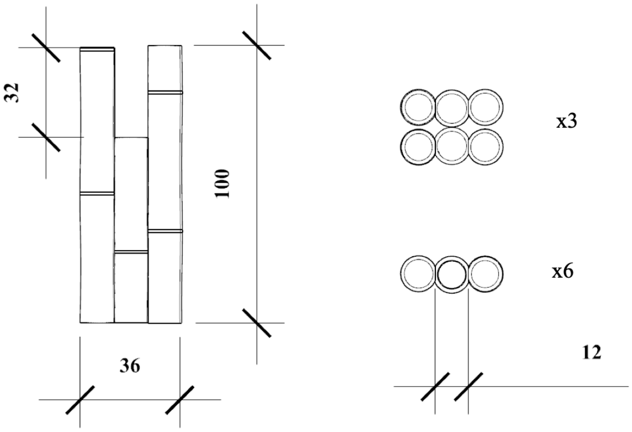




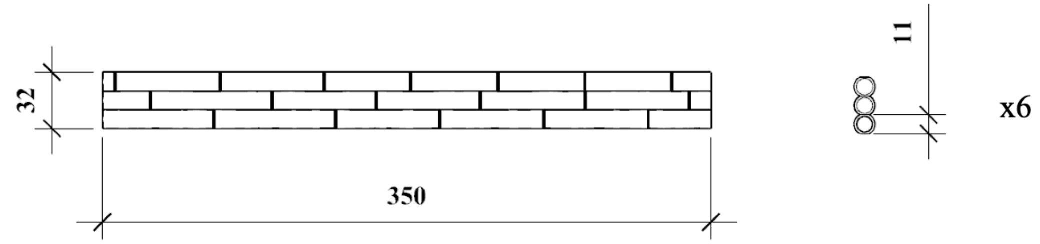




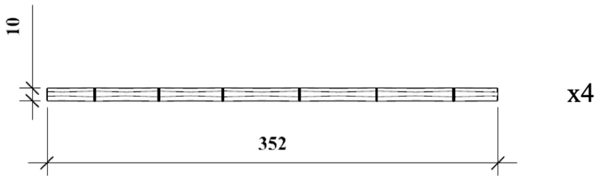
Columns

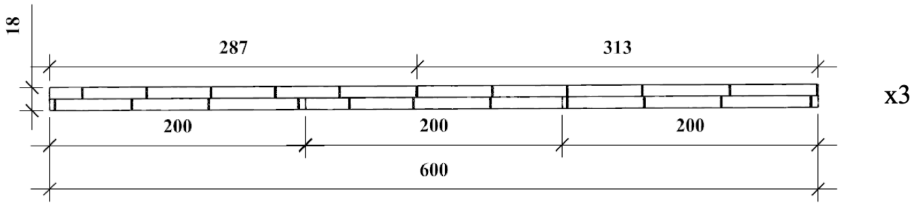


Sub-Floor Beams

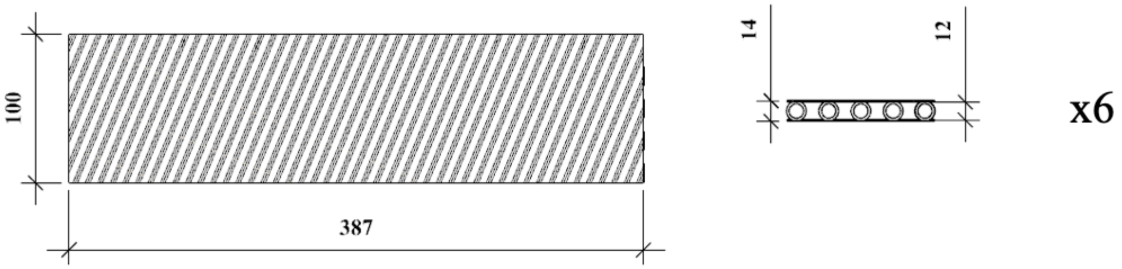


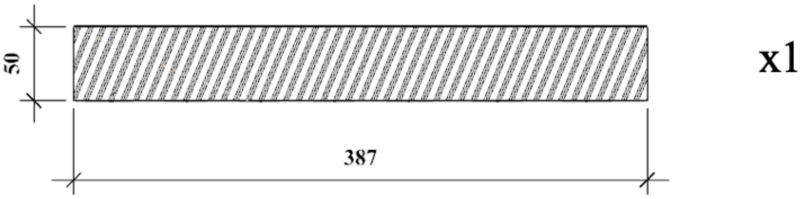
Roof Beams and Purlins

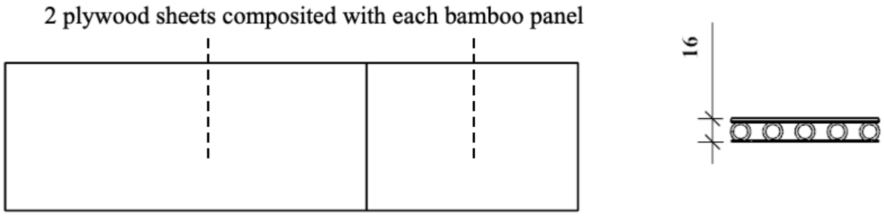




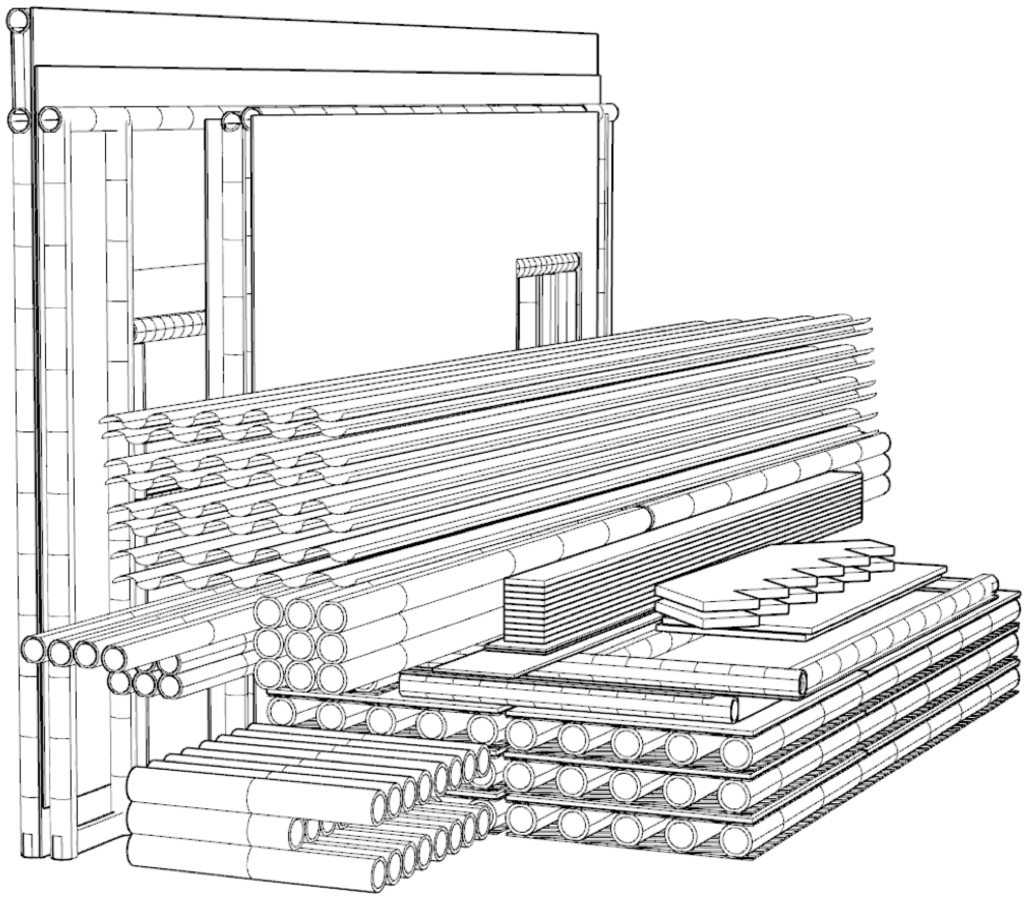
Floor Panels





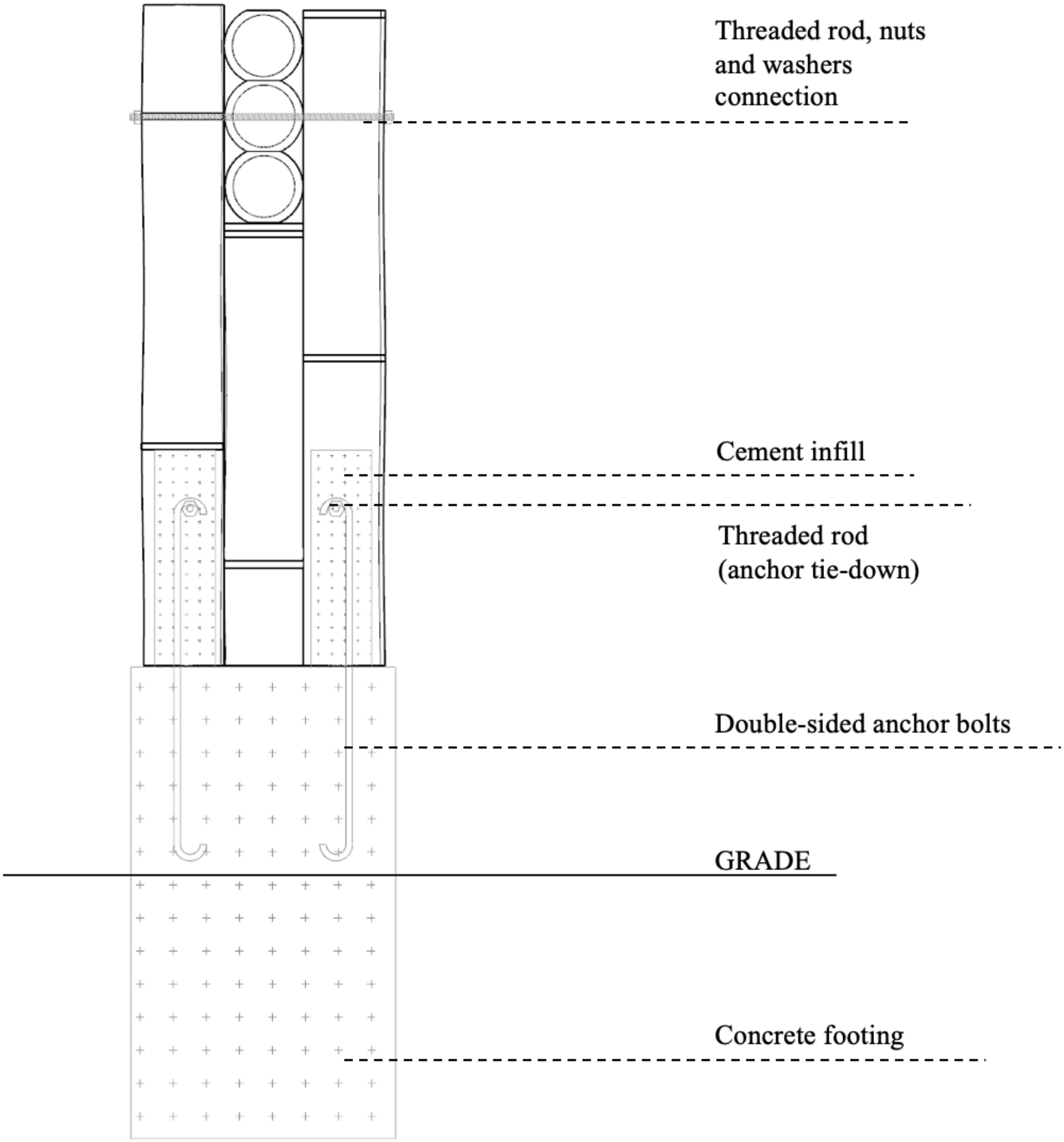


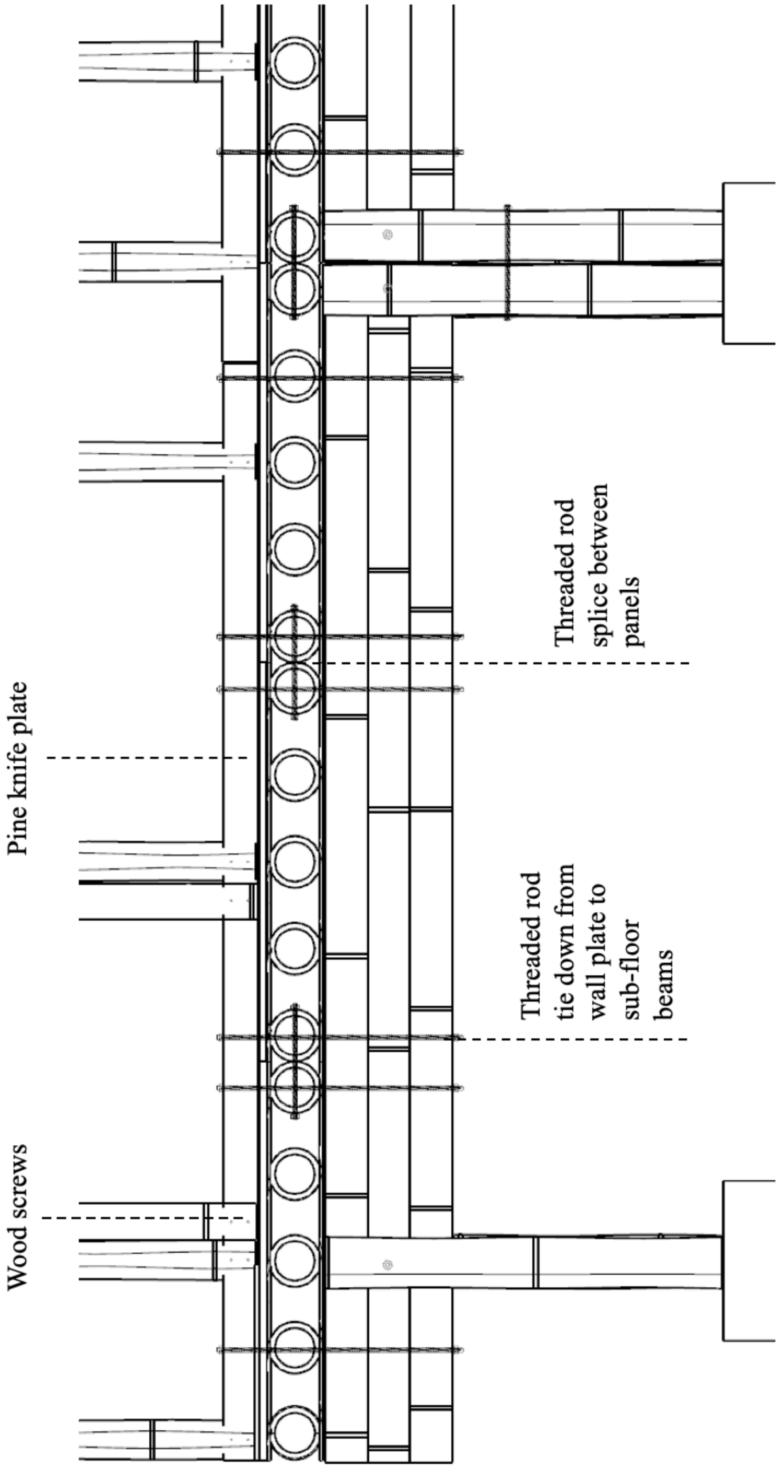
Prefab Part Packaging for Transportation

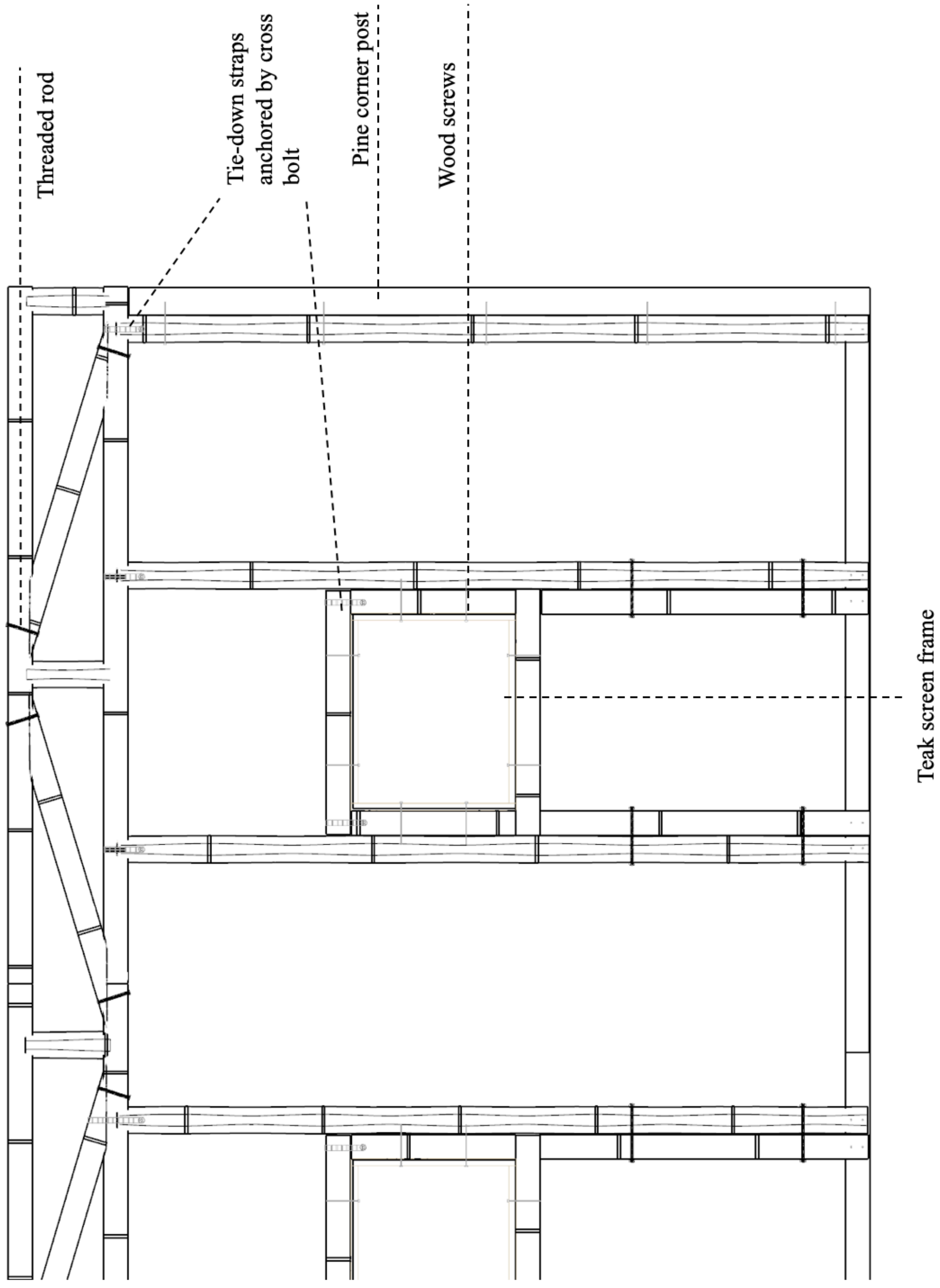


d. Structural Details

Foundation

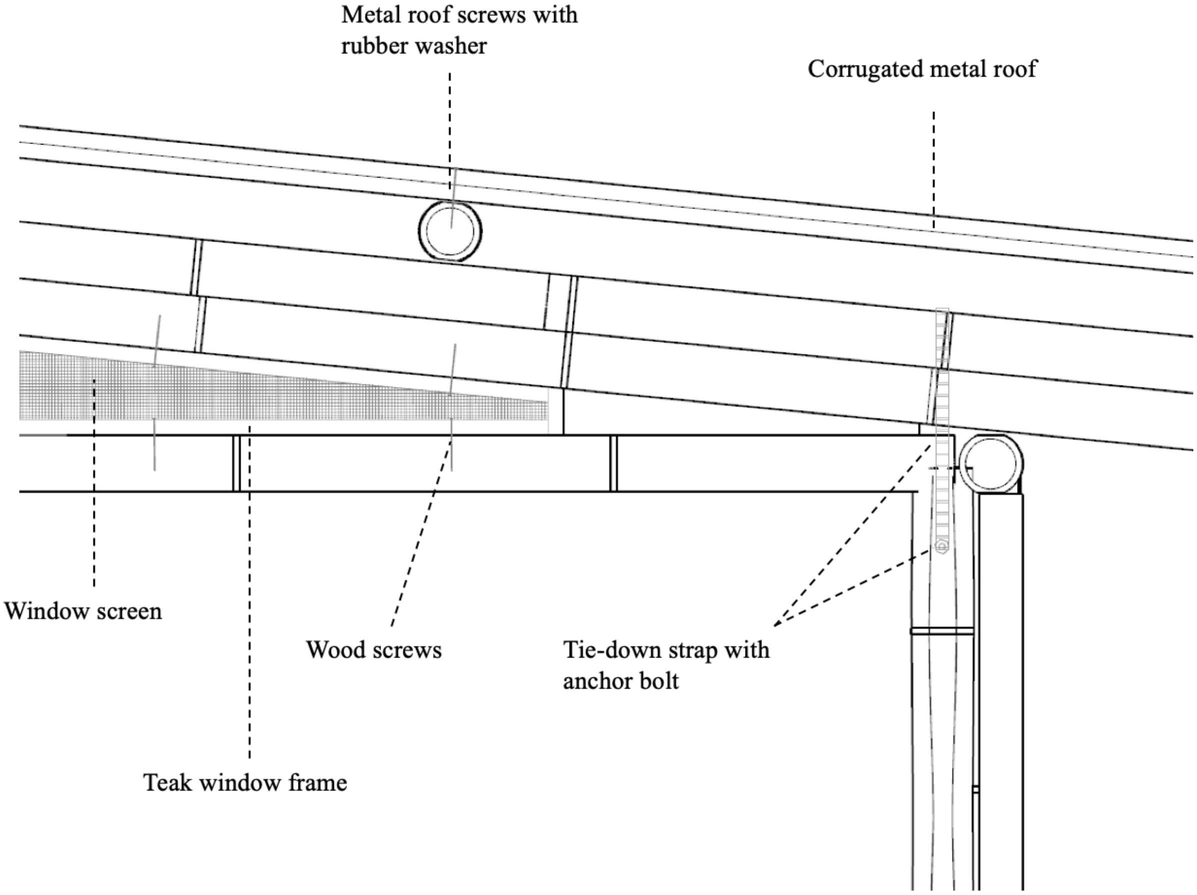



Pine knife plate
Wood screws
Threaded rod splice between panels
Threaded rod tie down from wall plate to sub-floor beams


Threaded rod
Tie-down straps anchored by cross bolt
Pine corner post
Wood screws
Teak screen frame

Wall System

Roof System


Metal roof screws with rubber washer
Corrugated metal roof
Window screen
Wood screws
Tie-down strap with anchor bolt
Teak window frame

APPENDIX B

BIRD OBSERVATION STRUCTURE

This Appendix contains further photographic documentation of the bird observation structure constructed as a part of the Ecuador field study.

Figure B1. Early Framing Process. Local bamboo maestros utilize rope to temporary hold bamboo in proper positions. VT student cuts off extra threaded rod from foundation connection- threaded rod is initially cut longer than needed to ensure easier workability and then trimmed after installation.

Figure B2. VT students apply a varnish to framing culms. Varnish helps seal and protect the bamboo from moisture and UV, while still displaying the natural grain patterns.

Figure B3. The author photographed with the structure towards the end of the framing process. Notice the temporary diaganol supports tied onto the right side of the frame, which also can act as an unofficial scaffolding for the maestros. The six-plus feet of vertical space under the structure allows for a secondary space to take in the views.

Figure B4. Finished Framing and Roof Installed. Triangular members in the walls and cross-bracing between the roof beams resist lateral forces. “Botas y sombrero”

Figure B5. Finished Cantilever. Floor panels extend 1-meter past the back support beam. Notice the deflection in the beam as described in section 4.2. The ends of all exterior exposed culms (like the beam here) are enclosed with cement mortar.

Figure B6. (*left)* Foundation connection. The group is connected to each other in two directions and then anchored to the teak stump. Notice the stark color difference between this bamboo and the varnished bamboo to the right. *(right)* Column to roof joint. While beautiful and interesting, this is a good example of how intricate traditional bamboo joints can be. A four-culm column, roof joist, roof cross-brace, and two wall members all meeting in one corner. The diaganol poles connect with a fish mouth joint.

APPENDIX C

CLB PANEL SPAN CALCULATIONS

This appendix contains calculation data for cross-laminated *Guadua angustifolia* floor panels to determine the maximum allowable simple span.

CLB FLOOR PANELS

Guadua Core Layer does majority of the work (MOE~ 14,000-20,000 MPa, using 14,000 to be safe, equates to 2,030,000 psi)

Because of the lack of composite action between all 3 layers, consider the h in calculating MOI to be the height of the core layer only (3.5 in.).

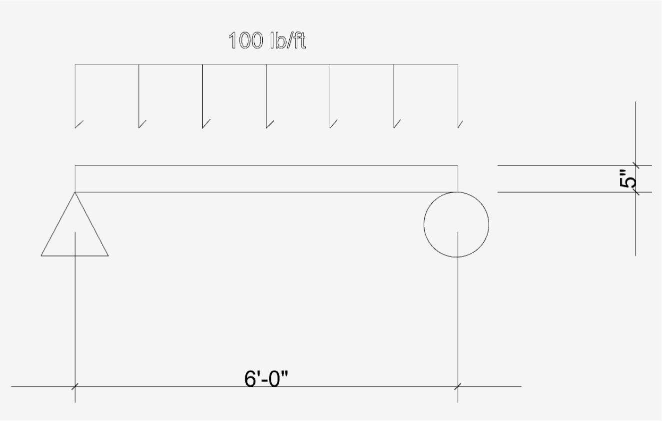
Loading:
Live= 40psf
Dead= 10psf → Average panel loads 7psf (Over-design to 10)
50psf total

Equations:

$$\Delta allowable = \frac{L}{360}\ ,\ \Delta max = \frac{5\omega L^4}{384EI}\ ,\ I = \frac{1}{12}bh^3$$

Panel 1 (2X6)

Test Panel Dimensions
24"x72"x5"



$\Delta allowable$ = 72/360 = 0.2 in.
E = 2,030,000 psi
$I = \frac{1}{12}(24in)(3.5in)^3$ = $85.75in^4$
Uniform Loading = 50 lb/ft^2

$$\omega = \left(50\frac{lb}{ft^2}\right)(2ft) = 100\frac{lb}{ft}$$

$$\Delta max = \frac{5(\frac{100lb}{ft})(\frac{1ft}{12in})(72in)^4}{384\left(\frac{2{,}030{,}0001b}{in^2}\right)(85.75in^4)} = \frac{1.119744e9}{6.68438e10} = 0.02\ in < 0.2\text{ in}$$ → Max under allowable

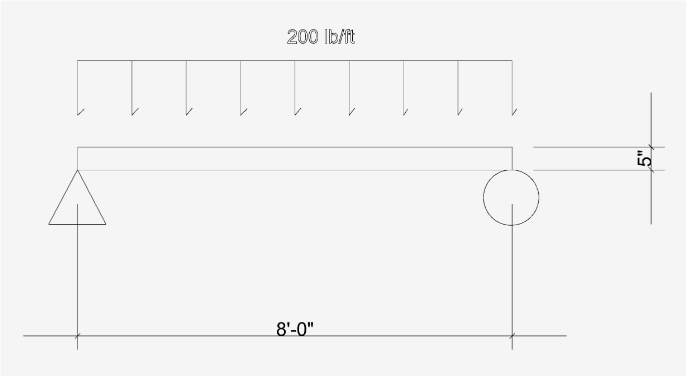
Panel 2 (4X8)

Dimensions
48”x96”x5”

$\Delta allowable = 96/360 = 0.27$ in.

$I = \frac{1}{12}(48in)(3.5in)^3 = 171.5in^4$

$\omega = \left(50\frac{lb}{ft^2}\right)(4ft) = 200\frac{lb}{ft}$



$\Delta max = \frac{5(\frac{200lb}{ft})(\frac{1ft}{12in})(96in)^4}{384(\frac{2{,}030{,}0001b}{in^2})(171.5in^4)} = \frac{7.077888e9}{1.33688e11} = 0.05\ in < 0.27$ in → Max under allowable

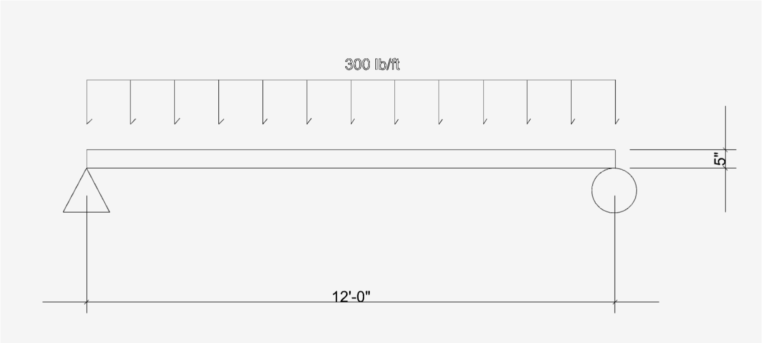
Panel 3 (6X12)

Dimensions
72”x144”x5”

$\Delta allowable = 144/360 = 0.4$ in.

$I = \frac{1}{12}(72in)(3.5in)^3 = 257.25in^4$

$\omega = \left(50\frac{lb}{ft^2}\right)(6ft) = 300\frac{lb}{ft}$



$\Delta max = \frac{5(\frac{300lb}{ft})(\frac{1ft}{12in})(144in)^4}{384(\frac{2{,}030{,}0001b}{in^2})(257.25in^4)} = \frac{5.37477e10}{2.00532e11} = 0.27\ in < 0.4$ in → Max under allowable

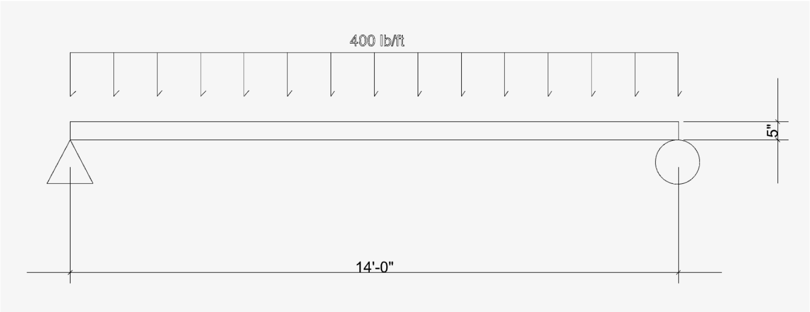
Panel 4 (8X14)

Dimensions
96”x168”x5”

$\Delta allowable = 168/360 = 0.47$ in.

$I = \frac{1}{12}(96in)(3.5in)^3 = 343in^4$

$\omega = \left(50\frac{lb}{ft^2}\right)(8ft) = 400\frac{lb}{ft}$



$\Delta max = \frac{5(\frac{400lb}{ft})(\frac{1ft}{12in})(168in)^4}{384(\frac{2{,}030{,}0001b}{in^2})(343in^4)} = \frac{1.32766e11}{2.67375e11} = 0.49\ in > 0.47$ in → Max over allowable.

Panel 5 (12X12)

Dimensions
144”x144”x5”

$\Delta allowable$ = 144/360 = 0.4 in.

$I = \frac{1}{12}(144in)(3.5in)^3 = 514.5in^4$

$\omega = \left(50\frac{lb}{ft^2}\right)(12ft) = 600\frac{lb}{ft}$

$\Delta max = \frac{5(\frac{600lb}{ft})(\frac{1ft}{12in})(144in)^4}{384\left(\frac{2{,}030{,}0001b}{in^2}\right)(514.5in^4)} = \frac{1.07495e11}{4.01063e11} = 0.27\ in < 0.4$ in → Allowable over max

Panel 6 (12X16)

Dimensions
144”x192”x5”

$\Delta allowable$ = 192/360 = 0.53 in.

$I = \frac{1}{12}(144in)(3.5in)^3 = 514.5in^4$

$\omega = \left(50\frac{lb}{ft^2}\right)(12ft) = 600\frac{lb}{ft}$

$\Delta max = \frac{5(\frac{600lb}{ft})(\frac{1ft}{12in})(192in)^4}{384\left(\frac{2{,}030{,}0001b}{in^2}\right)(514.5in^4)} = \frac{3.39739e11}{4.01063e11} = 0.85\ in > 0.53$ in → Max over allowable

Panel 7 (12X14)

Dimensions
144”x168”x5”

$\Delta allowable$ = 168/360 = 0.47 in.

$I = \frac{1}{12}(144in)(3.5in)^3 = 514.5in^4$

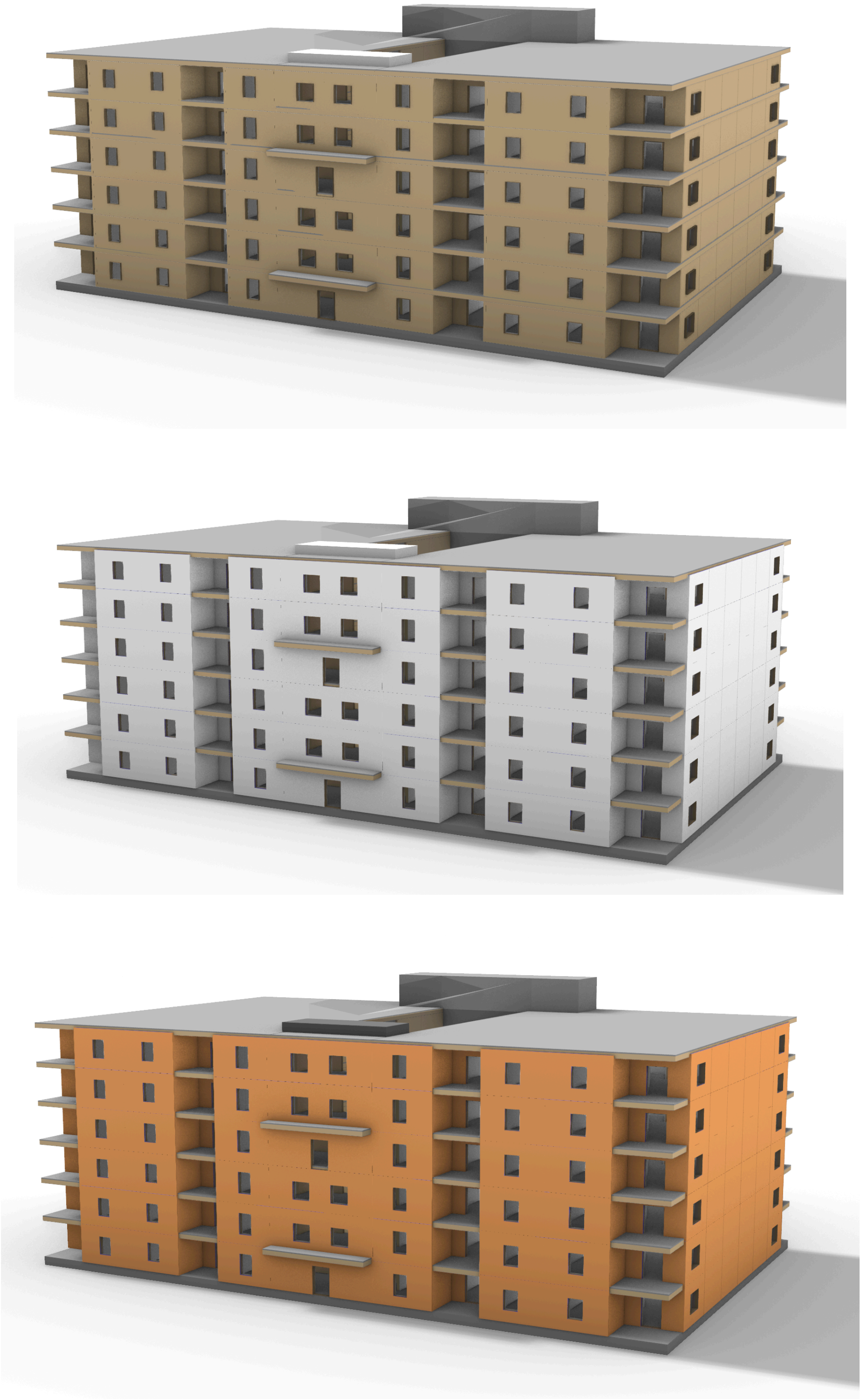
$\omega = \left(50\frac{lb}{ft^2}\right)(12ft) = 600\frac{lb}{ft}$

$\Delta max = \frac{5(\frac{600lb}{ft})(\frac{1ft}{12in})(168in)^4}{384\left(\frac{2{,}030{,}0001\square}{in^2}\right)(514.5in^4)} = \frac{1.99149e11}{4.01063e11} = 0.5\ in > 0.47$ in → Max over allowable

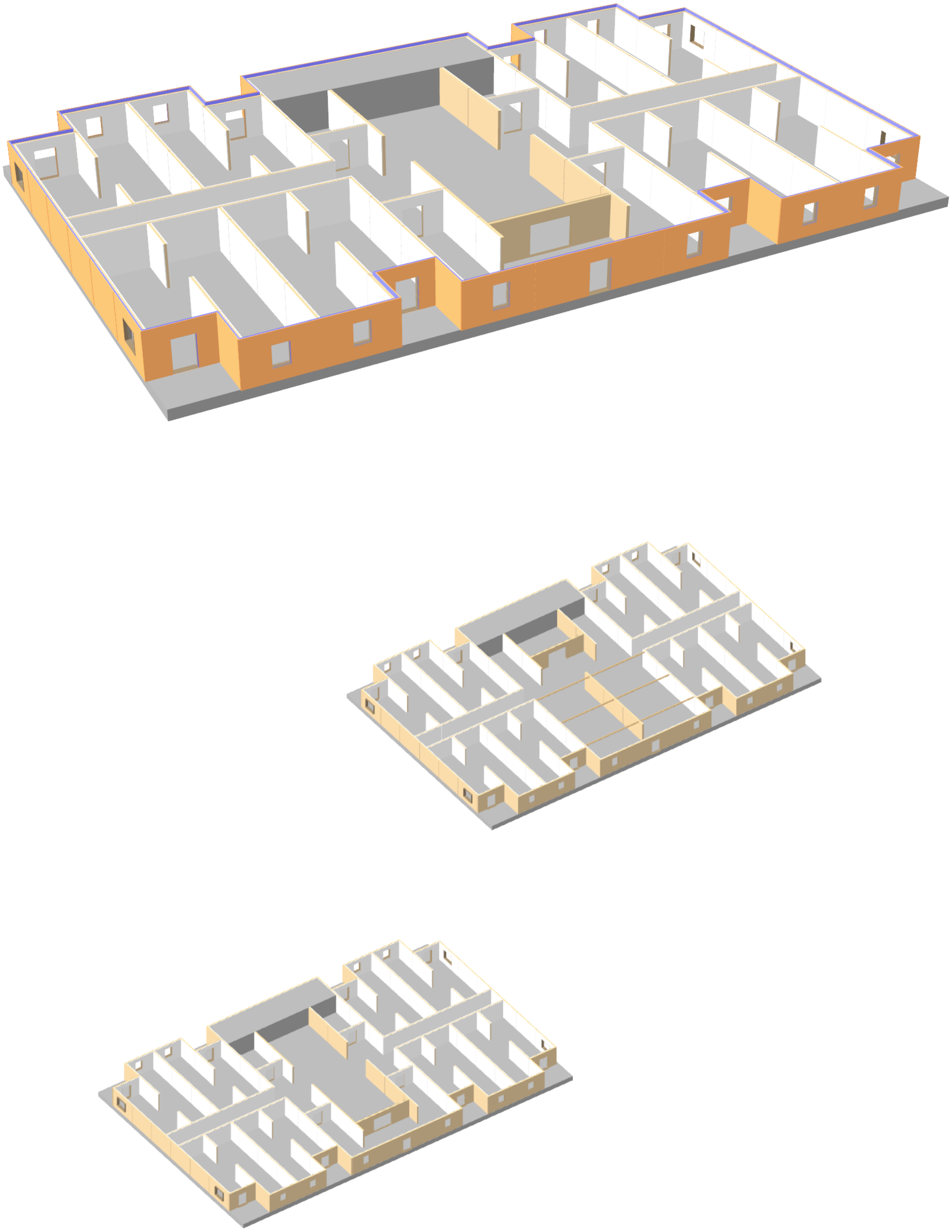
APPENDIX D

FUTURE WORK CONCEPTS: MASS BAMBOO

This appendix features previous work by the author on mid-rise “mass bamboo” concepts that is recommended as future work to this thesis. Contained is a building example with floor and wall details.



Exterior Finishes



Structural Plans

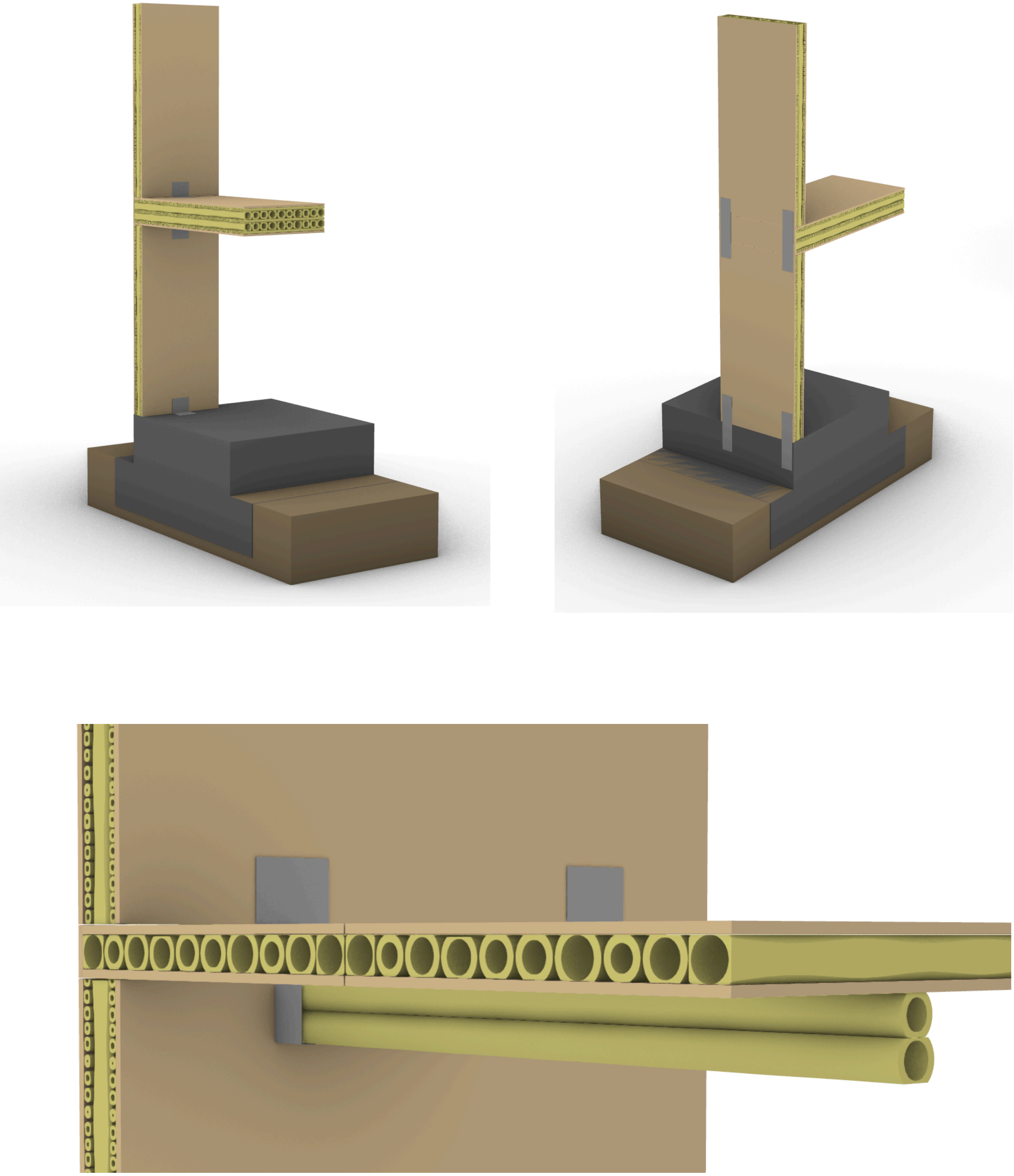
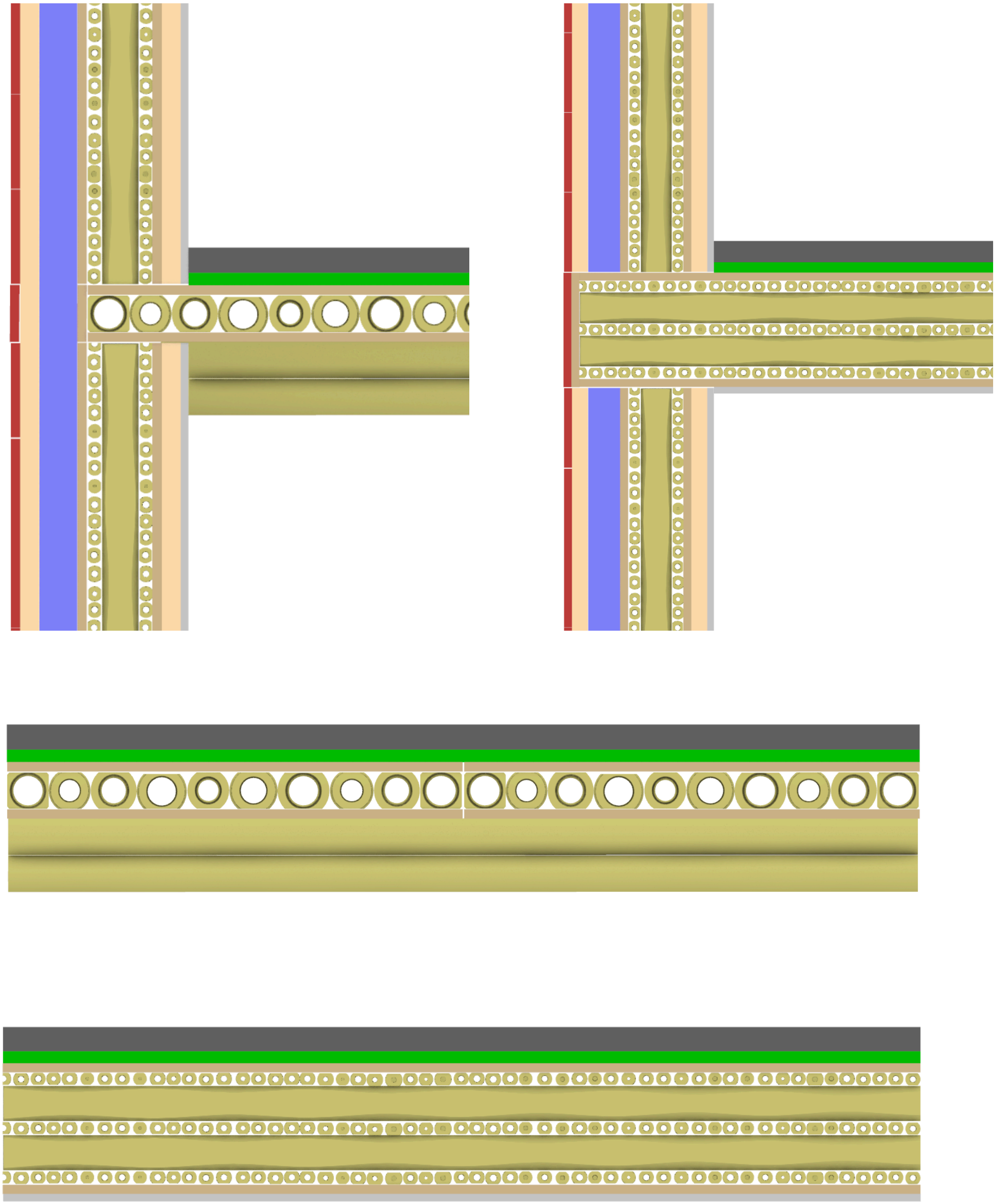
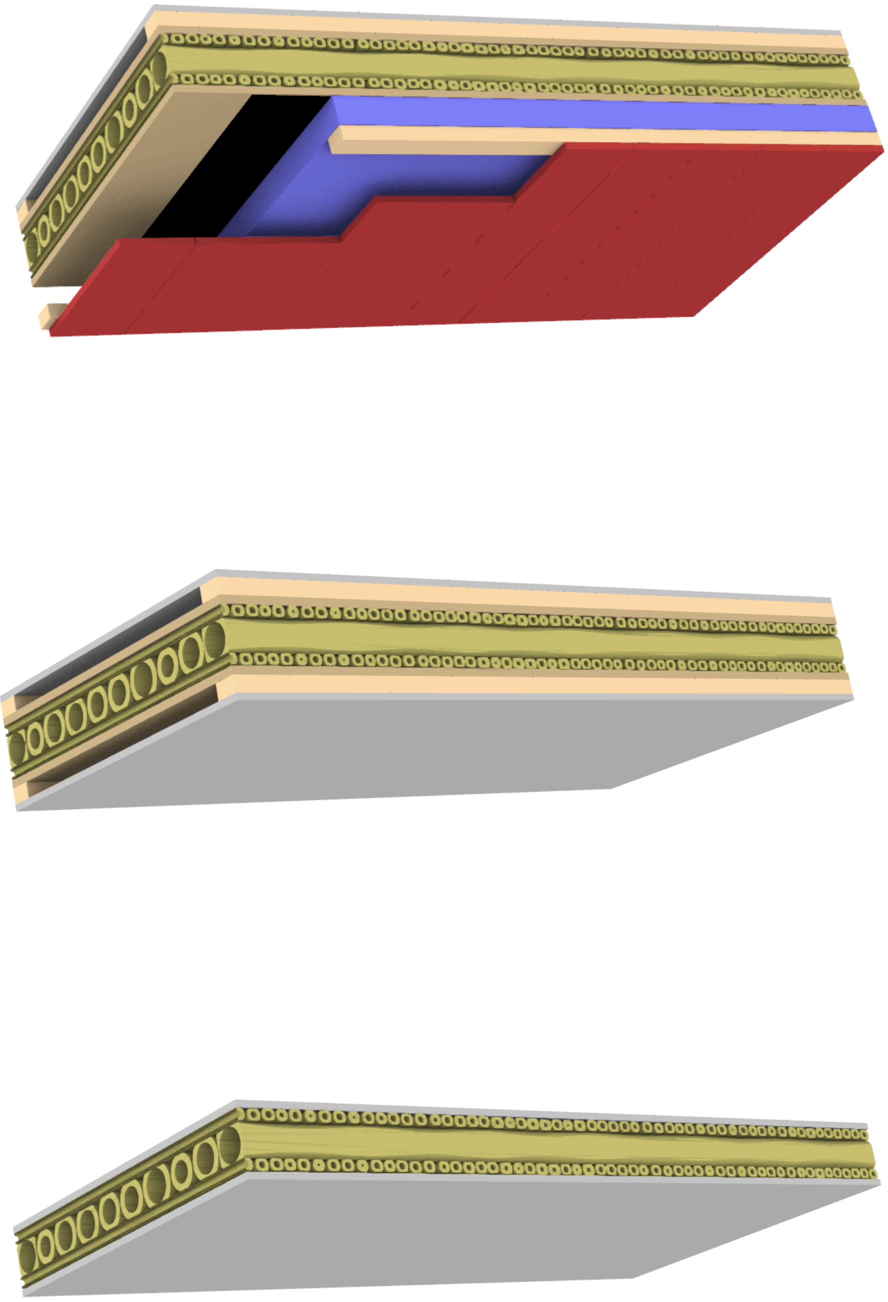


Plate Connectors



Floor and Wall Sections



Exterior and Interior Wall Compositions