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SMART BAMBOO SYSTEMS: COMBINING MATERIAL INTELLIGENCE WITH MODERN MANUFACTURING

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ABSTRACT
Rising demand for housing in the global south must be met while focusing on lowering carbon emissions to mitigate the growing influence of climate change. Current bamboo structures typically consist of (1) lattice-based structures using full culm bamboo, which do not create modern building enclosures, or (2) bamboo composites which require disaggregation and reconstitution of the bamboo, increasing the carbon footprint. This paper explains our concept, Smart Bamboo (SB), a lightly modified bamboo composite system that uses digital analysis and fabrication tools to create panelized building systems that utilize the sectional properties of full culm bamboo with composite cross-lamination strategies.

KEYWORDS
Structural; timber; bamboo

INTRODUCTION
The potential of bamboo as a robust and ecologically responsible construction material is well documented and a growing cadre of academics and practitioners in the architecture, engineering, construction and industrial design industries are contributing to this area of study. This is evidenced by an increasing number of surveys or summaries of the basic benefits of bamboo in various journals and conference proceedings, typically accompanied by several case studies of well-known bamboo construction projects. (Apsari & Dewi, 2021; Lapina & Zakieva, 2021; Skuratov et al, 2021; Yadav & Mathur, 2021) Although there is a growing interest and appreciation for bamboo buildings, its adoption through the industry is slow. This is mainly due to the unique challenges of working with the material and its common perception as an unreliable material. While bamboo enjoys a rich history of use in informal construction, textiles and other crafts, and a similar proliferation in high-end boutique resort construction, we are primarily interested in its potential as a low-cost, low embodied carbon structural material to displace concrete and steel in rapidly densifying and urbanizing tropical and sub-tropical areas where bamboo is a local resource. (Figure 1)

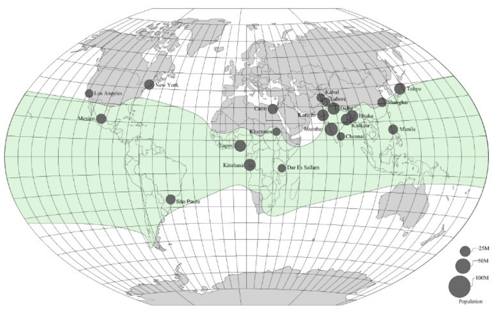


Figure 1: Most growing population centers align with areas of prevalent bamboo growth (green).

Bamboo construction falls into two main categories. Hector Archila and David Trujillo have identified these efforts as “bamboo engineering” and “engineered bamboo.” (2016) We prefer to emphasize the position of these approaches as two ends of a spectrum of bamboo work; lattice-systems and homogenized composites respectively. Lattice-systems rely on single culms used as columns, beams, and various strut configurations. These projects often leverage the incredible lightness and tensile integrity of the plant to create grand organic and mathematically rich designs. With respect to bamboo’s adoption at scale in contemporary green building, the challenges of lattice-system approaches are twofold: (1) creating robust joints between poles with a high degree of perceived reliability and (2) developing systems that allow for the tightly sealed, climate-controlled interiors required by contemporary building typologies. These conditions lead to lattice structures that most often are either temporary and open-air, (Figure 2a) or use bamboo in a limited and/or somewhat ornamental fashion (Figure 2b).

a) ZCB Bamboo Pavilion. K. Crolla

b) Bamboo House. M. Cardenas

Figure 2: Contemporary lattice-system bamboo structures.

On the other end of the bamboo construction spectrum, homogenized composites break down the culm into aggregate scrimber, fiber strands, or chips, which are then mixed with adhesive and reconstituted as pressed panels using heat and pressure. While these products have the regularity necessary for the construction of modern tightly sealed interiors, (Figure 3a) they also disaggregate the plant from its original morphology, eliminating a portion of the structural potential inherent to its growth as a round culm. (Figure 3b) The question posed in this research is how to achieve the benefits of both engineered bamboo and bamboo engineering.

a) LBL Building. Nanjing Forestry University

b) Engineered bamboo boards

Figure 3: Contemporary homogenized composite bamboo

To that end we are creating a series of building products which retain some of the sectional properties of bamboo culms while taking advantage of the panelization common to composite products. One of our main concerns is to track and analyze the carbon sequestration associated with this system. We refer to the system as Smart Bamboo (SB), as it will combine digital sensing, structural analysis, and computational design workflows to create semi-regular, engineered bamboo constructions that maximize the retained natural structural integrity of each culm. This research has included a systematic examination of the manufacturing and processing needs for the development of both single and multi-species cross laminated panels, including structural testing, machining and production prototyping, pole scanning and modeling, pole splicing, panel connection prototyping, adhesive testing and refinement, surfacing explorations, and the development of computational tools for analysis and design.

The purpose of this paper is to establish the basis of Smart Bamboo as a structural building system that utilizes individual pole morphological data and computation to organize lightly modified bamboo culms into reliable structural assemblies. This includes (1) description of the various panel prototypes produced so far, including preliminary qualitative observations regarding their structural capacities; (2) description of how these components will be aggregated together in the context of building construction, including strategies for joining panels; (3) how IOT sensing can be used together with computation to optimize the use of an available bamboo stock toward the structural needs of a building; and (4) necessary critical path research toward the realization of a Smart Bamboo complete building system, such as fire barriers, insulation, adhesives, finishes, additional structural testing, etc.

CROSS-LAMINATED BAMBOO PANELS & PERFORMANCE

Any comprehensive Smart Bamboo structural system will by necessity require a diversity of components to construct an entire building. Just as Mass Timber incorporates a variety of components including cross-laminated timber, glue laminated timber, laminated veneer lumber, conventional wood framing, and heavy timber, a Mass Bamboo system would utilize a number of different bamboo composites and assemblies to create a complete structural building system. To date, we have tested prototypes for panels that could be applied to floor, wall, and roof assemblies, as well as trusses and stacked laminated beams that could provide floor and roof support for long spans. A main priority in the development of any of these components is minimizing machining or other alteration of the bamboo culm that may degrade a culm's natural structure or generate excessive waste or byproducts. This strategy aims to reduce energy and labor inputs, correlating to lower environmental and economic costs. Because of the variation of mechanical properties within species, this system will require larger sets of testing data to establish aggregate minimum performance of different species, and a deeper understanding of the impacts of various growing conditions (soil moisture, pH, etc). To date, structural testing of both single poles and composite assemblies within this system have proved promising as a proof of concept toward the realization of the Smart Bamboo system. Just as cross-laminated timber has become the foundational component of Mass Timber construction, we believe the Smart Bamboo cross-laminated bamboo panel will become the foundational component of a Mass Bamboo system. For this reason, this paper will focus primarily on our efforts around the development of this product.

On the selection of bamboo species

Although no comprehensive evaluation of possible species has been performed, species have been selected based on several criteria; foremost we began with species that we had gained some familiarity with. Hauptman traveled through Asia including to southern Vietnam where he encountered some very solid species, specifically what we came to know as Tam vong, referred to in English as Iron bamboo, but known worldwide as Calcutta bamboo. This is one of the smaller timber species with an average diameter of under 2 inches (50 mm) and only growing to a total height of around 30 ft (9 m) from ground to tip. It should be noted that the scientific name for the species is not definitively known to the authors. We have been told by various experts and read in the literature that it could be one of two species: *Dendrocalamus strictus* or *Thyrsostachys siamensis*. (Tang, 2012)

We have also been using a species for which we have not come to know a common English name, but in Vietnamese is called Tre Gai, or 'thorny bamboo.' We believe the scientific name to be one of the two following: *Bambusa stenostachya* or *Bambusa blumeana.* As we learned to work with these two species, we began to expand our field of inquiry to other large woody species that presented similar attributes with regard to size, strength, and availability in the tropical and subtropical regions we wish to target. This led us to work with Guadua, or *Guadua angustifolia*, a dominant species in the western hemisphere.

Cross laminated bamboo panel

First inspired by the success of cross-laminated timber panels, it was quickly realized that the effort to create an engineered cross-laminated composite while maintaining the structural benefits of bamboo's natural morphology rapidly multiplied the possible permutations of a cross-laminated bamboo panel beyond that typically found in cross-laminated timber. In an effort to begin understanding the structural effects of different organization of parts within the panels, several rounds of test panels were created and analyzed using 3-point bend testing to determine the optimal arrangements of bamboo culms within a cross-laminated panel. A series of three-layer panels, 2' x 6' (610mm x 1830mm), were produced using various permutations of bamboo species, orientation patterns and adhesives. Panel production was divided into three generations which are shown below in Table 1. Each generation tested some basic assumptions about panel performance, with successive generations using the data gained from the previous generation to make further projections about performance and possible improvements to panel organization and assembly.

Table 1: Description of tested panels. The angles in the names are illustrated in Figure 4 below.

Name	Outer Layer	Inner Layer	Adhesive
First Generation			
0HTG-90TG	Half Tre Gai (B. blumeana) 0 degrees to Load (Major Direction)	Whole Dressed Tre Gai 90 degrees to Load (Minor Direction)	Crosslinked Polyvinyl Acetate (PVA) with Woven Bamboo Mat
90HTG-0TG	Half Tre Gai 90 degrees to Load	Whole Dressed Tre Gai 0 degrees to Load	PVA with Woven Bamboo Mat
0HTG- UTG	Half Tre Gai 0 degrees to Load	Tre Gai sections Oriented Vertically	PVA with Woven Bamboo Mat
Second Generation			
90IB-0TG	Whole Dressed Iron Bamboo (T. siamensis) 90 degrees to Load	Whole Dressed Tre Gai 0 degrees to Load	PVA
45IB-0TG	Whole Dressed Iron Bamboo 45 degrees to Load	Whole Dressed Tre Gai 0 degrees to Load	PVA
Third Generation			
90IB-0TG (A)	Whole Dressed Iron Bamboo 90 degrees to Load	Whole Dressed Tre Gai 0 degrees to Load	Algae-based Polyurethane
45SpG-0G	Split Guadua (G.angustifolia) 45 degrees to Load	Whole Dressed Guadua 0 degrees to Load	PVA
3-Stud Wall	1/2 inch Gypsum Wallboard; 7/16 inch Oriented strandboard	3 Tre Gai Poles 0 degrees to Load	Drywall Screws / PVA

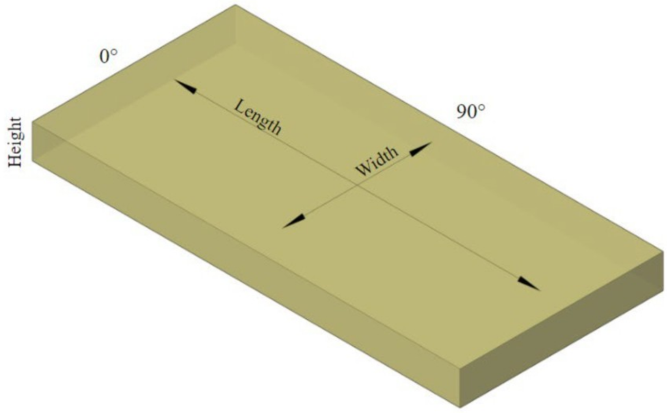


Figure 4: Panel labelling nomenclature orientation

While we have tested many variations of culm orientation within each set of panels, the main structural concept of the panels has remained consistent throughout. The system has been based on a 3-layer cross-laminated composite consisting of a core layer, and two outer lath layers. (Figure 5) Although not a critical component of initial structural testing, we envision a final skin layer applied to the outer surfaces of each side of the panel, depending on the surface orientation of interior or exterior, and needs of the particular panel relative to exposures and programming of the structure.

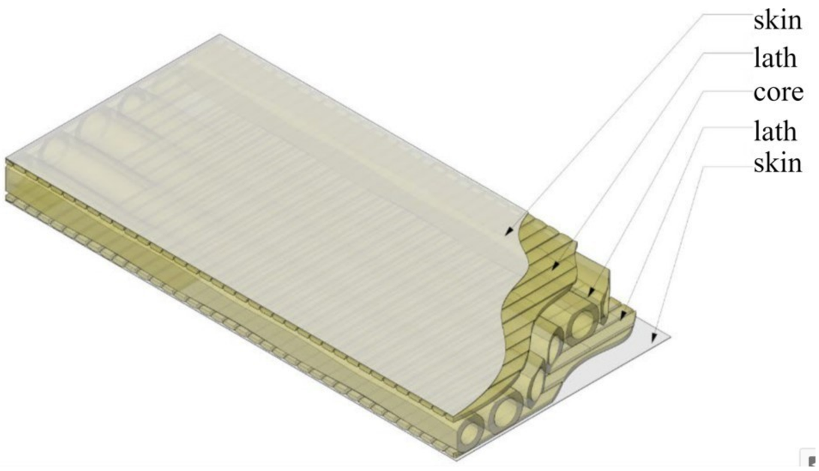


Figure 5: Smart Bamboo typical panel construction

The first-generation panels used only Tre Gai (*Bambusa stenostachya*) for all layers. The outer layers used a halfed culm. The middle layer in the first two panels (0HTG-90TG and 90HTG- 0TG) used a whole pole dressed on two faces. The third panel, 0HTG- UTG used a middle layer of Tre Gai sections cut to width and oriented vertically. (Figure 6) All of the panels in the first generation used crosslinked polyvinyl acetate (PVA) adhesive and a woven bamboo mat between layers. Results of the first-generation tests are shown in the load-displacement curves in Figure 7. Surprisingly, the 0HTG-90TG and 0HTG-UTG both had low strength and stiffness compared to the 90HTG-0TG panel and most other subsequent tests. Placing off axis bamboo in the middle layer was found to create excessive rolling shear - much greater than observed in wood and CLT constructions - which dominated the behavior and caused low strength and stiffness. The woven mat product was originally installed in an attempt to increase gluing surface but was also found to act as a failure element, creating a noise during testing similar to frying bacon where the internal structure of the mat failed before the poles.

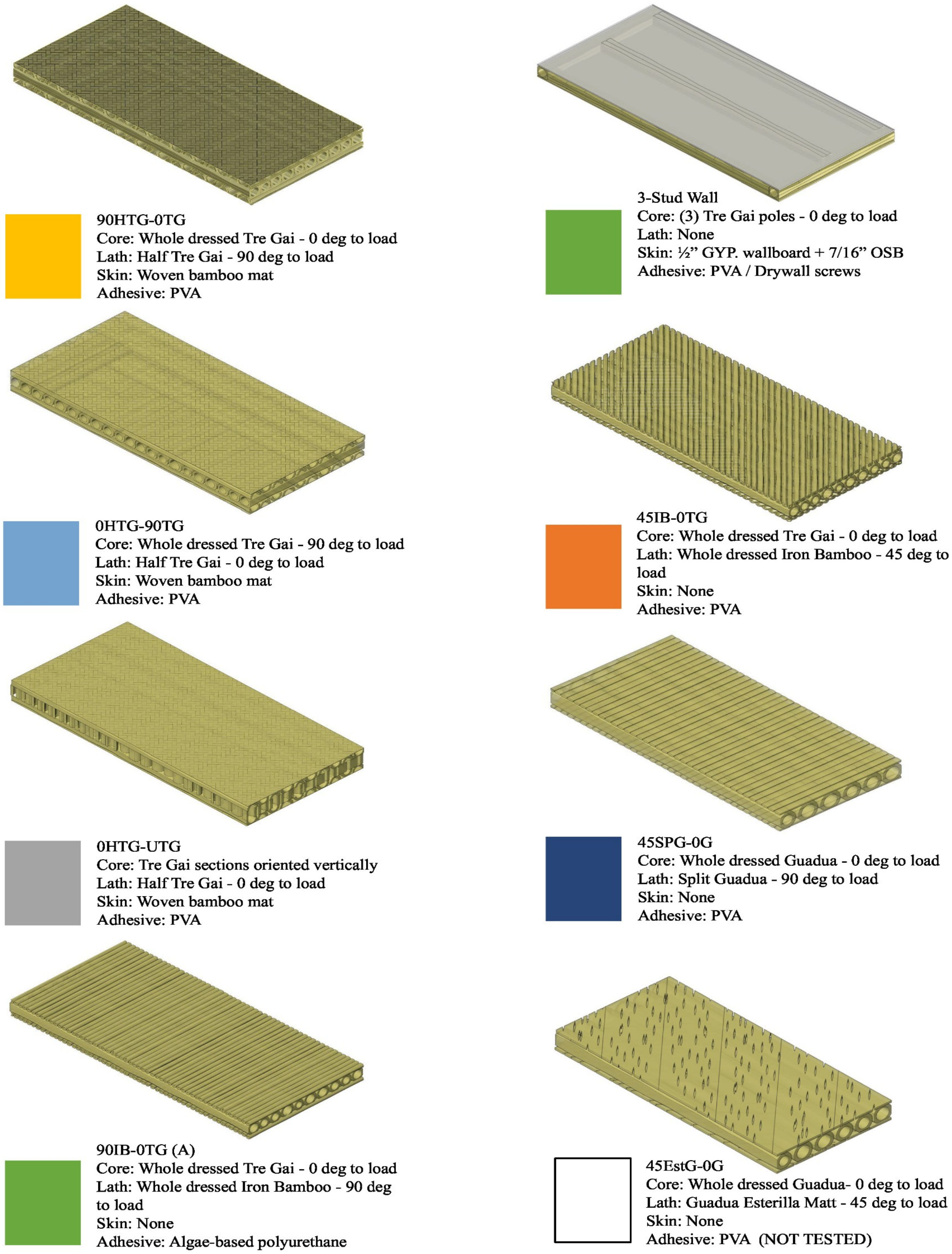


Figure 6: Smart Bamboo test panel configurations. Color blocks correspond to load displacement curves below in Figure 7.

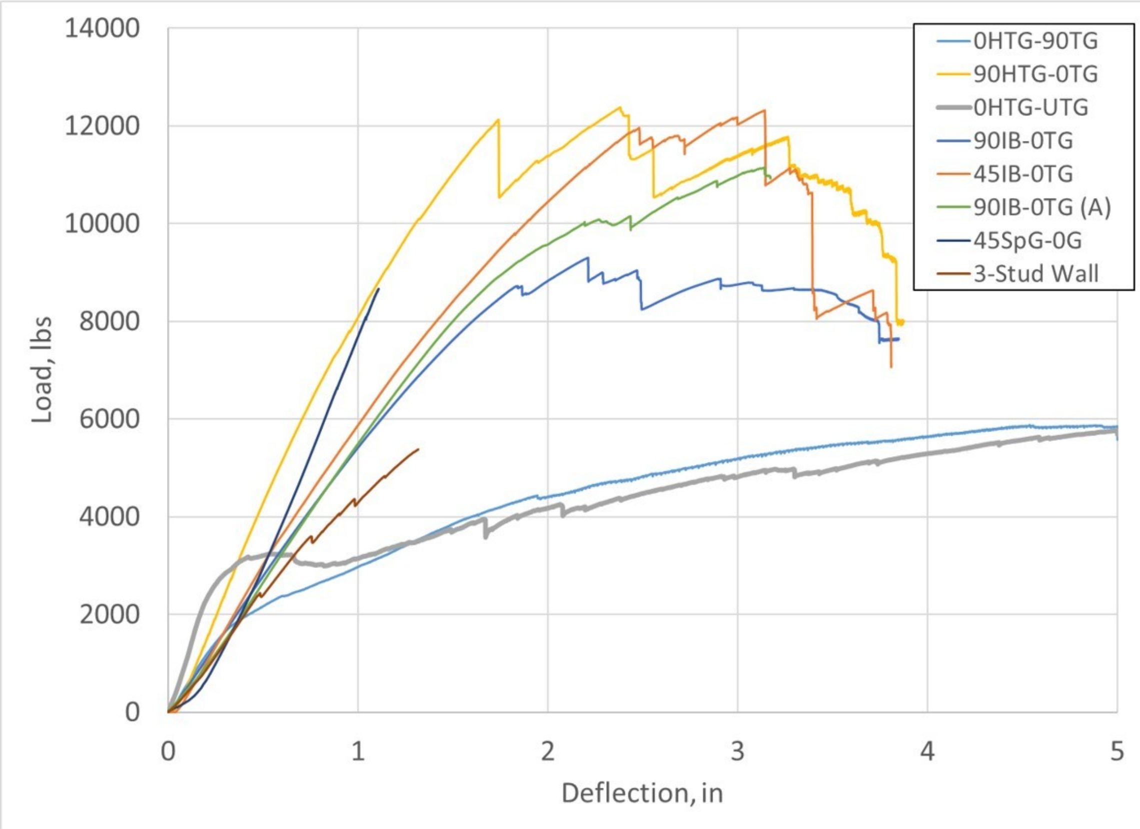


Figure 7: Load displacement curves from 3-point bend testing

Based on observations from the first generation of panels, the second generation eliminated the woven mat and examined the effect of different cross-laminations in the outer layer. These panels also introduced the use of *Thyrsostachys siamensis*, or iron bamboo, for the outer layers. Two angles of Iron bamboo were applied - 90 degrees to loading, and 45 degrees to loading. The 90IB-0TG had a lower load and stiffness than the 90HTG-0TG from the first generation testing, while the 45IB-0TG had a similar load and slightly lower stiffness to the 90HTG-0TG. The 45-degree outer layer tended to align more bamboo fiber in the direction of loading than the 90IB-0TG sample. (Figure 8)

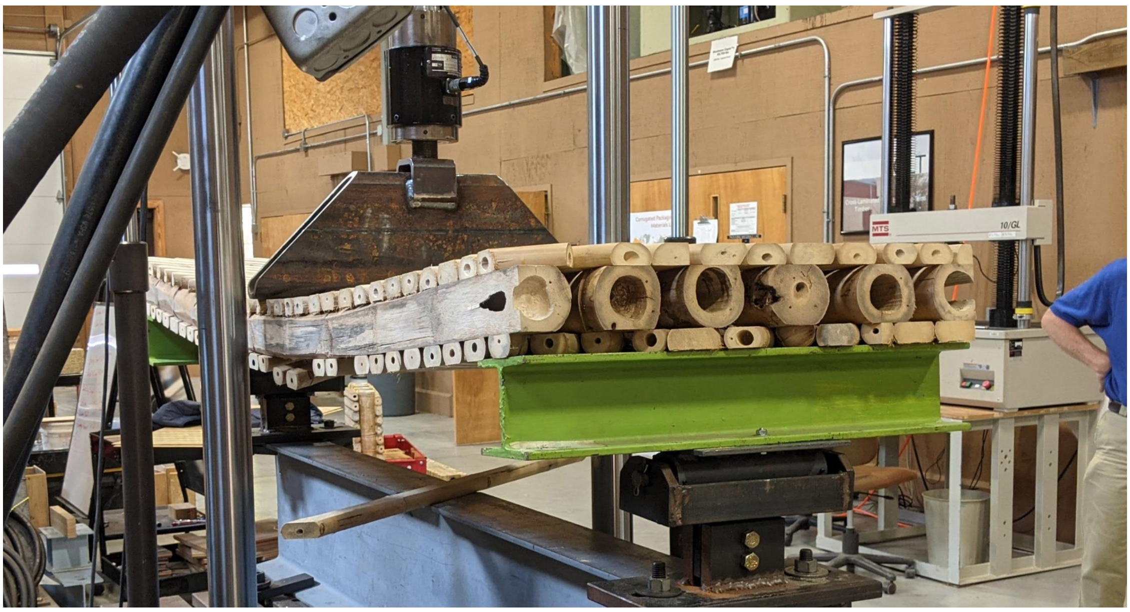


Figure 8: Panel 45IB-0TG during 3-point bend testing.

The third generation of test panels explored a variety of other factors including adhesive type, different species and more traditional US residential construction. First, the 90IB-0TG panel from the second generation was replicated using a bio-polyurethane adhesive from the California Center for Algae Biotechnology rather than the previously used PVA. Next, a panel of Guadua (*Guadua angustifolia*) was constructed, using a set of split poles placed at 45 degrees for the outer layer. Finally, to demonstrate similarities with more conventional US residential construction practices, a wall-type panel consisting of three Tre Gai poles with a short Tre Gai section at each end for bearing were covered by ½ inch (13mm) gypsum wallboard on one side and 7/16 inch (11mm) oriented strand board on the other side. The drywall and OSB were attached with a combination of PVA and drywall screws. Results for the 90IB-0TG (A) and 45SpG-0G poles were similar to the previously tested 90/0 poles from the first and second generations, while the 3-Stud Wall had the lowest strength and a stiffness less than the 90/0 panels, but still greater than the 0/90 panels. It is worth noting that the 3-Stud Wall panel is an outlier in relation to the other tested panels in that its primary application within a structure would be a non-load bearing wall, with no application as a floor or roof member. 3-point bend testing with loading perpendicular to the long direction of the panel therefore seems in inaccurate assessment of its intended use.

These test results demonstrate some fundamental differences between bamboo panel design and cross laminated timber, namely a reversal of the typical 0 and 90 layers found in cross-laminated timber to reduce excessive rolling shear in bamboo. The use of various bamboo species demonstrated similar stiffness and strength values for panel construction. Changes in adhesive at this time were inconclusive in demonstrating differences in strength and stiffness. As a preliminary data set, the first three generations of panels tested support the hypothesis that a minimally modified, cross-laminated bamboo panel might perform structurally as well as a comparable cross-laminated timber panel, thus offering a solution for a prefabricated and modular building system for the tropics that has the capacity for large scale carbon sequestration.

Addressing Eccentricity

Over multiple generations of panel tests, the observation of bamboo culms, machining of various bamboo species into parts, and the fabrication of assemblies have led to deeper understanding of bamboo's eccentricities. This understanding has in turn led to the refinement of working methods and processes, and the development of further design solutions to maximize the predictability and uniformity of an inherently irregular material. One such solution that may prove novel is the integration of a pole splicing technique into the panel logic as a method for controlling panel stock diameter, thickness, and the straightness of culm sections.

Because the bamboo culm, particularly that of Tre Gai (*Bambusa stenostachya*), is not straight, and because both the diameter and wall thickness tapers from end to end, facing a culm on two opposite sides in such a way as to maintain an even thickness with an adequate gluing surface is difficult beyond lengths of 6 feet (1.8m). Non-straight culms also impact the nesting of parts within a panel, potentially increasing gaps between culms and decreasing the final density and ultimate performance per cross-sectional area of a panel. As a way to compensate for these factors, an interlocking joint was developed that could be quickly cut in alignment with the long axis of the culm using a CNC router. (Figure 9a) This enables shorter sections of culm to be interlocked into longer panel parts while providing a means to straighten culms that are bent too far out of axis. (Figure 9b) This strategy also allows similar diameter and wall-thickness sections of culm to be joined with each other as a way to maintain panel thickness consistency and maximum gluing surfaces. While mechanical testing is needed to validate the structural performance of this method, our hypothesis is that increasing the reliable straightness, thickness, and glue surface of culm stock within a panel will at least mitigate any negative impacts from the severing of full culm lengths and splicing of smaller parts. This splicing method should prove useful in panel assemblies as well as glue laminated bamboo beams.

a) CNC routed splice joint b) Splice joints arrayed in panel

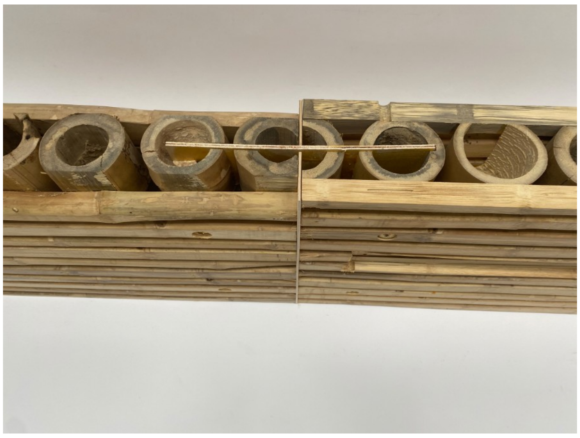
Figure 9: Splice joints help to address culm irregularity.

AGGREGATED CONSTRUCTION & PANEL JOINERY

After validating our assumptions for the structural potential of Mass Bamboo with the second generation of test panels, parallel investigations were begun to develop methods for scaling the system into aggregated constructions. Multiple iterations of full-scale installation designs were developed with the intent to test a variety of panel to panel assembly conditions at something closer to the scale of a building. A design was selected which presented the opportunity for the fabrication of larger panels up to 3' x 10' (1 m x 3 m) and the testing of a variety of panel joint conditions. The installation was designed at a scale that would encourage human engagement, both to test the durability of construction and to promote interest and exploration from those engaging with the assembly. Joint prototypes were developed and assessed for ease of fabrication, reliability and durability.

Joinery development

A variety of joints were developed for prototyping that could accommodate the connection of panels (1) edge-to-edge in a linear assembly, (2) at right angles with one panel ending into another, (3) at right angles with one panel crossing over another, and (4) at right angles with one horizontal panel intersecting one vertical panel. In a linear assembly, edge-to- edge butt joints were considered with both internal and external mending plates. The internal method consisted of cutting a thin slot along the entire length of both edges with a skilsaw, inserting plywood as a splice, and then bolting all the way through the panel and plywood on both panels. (Figure 10a) The external method consisted of cutting shallow reliefs along the length of the front and back panel edges using a CNC, aligning a plywood splice on either side, and bolting through. (Figure 10b) The prototype of the external plate was unreliable due to the bolts being too near the edge of both panels, providing much less strength than the internal method which allowed hardware to pass through the second pole in from the edge. While the detail could have been adjusted to increase the fastener distance from the edge, the internal method was preferred for ease of fabrication and aesthetic considerations.



a) Internal splice joint b) External splice joint

Figure 10: Edge-to-edge splice joints

For the corner condition joints were tested as both a rabbet joint and a corner butt joint that utilized inserted wooden bucking blocks for fastening. The rabbet joint consisted of cutting a deep shoulder, almost through the entire middle layer using a CNC, to receive the second panel. Lag screws were then driven through the remaining lap on the rabbeted panel and into the unaltered panel. (Figure 11a) The butt joint was a similar process but requires less machining. Rectangular openings were cut to size in strategic locations along the panel edge, and a bucking block was inlaid, providing a solid mass of material for a screw to be embedded reliably. (Figure 11b) Without this bucking, the majority of threads on a screw are likely to end up in a void in the bamboo and fail to provide a reliable connection. Ultimately, the butt joint was chosen because it requires the least machining and therefore had the highest material and labor efficiencies. Although rabbet joints are commonly considered more robust in furniture design, we were confident that the butt joint was more reliable because it did not have the additional risk of delamination.

a) Rabbet style joint b) Butt joint with blocking

Figure 11: 90-degree corner joints

As a right-angle condition with one panel crossing over another, a simple slot joint was produced. This was fabricated using a 3-axis CNC router with a three inch wide straight two-flute cutter to provide an initial rough out, and then a smaller diameter cutter to machine cleaner internal joint edges. Although we used a CNC process to create this joint in our facility, this joint is simple enough to be cut using analog tools such as a framing skilsaw, handsaw, or a combination of the two.

Full scale installation

After testing prototype joints at a smaller scale, large panels were fabricated for the construction of the installation assembly. (Figure 12) While the simple slot joint and butted corner joint were replicated in this construction nearly identically to those produced in the prototype tests, the availability of materials and tools forced further experimentation to create an edge-to-edge detail which used bored holes and an inserted piece of 1-½" diameter EMT conduit pipe cross bolted to secure through each panel. A large mortise and tenon like joint was used to embed a bench component horizontally on the faces of larger panels. The main challenges throughout the panel fabrication process were pole sorting and selection, layer nesting for panel assembly, and panel edge trimming.

Selection of tre gai for the middle layers was determined by a desired diameter of approximately 3.5 inches (90mm). This most often resulted in solid faces when machined, due to wall thickness being rather consistent over the length of a 13 foot (4 m) pole. The Iron bamboo, on the other hand, proved more difficult to sort consistently. Our available stock of iron bamboo includes 6 foot (1.8 m) poles and 18 foot (5.5 m) poles. The 6 foot parts are mostly cut from the same culm section as the lower segments of the larger poles, and therefore have a consistently larger wall thickness, some nearly solid all the way through. The 18 foot poles range greatly in diameter and wall thickness from base to top, with the top 6 to 8 feet being almost too thin walled for panel application. A proper sorting and grading system needs to be implemented for the iron bamboo moving forward because these thin walled poles create limitations for reliable fastening to the panel, lacking in local compressive strength of the outer layer.

Another challenge of fabrication at this scale was nesting of culms in each layer, moreso for the tre gai middle layer. While tre gai culms were selected to achieve target thicknesses and provide substantial surface for glue adhesion in each panel, more consideration needs to be given moving forward for the relationship of node locations in each culm to projected joint locations between panels. For example, fabrication of the slot joint in the final assembly left a thin sliver of a Tre Gai pole on one of the final panels, which is at risk of breaking off through repeated assembly of the joint, compromising joint resilience and potentially contributing to further delamination of the panel itself. The location of joints needs to be considered prior to panel fabrication and parts intentionally placed such that machining provides adequate bearing surface and node positioning that provides durability within each part.

Figure 12: Full Smart Bamboo test installation and student team

PARAMETERIZED BAMBOO
As illustrated above, one of the biggest obstacles to the use of bamboo in a standardized construction system is its inherent variation. While this proves an undeniable challenge for consistent and reliable work holding, machining, and precision modification of the bamboo culm, we also see this variation as an opportunity for the integration of bamboo's natural structural intelligence within the design paradigm of mass-customization. Through computation and digitally assisted manufacture it is possible to integrate this variation into a process that results in a rich design vocabulary informed by the specific qualities and performativity of the material at hand. By the use of IOT sensing technology, such as photogrammetry, laser scanning, and others, each piece of bamboo stock can be cataloged in a real time and on-demand digital library. This library of available stock is then integrated into a computational script that uses evolutionary solvers to find the most appropriate bamboo culm for each member of an assembly based on a set of assigned criteria.

Beginning with an ideal structural model, the script analyzes each piece of the stock in the library to optimize its placement in areas of the structure where their morphological qualities will be most appropriate. Bamboo stock can be sorted by diameter and correlated wall thickness in order to assign denser and more reliable stock in areas of greater structural demand, and stock with less integrity or performance value in areas of lower structural demand. In a process of generative design, the form of the structure itself can be computationally tied to feedback from pole morphology. (Figure 13) Node positions along each culm can be analyzed to optimize part placement to align nodes with optimal areas that increase the strength of joints between components and also adjust the form of the structure if necessary to create optimal nodal relationships. To date, these computational tools have been developed with a focus toward lattice-systems as part of other avenues of research, but we are confident that the same algorithmic logics can be readily applied to the panelized Smart Bamboo system presented here.

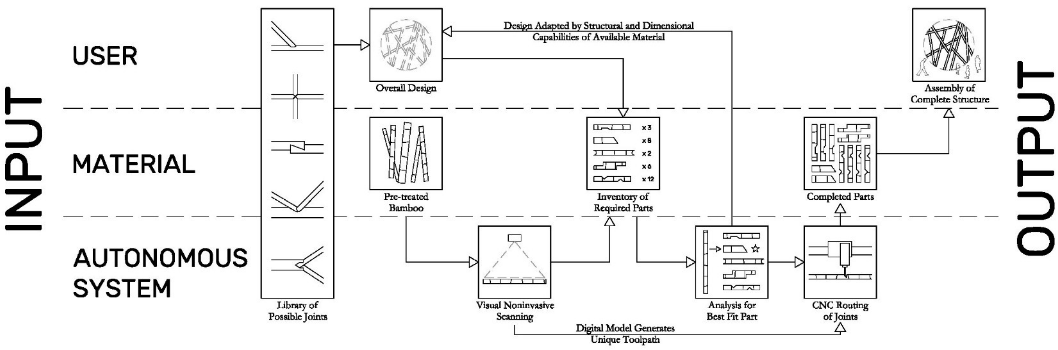


Figure 13: Non-standardized materials workflow. Kyle Schumann

In order to optimize the use of available bamboo stock, we are developing scripts to analyze parts for node location, node spacing, straightness, diameter, and projected wall thickness. Node location and spacing can suggest arrangements that lead to more efficient nesting of materials within panel layers, as well as positioning nodes in locations where they will help to carry loads and create solid fastening points for joint connections with other panels or components. Stock can be sorted by variations in pole straightness in order to promote efficient packing, suggest pole splicing locations (as described in *Addressing Eccentricity* above), or potentially suggest culms with more drastic curvature to be placed in regions of panels that may benefit from voids, such as necessary openings for fenestration or utilities. The diameter of stock can be correlated with data from structural testing in order to grade stock by its potential structural performance. Using this grading information, stock can be placed where it is most appropriate within an assembly. (Figure 14) This could mean placing particular pole stock strategically within a panel, but also within a larger structure.

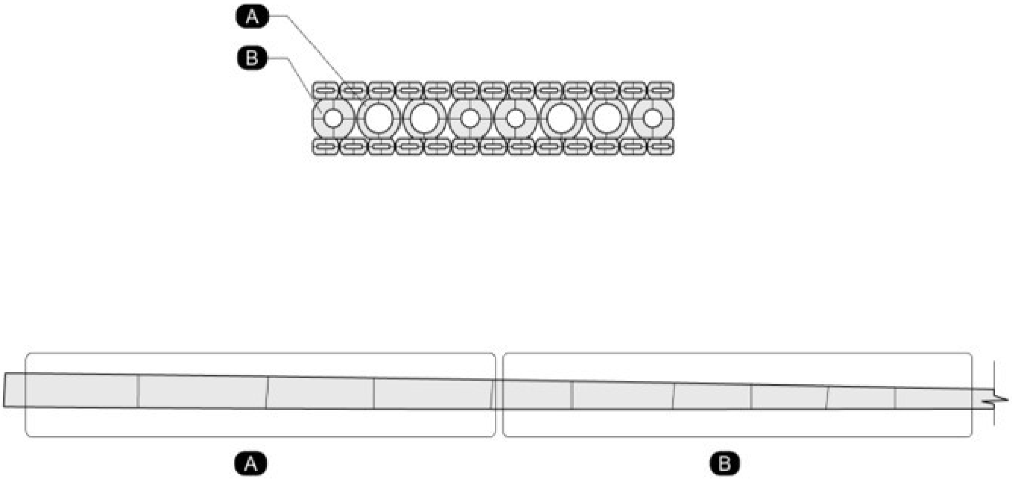


Figure 14: Optimizing material placement for structural performance

CRITICAL PATH

Having gathered substantial qualitative data supporting our hypotheses about the potential of Smart Bamboo as a structural building system, we are enthusiastic to continue this area of research along multiple lines needed to validate initial assumptions, improve the means and methods of manufacture and assembly, and incorporate considerations that have only been theorized or tested preliminarily to date. Additional ongoing research includes: (1) aggregated quantitative testing data to verify reliability of structural performance and establish a standard engineered product; (2) development of reliable and repeatable non-invasive grading tools and processes; (3) development of a robust fire barrier system that will allow the system to be utilized in mid-rise structures; (4) development of moisture/vapor barrier strategies that allow building enclosures that comply with contemporary performance standards; (5) the continued development and testing of bio-adhesives that can decrease the proportion of non-organic materials used in the system; (6) continuing investigations of building scale assemblies that lead to further insights into both the manufacturing process and optimal design of system components and interfaces; (7) the integration of building features and infrastructure, including fenestration, mechanical, electrical, and plumbing systems; (8) the application of building finishes such as interior wall finishes, exterior cladding finishes, and floor and roof surfaces.

Finally, an integral aspect of our vision of a Smart Bamboo system is its collaborative development by participants around the world. The incredible variety of bamboo species and their immense variation in morphology based on environmental conditions suggests that it is only through a concerted collaborative effort that enough data and knowledge can be aggregated and applied at the scale necessary for this system to make a meaningful contribution to the radical reduction of carbon in our atmosphere. Our intent is to support the development of an open-source library of data and information that empowers anyone to begin constructing with this incredible material. By lowering barriers to entry, we hope to encourage the adoption of these techniques far and wide, supporting the growth of new economic opportunities for farmers and workers in the global south and contributing to a broader movement toward sustainable construction and development.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.