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Meristem : Connectors for Cluster-Laminated Bamboo structures

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Abstract

This research explores the application and possibilities of fibrous bundling construction in Glue Laminated Bamboo (GLB) technology. In the design of the bamboo structure, connection nodes are the crucial part of structural load transfer. As the lignocellulosic material, the connection in raw bamboo have major difficulty in developing and applying. This research aims to mimic the force transfer mechanism observed in the meristem, which balances the dynamic forces through the branching system and growth distribution of vascular bundles. This study introduces the finger-jointing technique prevalent in manufacturing industrial laminated bamboo beams, increasing the homogeneous strength distribution of connection while mitigating the additional loading associated with heterogeneous materials and expressing bamboo's materiality. With the advantages of small sections, the bendable rod bundle has a great performance of adjustability. This paper is composed of these section, including: (1) research and comparison the current joint research in the bio-based construction field. (2) the comprehensive overview of cluster-laminated bamboo fabrication workflow (3) the performance validation of the bamboo rod connection method. (4) fabrication. This research established the digital fabrication workflow of cluster bamboo rod connection, assessed the bundling method and fabricated physical model for verification.

Keywords: bamboo construction, connectors, assemblies, glued laminate bamboo, lightweight structures

1. Introduction

Within the Post-pandemic Era, the increasing number of building investment projects made the urgent, widespread use of Low-carbon building materials more important than ever. Among today's building materials, Bamboo is one of the lowest hidden carbon emissions—a fast-growing, short-harvesting, and highly high carbon storage natural material.

However, the bamboo structure system is hardly widespread. Because the difficulties caused by bamboo connectors limit bamboo structures' complexity and geometrical possibilities and make bamboo hard to assess and regulate**.** The connector play a crucial role as the overall structural performance, not only bear the transfer of forces between the bamboo, but the jointing method and the manufacturing difficulty also determine how the bamboo joint can adapt to various structural forms. The natural attributes of raw bamboo, such as its uneven shape, varying diameters, and hollow and thin-walled structure, make bamboo regarded as an untamable structural system for a long time [1].

This research is situated within computational design and digital fabrication research fields that include, complex joinery, and lightweight bamboo systems. This study seeks to challenge traditional perceptions of laminated bamboo. The following will be the contributions of this research :

- Unveiled a novel connectivity applications and lightweight structural systems of cluster laminated bamboo in design applications
- Establishing a multi-members connection solution by the sequence of distributing logics
- Validate the performance of the bamboo rod connection method with tensile test and bending test.

2. Literature review

In the field of engineering bamboo, the fibrous system is not a hot research topic. Since 1914, people have been putting effort into finding an appropriate application for bamboo as a building material. Among these decades, the research began with bamboo splits as reinforcement materials of concrete to Glue laminated bamboo (GLB) to latest biologically based composite material [2]. To maximize the performance of bamboo fiber, we identified an opportunity in the use of processed bamboo rods, which were originally employed in crop protection structures.

Throughout the history of fibrous systems in architecture, the concept of fibrous bundling has been used in building construction for a long time. Like the Ma'dan in south Iraq and the South American Uros, the fibrous system combines individual member continuity with the potential for bespoke and locally differentiated material distributions [3]. The utilization of fiber systems in construction has gained attention lately, with more experiments and explorations being conducted in this field. (Figure 3) The project presented at the Centre for Information Technology and Architecture in 2017 [3] demonstrates the potential of fibrous systems and solving the complexity of multi-member assembling that emulates fibrous biological systems through their growth mechanisms and the utilization of generative design; they showcased the complexity and responsive possibilities of the fibrous system.

In previous research, the development of raw bamboo connectors often required integrating different materials, such as metal parts and concrete, to equal the pressure distribution and controllability of the connection. However, it makes a solid visual impact and complicated construction process and is problematic in assessing actual capacity [4].



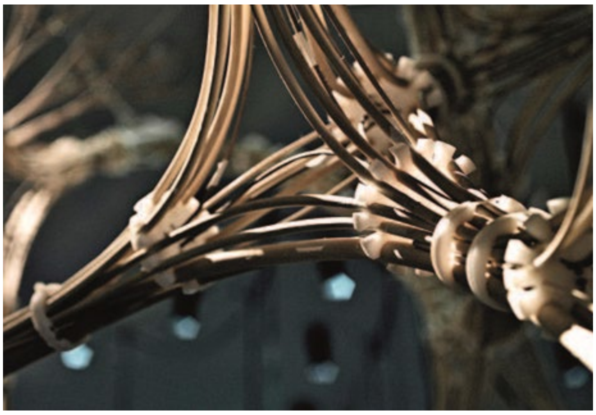
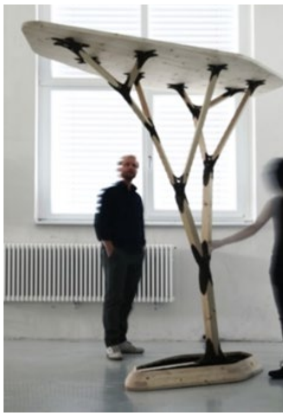



Figure 1: (Left Top) Airlab. 3DP joints [Verde, 2019] Figure 2: (Left Bottom) MJF 3DP joints [Kladeftira,2022]
Figure 3: (Mid) The Rise. Star nodes [Tamke, 2020] Figure 4: (Right) FRP+joinery [Chen,2021]

2.1. Bamboo Joints

As a non-standard material, joining bamboo has always been challenging among other engineered bamboo research. Besides the selection regulation of bamboo material, customized connections are the other popular solution. Additive manufacturing technologies are a favored topic in bespoke bamboo joint research. In 2018, Sombra Verde presented a 3DP joint with concealed fasteners and adaptor pieces to accommodate different pole sizes. In 2022, M. Kladeftira et al.(Figure 1) showcased a connecting system using multi-jet fusion (MJF) technology to ensure the balance of strength between the 3DP joint and bamboo.(Figure 2) The development of raw bamboo connectors often required integrating different materials, such as metal parts and concrete, to equal the pressure distribution and controllability of the connection. However, it makes a solid visual impact and complicated construction process and is problematic in assessing actual capacity [4].

Bolts or rivets play a crucial role in ensuring the structural integrity of adjacent units by fastening them together. However, the structural composition of bamboo, characterized by its lack of circular fibers in its stem, predisposes it to longitudinal splits. This inherent characteristic makes the majority of metal fasteners, directly detrimental to the structural performance of bamboo when used as a jointing material. Consequently, this research has pivoted towards the exploration of comb-jointing techniques, a method referenced from traditional woodworking, as a viable alternative for unit connections in bamboo structures. The comb-jointing method enables the creation of entire bamboo joints by addressing the critical design consideration of achieving an equal distribution of pressure, whether it be cane to cane or screw to cane. By employing extensive rods in the comb-jointing process, the friction generated between the canes facilitates their bonding. This bond is further reinforced when the assembly is tightly laminated with epoxy resin and Fibre-Reinforced Polymer (FRP), allowing for the direct transfer of force along the axial direction of the rods, thereby preserving the structural integrity of the bamboo.

This study devoted in discovering the benefits of bamboo-made joints. Because the advantages of good economic performance, high construction efficiency, simple and reliable transmission of force [1] Following the topic mentioned in introduction, without the metal parts and connectors, we are able to reduce energy consumption, and the dependence on metal resources. In addition to the sustainable benefits, the bamboo joints system can also prevent the reduction of load-bearing capacity caused by rapid high temperature, which often happens in metallic components. The heat transfer of metallic components leads to a rapid temperature increase in the connection, reducing the load-bearing capacity in case of fire and as a consequence the fire resistance of the entire structure [2]. The high concentration of silicic acid within the bamboo wall also make bamboo itself flame-resistant [4]. To be designated as flammable building material, The defects of hollow cross-section from raw bamboo can be solved by cluster laminate the solid bamboo rods.

3. Methods

This research aims to utilize a distribution logic to solve the complexity of multi-members connection system and the jointing variability. This research focused on the digital design-to-fabrication fabrication workflow of bamboo joints and constructed into five parts:

- Form-Finding in Active-Bending methods and the spring-based simulation
- Finite Element Analysis (FEA) for optimize structure segmentation and member distribution
- The logic of the member distribution pattern of branching
- Material study and the manufacturing method of laminated bamboo rods
- Structural asssesment of the connection methods

3.1. Manufacturing Feasibility

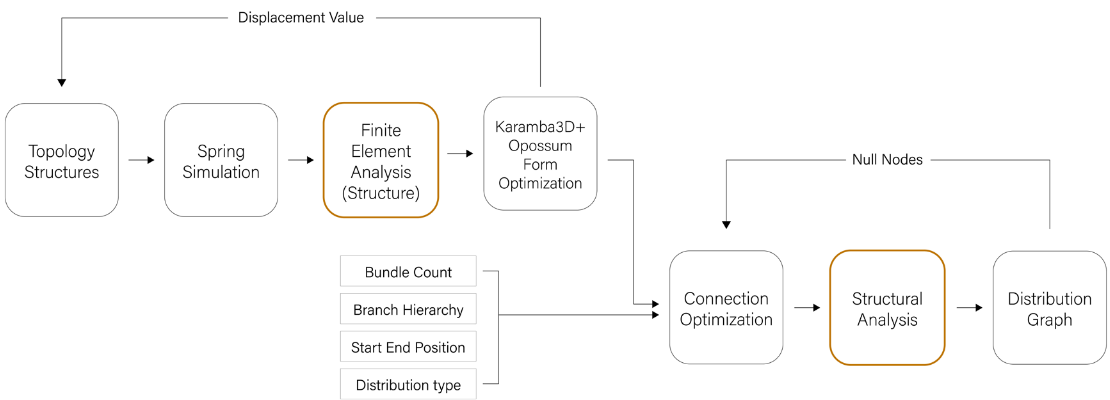


Figure 5. Design-to-Fabrication Workflow.

From design to manufacture, this design establishes a workflow to manufacture the cluster-laminated bamboo structure, from form-finding to structure optimization. After we get the connecting pattern and the members connection information of nodes from a distribution logistic system. In the fabrication part, our idea is to reposition these rods to a precise start and end position by the formwork, the capacity of elastic deformation of bamboo rods will self-forming each rod to the shape we want. (Figure 5)

3.1.1. Form-finding

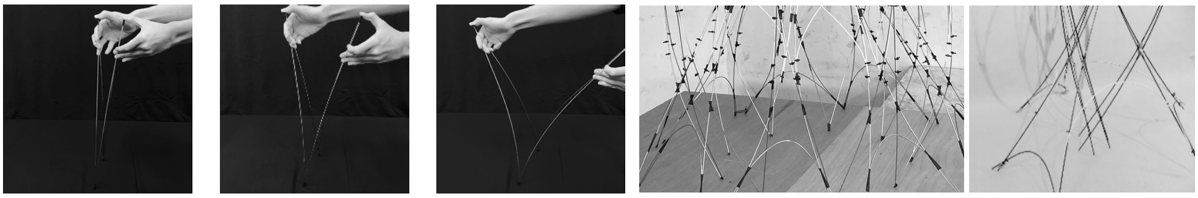


Figure 6. Bending Active Form Finding Experiments.

In the form-finding process, we develop the form through the physical model in the previous research. The structure form shows its elastic properties through an active bending process. Utilizing bending-active as the forming strategy, this study advances the form by using the parametric tool Grasshopper plugin Kangaroo to simulate the elastic behavior of bending-active by spring component. (Figure 6)

3.1.2. Structure Optimization

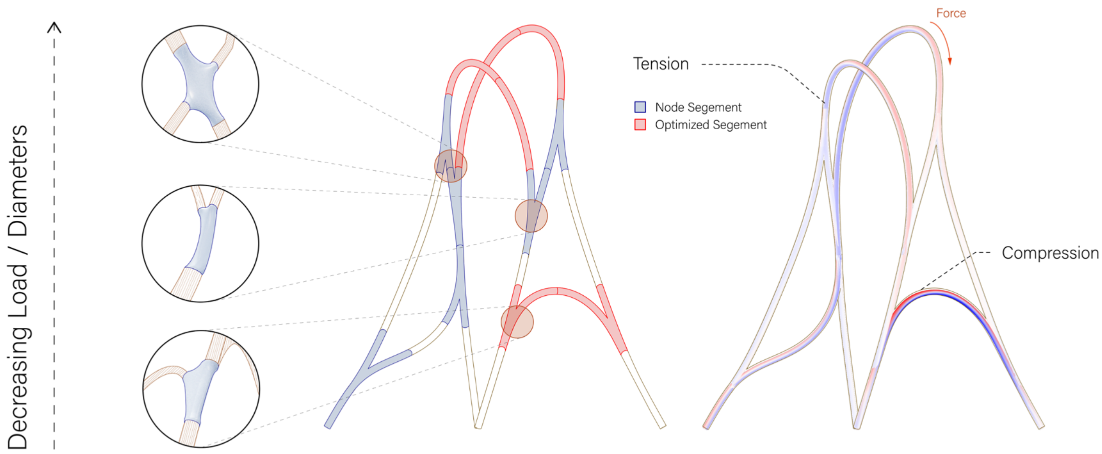


Figure 7. Structure Segmentation and Structural Optimization.

To manifest the adaptability and variability of the innovative jointing method, the idea of forming morphology in the study aims to creating diversified connect situation, like branching, interweaving, and overlapping, With the advantages of small cross-section of bamboo rod and highly controllable digital framework, complex joinery can be easily produced and manufactured.

From form-finding to segmentation optimization to node optimization of rod distribution, the Grasshopper plugin Karamba3d for FEA (Finite Element Analysis) was utilized in this research to achieve static equilibrium and prevent stress concentrations. Below is our structure optimization step:

1. Form-finding optimization with Galapagos + Karamba3d
2. Structure segementation optimization
3. Weak area reinforcement optimization
4. Bamboo member distribution optimization

Through material testing and simulation, the bending limit of bamboo rods can be quantified and should be considered in the form-finding process. Therefore, we utilized Karamba3D with the evolutionary solver Galapagos to find the result with minimal displacement. When the final structure is determined, the segmentation process should begin with defining the node separation positions. accompany with the consideration of utilization and displacement value from FEA data, the area where may encounter stress concentration can be identify and optimized by splitting segment into smaller sections or thicken the diameter of section, the distribution of extra rods was allocated based on the area needing more compression or tension support.

The form of bamboo joints is associated with the continuity curves from the topological distribution. Before the distribution process, the structure need a simulating node to analysis the integrated structure performance, By setting the end of the input rods as the domain boundary, shrink-wrapped algorithm was used to simulate the intersect nodes in this research. (Figure 7)

3.1.3. Distribution logic

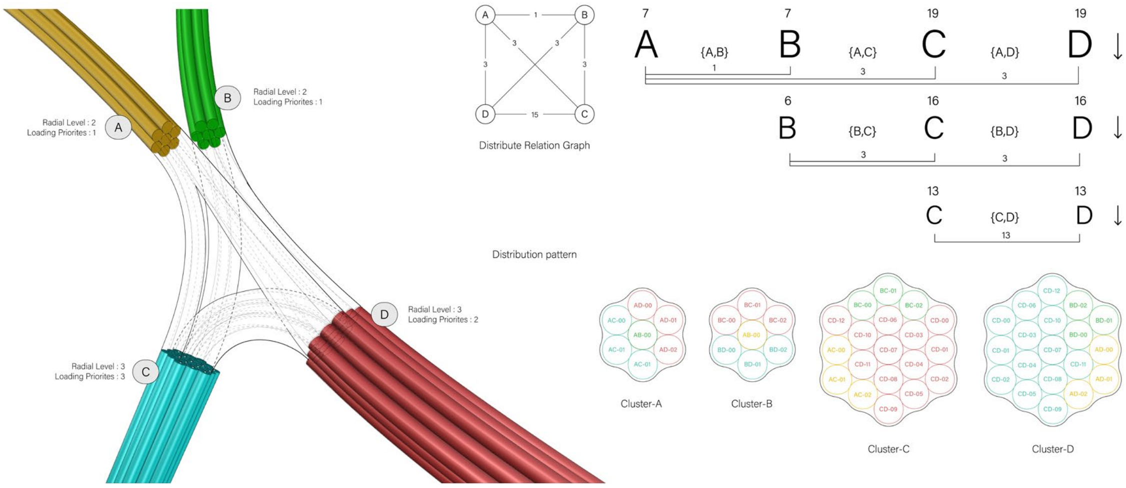


Figure 8. Distribution Process.

According to the optimization method for FE analysis outlined in section 3.1.2, optimizing the continuation of the multidirectional connector requires addressing not only the variation in the number and direction of the cluster bamboo bundles, but also the even distribution of forces between bamboo elements, which can be influenced by the distribution pattern of structure.

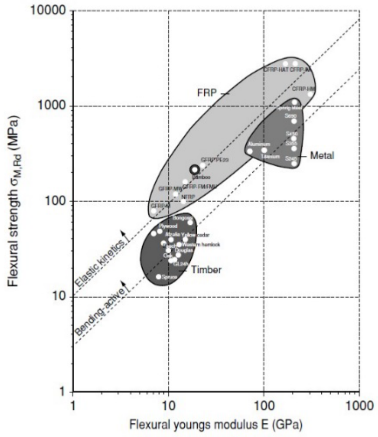
In solving the complexity of multi-members connection system and the jointing variability, we created a distribution logic sequence to optimize the interweaving pattern and connect sequence which based on karamba3D's load analysis.

- The branches will be processed in descending order based on the number of branches and then traversed accordingly. The allocation process will be done in two stages. In the first stage, there will be a proportional allocation of rods in each branch to the target branch, intercepting from the specified branch to the target branch in proportion to the target branch.
- In the second stage, the remaining unmatched rods will be marked as null objects and then reallocated to the branches that Karamba3D has analyzed to have larger compression. Through this iterative process, the numerical relationship between clusters will be defined.
- In the third stage, topological distribution will be generated in Grasshopper for Rhino using C# scripting. For better continuity and shorten the connect distance, topological distribution

3.2. Material Study

Into the research field of engineering bamboo, processed bamboo rods, which were initially used as temporary structures for agricultural purposes, have hardly been discussed. In current bamboo construction, natural and raw properties prevent the development of automatization, reproducibility, and normalization of bamboo [6]. This study explores the potential advantages of bamboo rods, which are standardized to have the strength of solid circular cross-section and higher torsional strength.

To validate the bending strength of single bamboo rods, this research used the bending experiment to test the maximum bending strength. (Figure 9,10)



Type: metals	Flexural strength $\sigma_{M,Rd}$ (MPa)	Flexural youngs modulus E (GPa)	Ratio
S245	245	210	1.17
S355	355	210	1.69
S450	450	210	2.14
S690	690	210	3.29
Spring steel	1100	210	5.24
Titanium	340	102	3.33
Aluminum	330	70	4.71
Timber			
Spruce	16	8	2
Pine	24	11	2.18
Douglas	30	12	2.5
Western hemlock	35	13	2.69
Yellow Cedar	40	15	2.67
Oak	30	10	3
Beech	35	10	3.5
Afzelia	40	11	3.64
Bongossi	60	17	3.53
GL24h	24	11.6	2.07
GL28h	28	12.6	2.22
GL32h	32	13.7	2.34
GL36h	36	14.7	2.45
Plywood F25	25	5.5	4.54
Plywood F40	40	6.0	6.67
Plywood F50	50	7.0	7.14
Plywood F60	60	9.0	6.67
Bamboo	213	19.13	11.13
FRP*			
CRFP-HAT	2800	165	16.97
CRFP-IM	2800	210	13.33
CRFP-HM	1350	300	4.5
P E 23	300	23	13.04
GRFP-M	80	7	11.43
GRFP-MW	120	12	10
GRFP-FM/FMU	160	15	10.67

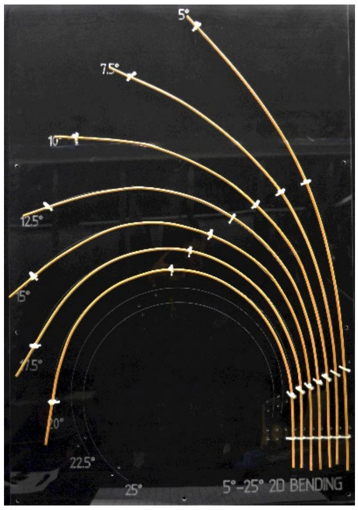


Figure 9: (Left) Materials with ratio of strength σM (MPa) to stiffness E (GPa). [Lienhard, 2013]
Figure 10:(Right) The visualization of bending strength test of single bamboo rod.

3.3. Laminated Bamboo Rod

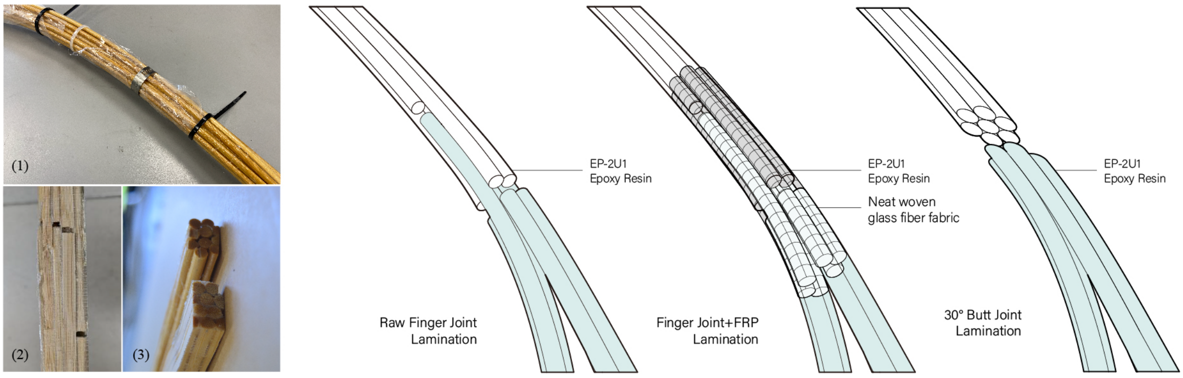


Figure 11. Laminated bamboo rod connection methods.

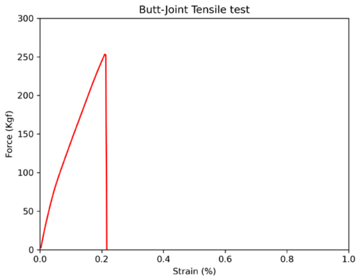
In the manufacturing process of cluster-laminated bamboo rods, structural performance is directly related to the compactness of the laminated object, different from other Glue laminated bamboo products; bamboo rod's circular cross-section makes it hard to integrate tightly, minimal contact area defects when laminating other rods, so we conducted experiments using various methods to strengthen the performance of laminate the connection part. (Figure 11)

These methods included Raw finger jointing, Finger jointing with FRP, and a 30-degree bevel cut. In the first method, we conducted finger-jointing, often used in wood crafting, to achieve sufficient friction and contact area. In the second method, in addition to finger-jointing, glass-fiber is added as the reinforcement material, the filler material creates the necessary cohesion. In the method of a 30-degree bevel butt joint, a 30-degree angle is used to increase the contact area during lamination.

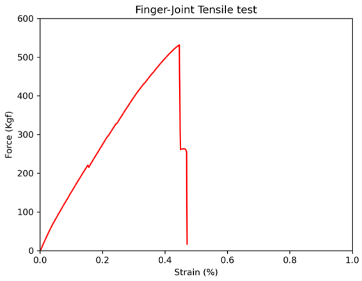
The design of bamboo joint in this study is constructed of fibrous bundling material. The mechanics of bundling are based on fiber-to-fiber friction to find the sufficient compound performance. This study assesses different jointing methods to verify the structural performance of jointing. The Assessment includes two phases: the First phase is the tensile test, and the Second is the bending test.

3.4. Assessment of the Connection methods

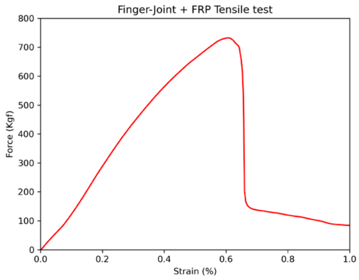
A1. Tensile test – Butt Jointing.



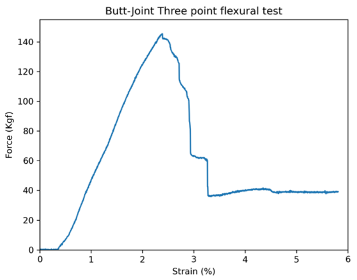
A2. Tensile test – Fingering Jointing.



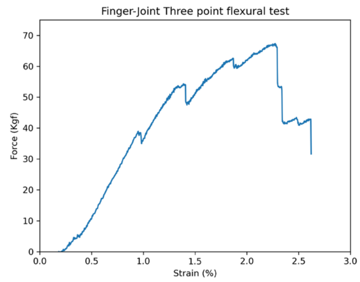
A3. Tensile test – FRP+Fingering Jointing.



B1. Bending test –Butt Jointing



B2. Bending test –Fingering Jointing.



B3. Bending test – FRP+Fingering Jointing

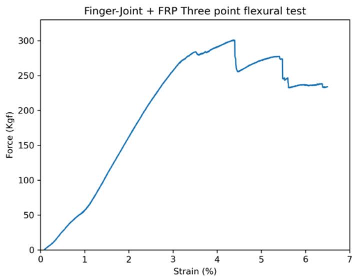


Table 1: chart information of tensile test.

items	Length (mm)	Width (mm)	Thickness (mm)	Tensile Strength at Max. Load (kgf)
FRP+Finger Jointing	398	20.96	15.15	732
Finger Jointing	397	22.54	14.26	531
Butt Jointing	402	21.13	15.01	253

Table 2: chart information of bending test.

items	Length (mm)	Width 1(mm)	Width 2(mm)	Width 3(mm)	Flexural Strength at Max. Load (kgf)
FRP+Finger Jointing	300	23.2	22.05	21.5	301
Finger Jointing	293	22.25	21.35	21.67	58
Butt Jointing	293	21.97	21.72	21.67	142

In order to find the sufficient compound performance, We prepared each 3 specimens for tensile test and bending test. Including Butt jointing method, Fingering jointing method, Fingering Jointing with FRP(fiber-reinforced plastic) method.

Based on the assessment results, we can clearly see a significant difference between finger jointing (A2) and butt jointing (A1). The tensile strength of finger jointing is relatively higher compared to the highest tensile value of butt jointing. Specifically, the tensile strength at maximum load for the finger jointing (A2) specimen can reach 531 kgf. This demonstrates that finger joints can already be frictionally bonded, allowing for a complete transfer of power. Furthermore, with the reinforcement of glass fiber, FRP + Finger Jointing can achieve even 732 kgf, fiber reinforcement increases the load capacity three times than butt jointing (A1).

In the bending test, the performance of Fingering Jointing (B2) is much lower than Butt Jointing(B3). Because as an adhesive, epoxy cannot fully bond the rod members into a single unit. After experimentation, we believe that FRP+Fingering Jointing (B1) has the most desirable result, even exceed the the one without jointing (B2). The result showing that the high-performance of fiber reinforcement making it most developable in cluster-laminated bamboo.

4. Physical model fabrication

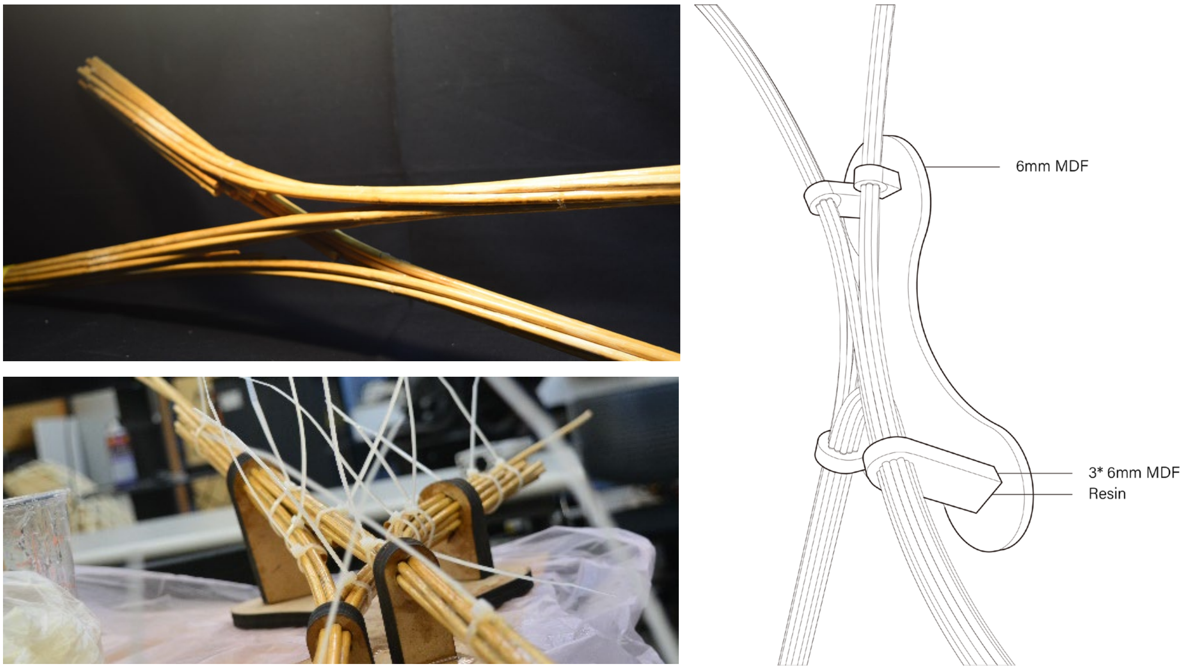


Figure 14. 1:1 scale cluster-laminated bamboo joint part and formwork.

Our 1:1 scale formwork experiment of the jointing method is the filling-locator method, the fabrication setup is including a 6mm Medium-density fiberboard (MDF) made guiding formwork, and the cable ties to fasten the bamboo rods. The filling-locator method means that the member of the rods is fixed and positioned by the friction between the rods within the space arranged by the guiding formwork. After positioning, epoxy resin will be applied evenly to the rods for lamination, After curing, the formwork can be removed by damaging the formwork. (Figure 14)

5. Conclusion and Future Work

This study aims to explore the possibilities of fibrous systems in architectural application, developing processed bamboo rods as fiber units. This raised the structural potential of individual member continuity and the constructability of cluster glue-laminated bamboo.

This research showcased an innovative bamboo-made jointing design-to-fabrication method and validated it with mechanical test results and a viable fabricating process. We were exploring the potential, pitfalls, and complexities of cluster-laminated bamboo systems.

However, this research also pointed out the area for improvement: One is the joint formworks, although joint formworks guide the bamboo rods, manual intervention is still essential to adjust the bending curvature; therefore, accurately automating the curvature control will be the next goal of this study. Bamboo-made joints remove the need for bolts, cement, etc., and other extra building materials. Therefore, this paper will require more substantial structural performance to design connectors, which will be validated through experimental comparison. The result shows that the structural performance of finger joints + FRP solution has the most potential for development as engineering bamboo materials. However, the manufacturing process of impregnating and winding fibers requires a large amount of manual intervention due to the complexity of the manufacturing process. Hence, automation will be a necessary research topic if larger-scale structures are to be produced.

This study provides a valuable contribution to highlighting the potential of cluster-laminate bamboo as an engineering bamboo material. With the design to fabrication workflow, The experimental results of assessments also confirm the practicality of the bamboo joints method for cluster-laminate bamboo.

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