Shell Structure of Bamboo Composite

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Abstract. This research is aimed at proposing a lightweight shell structure made from a bamboo composite. The research explores the addition of glass fiber to bamboo veneer for adhesion to produce a bamboo composite. Adding glass fiber improves the material's elasticity and ductility and strengthens the bond between units of laminated bamboo veneer. Moreover, we utilized a simulation tool to analyze the structural performance and compare the shell structure's mechanical differences before and after adding the glass fiber. In terms of fabrication, this paper presents a computational workflow for mesh segmentation and unrolling as well as a design for unique snap- fit joints for the connection between mesh strips. Finally, this paper outlines the fabrication of one part of the overall form as a demonstration case to verify the proposed method.

Keywords: Digital Fabrication, Bamboo composite

1 Introduction

Because of bamboo culm's growth characteristics (joints, diameter, hollowness, etc.), its material characteristics and dimensions are inconsistent. Therefore, the current research on and uses for construction of bamboo are mainly based on bamboo culm or simple processing for subsequent application (Huang, 2017). Among bamboo materials, laminated bamboo has the most representative development and utilization. Laminated bamboo originates from natural materials and has excellent mechanical properties in addition to being environmentally friendly (Sharma et al., 2015). Relevant studies have pointed out that laminated bamboo's properties are similar to those of wood, and laminated bamboo has been compared with traditional wood in the construction of tructural beams (Echavarria et al., 2012). Hence, laminated bamboo is widely used to make various composite engineering material products, such as strand board, laminated lumber flooring, and construction beam material. However, aside from the traditional beam column structure application, laminated bamboo's mechanical performance in shell structures and its natural fiber material characteristics' effects on structures have rarely been discussed.

2 Objective

In this study, we developed a bamboo composite snap-fit joint method suitable for shell structures. To improve the shell structure's overall mechanical strength, we supplemented bamboo veneer with glass fiber, which is laminated in different fiber directions, to form a bamboo composite. The bamboo composite material completes the lightweight construction by improving the original natural fiber's poor splitting tensile strength and bending strength. This paper presents this material's properties. In terms of the joint design, we consider and discuss the fiber's texture and the snap-fit size and design appropriate joints and patterns to facilitate the joint test. In the second part of this paper, we develop a computational workflow for production and manufacturing and demonstrate the bamboo composite's bending strength on complex curved surfaces. We aimed to build a large-scale pavilion by designing a free-form thin shell structure. In this paper, we take a part of the structure (ratio 1:3 and 1:1) as a demonstration case to verify feasibility.

The current process is as follows: (1) Generate the desired form based on the parametric 3D modeling software Rhino and Grasshopper, and analyze the structure using Karamba3D. (2) After determining the shape, split the mesh, cut it into strips, and unroll them into 2D curves. (3) Automatically generate snap-fit joints on the strips. (4) Laser cut the strips, and then assemble them (Figure 1).

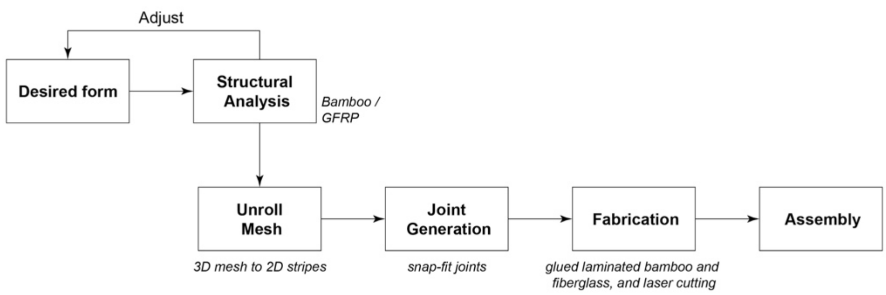

Figure 1. Shell structure made from bamboo composite.

3 Material

Bamboo is slightly similar to wood in structure, and it has strong directionality. Basic material tests show that bamboo has a high tensile strength in the parallel fiber direction, but its splitting strength (i.e., the shear force perpendicular to the fiber direction) is much lower than its tensile strength (i.e., the stretching stress in the fiber direction; You, 2009). Generally, in bamboo structures, damage is rarely caused by axial tension and is mostly due to bending (namely, flexural damage) or buckling caused by an excessive axial load (Lin et al., 2011). Therefore, in our preliminary study, we conducted an experiment with bamboo laminated in the fiber direction to improve its splitting strength and bending strength. After the experiment, we determined that if a construction with a higher bending degree is needed, it may be unable to bear high-strength structural force, depending on the glued bamboo-laminated material's properties. Thus, the laminated material may be easy to break. Previous studies have shown that material structure can be optimized by controlling the fibers' arrangement in different directions of bamboo sheets (30、60 and 90 degrees) (Chieh et al., 2022; Figure 2) and adding glass fiber material to become bamboo composite material (Thwe & Liao, 2003) to improve the shell structure's overall mechanical strength and make it more difficult to crack. In this study, we added bamboo veneer vertically and horizontally arranged and GFRP at a ratio of approximately 2:1 for gluing lamination to improve the material's elasticity and ductility, strengthen the joint strength between parts, and, thus, meet the fabrication requirements.

The bamboo composite used in this study comprised 7 layers, including 4 layers of bamboo veneer and 3 layers of fiberglass material. Based on the bamboo material's fiber direction, we mainly used bamboo veneer cross-laminated with GFRP material and epoxy resin as the adhesive for gluing. Finally, we used a heavy weight to press the materials together to bond more closely while the adhesive dried, thus completing the bamboo composite. The detailed steps are as follows: (1) First, spread a layer of release paper and polyester wadding on the predefined production platform to absorb excess adhesive and prevent it from spilling out of the platform. (2) Place the material in a specific order (Figure 3), and evenly apply the epoxy resin between each two layers. (3) After bonding, place a layer of release paper and polyester wadding on materials, and place a heavy weight on the top of them until the epoxy dries. (4) Repeat the above steps until sufficient material has been produced (Figure 3).

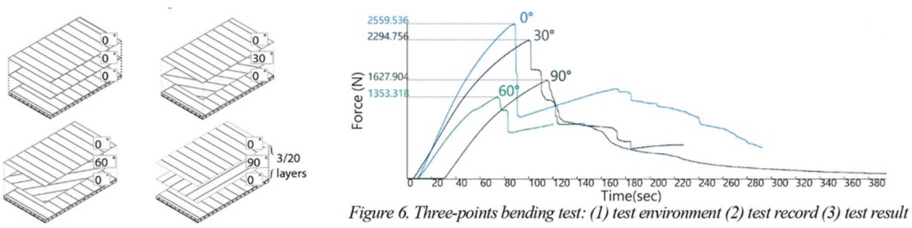

Figure 2. Robotic fabrication process of glued laminated bamboo for material-efficient construction (Cheng et al. 2022).

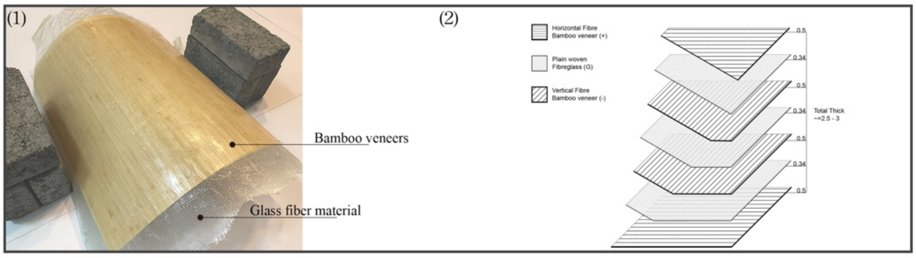

Figure 3. (1) Bamboo composite. (2) Gluing schematic diagram.

4 Design Experiment

In this study, we aimed to build a large-scale pavilion by designing a thin shell structure with a complex curvature. In this paper, we take a part of the structure (ratio 1:3 and 1:1) as a demonstration case (Figure 4) to verify the proposed snap-fit method and demonstrate the bamboo composite's bending strength on complex surfaces. When generating the form at the design end, the surface's curvature is excessively large, making it impossible to bend the material. Therefore, it is necessary to use structural analysis software to optimize the form and eliminate the problem of excessively large bending curvature.

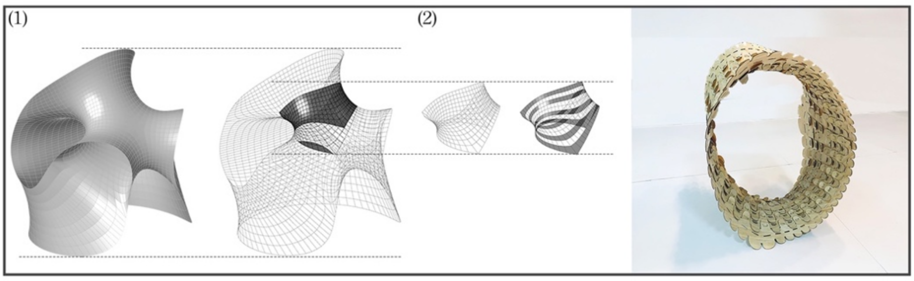

Figure 4. (1) Shell structure design. (2) Part selected for the demonstration (ratio 1:3).

4.1 Structural analysis

After we generated the desired form using Rhino and Grasshopper, we conducted structural analysis using Karamba3D (Figure 7), which analyzes the distribution and value of a model's stress and deformation before optimizing the model to mitigate any excessive curvature of its shape. In terms of parameters the external force adopts self weight and 18 km/hr air speed. Because we did not obtain the material parameters of the bamboo composite used in this study, we used those of bamboo and GFRP to calculate the approximate values. We compared the overall structure difference before and after form optimization and evaluated different materials' influences on the shell structure (Figure 5). The analysis's results are as follows:

(1) Based on the bamboo material's parameters, the structural strength increased by 1.5–1.8 times after form optimization, which shows that the form adjustment improved the material's structural stability (Table 1).

(2) Before the shape adjustment, building a large-scale shell structure with the required structural strength using only bamboo material, the material's thickness should be at least 5 mm. When using bamboo material with GFRP, the material's thickness can be 2 mm to achieve the same structural performance (Table 2).

(3) After the adjustment of shape, the bamboo material and the glass fiber material are mixed in proportion to estimate the displacement, and the material parameter setting is tried to be closer to the bamboo composite material properties, so that the estimation result can be predicted more accurately. The results show that when the glass fiber material content is 33% and the thickness is 3mm, the displacement is 9.39 cm. When the content is increased to 50%, the displacement is reduced to 7.47 cm (Table 3).

(4) When the thickness exceeds 3mm, the overall displacement tends to be gentle. Continuing to increase the thickness of the material cannot effectively improve the structural strength. Considering the production cost of bamboo composite materials, a thickness of 3mm is selected for subsequent development (Figure 6).

After discussions with structural engineers, the displacement needs to be controlled within 15 cm, and the overall structure is relatively safe. Therefore, after adding the safety factor (the intended load-bearing capacity of the structure), the bamboo composite material proposed in this research chooses the thickness of about 3mm and the glass fiber material content of 33% for subsequent manufacture.

Table 1. Comparison of structure performance before and after geometric modification.

	Material	Thickness				
		1 mm	2 mm	3 mm	4 mm	5 mm
Stress	Bamboo	256.00%	67.00%	30.10%	18.00%	12.20%
Stress	Bamboo	141.10%	41.80%	19.80%	12.00%	8.60%

Table 2. Strength and displacement comparison of bamboo and GFRP.

	Material	**Thickness**				
		1 mm	**2 mm**	**3 mm**	**4 mm**	**5 mm**
Stress	Bamboo	141.10%	41.80%	19.80%	12.00%	8.60%
Stress	GFRP	4.80%	1.50%	0.70%	0.50%	0.30%
Displacement	Bamboo	277 cm	43.5 cm	14.7 cm	6.82 cm	3.8 cm
Displacement	GFRP	31.7 cm	5.12 cm	1.83 cm	0.89 cm	0.52 cm

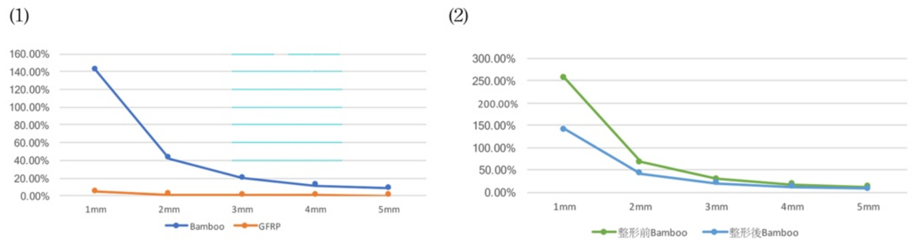

Figure 5. (1) Strength comparison before and after geometric modification. (2) Comparison of thickness and strength of bamboo and GFRP.

Table 3. Displacement comparison chart.

	Material	**Thickness**				
		1 mm	**2 mm**	**3 mm**	**4 mm**	**5 mm**
Displacement	Bamboo	286.52 cm	41.28 cm	13.49cm	6.14 cm	3.35 cm
Displacement	GFRP	29.44 cm	4.35 cm	1.46 cm	0.69 cm	0.40 cm
Displacement	B+G Composite(33%)	199.11 cm	28.72 cm	9.39 cm	4.28 cm	2.34 cm
Displacement	B+G Composite(50%)	157.98 cm	22.81 cm	7.47 cm	3.41 cm	1.87 cm

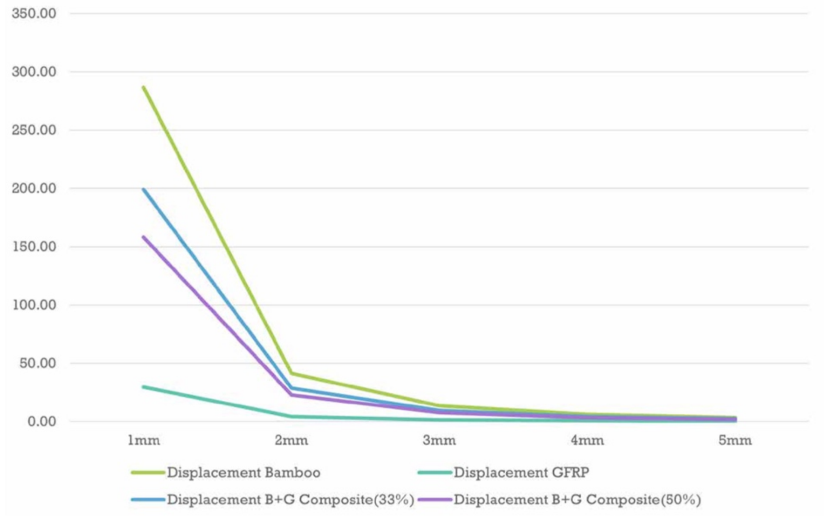

Figure 6. Displacement comparison chart.

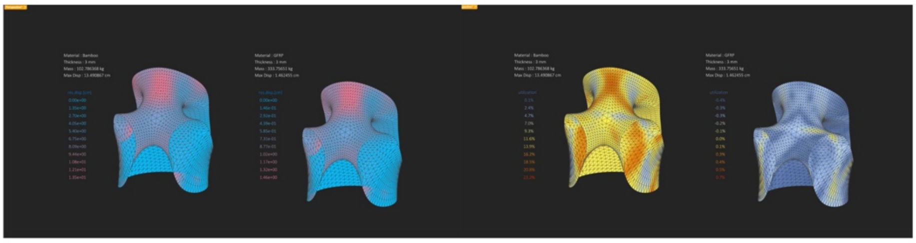

Figure 7. Structural analysis using Karamba3D.

4.2 Mesh segmentation and unrolling

We used Ivy, a plug-in for Grasshopper, to generate clusters of 2D strips and joints from 3D mesh. The arithmetic logic is as follows: (1) Find the mesh's outer edges. (2) Find the shortest distance between the mesh's vertices and its outer edges. (3) Compare the distance with 0 to obtain the Boolean value. (4) Use this Boolean value to split and cut pieces of mesh to generate a cluster of strips. (5) Continue cutting strips according to the above steps until the mesh is completely split. (6) Unroll strips into 2D planar curves for the subsequent joint design (Figure 8).

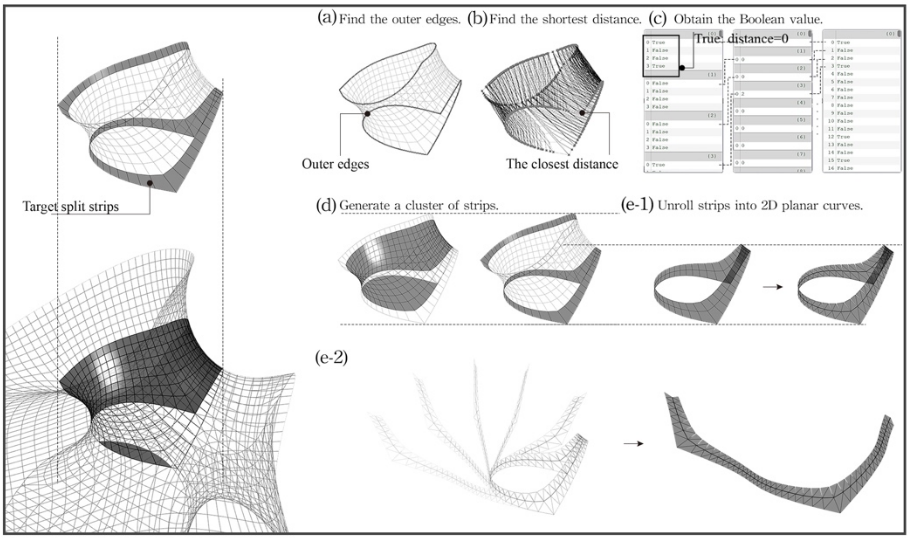

Figure 8. The mesh segmentation and unrolling process. (a) Step 1. (b) Step 2. (c) Step 3. (d) Step 4. (e-1; e-2) Step 6.

4.3 Joint design

After the previous step, we designed snap-fit joints for the connections between the strips. In the preliminary study, we used the friction force generated by the overlapping of the materials and the contact surface for our design and experiment. However, we found that when the material bends, its contact area tends to decrease, resulting in insufficient friction force, which becomes a structural weakness. Therefore, we adopted the snap-fit method instead and used the front and back folding buckle for fixation to increase the contact area and improve the structural strength. In this way, a part of model with a ratio of 1:3 was carried out. The test results are as follows:

(1) Because of the thickness of the material, the junction cannot be folded and buckled smoothly. The surrounding material fibers are often damaged due to the excessively large angle required for fastening, lead to the structural strength lost.

(2) Bamboo composite material with a ratio of 1:1 has a thickness of about 3mm, and has a certain hardness. It cannot be buckled by manual force, and needs to rely on other tools to assist. It is difficult to construct.

To sum up, the method of judging the fastening is not suitable for the actual construction situation, and when the bamboo composite material is folded and overlapped at the ratio of 1:1, it has a high degree of friction. Therefore, due to the required thickness, this fastening method is not applicable, and the upper and lower layers are kept folded back and forth

(Figure 10), and fixed directly with wooden tenons at the breakpoint (Figure 11).

In this study, the snap-fit joints were automatically generated based on 2D planar strips. To prevent the joints from being the weak points of the overall structure, we doubled the number of layers of mesh strips. The high number of overlapping layers increased the structure's overall strength (Figure 9).

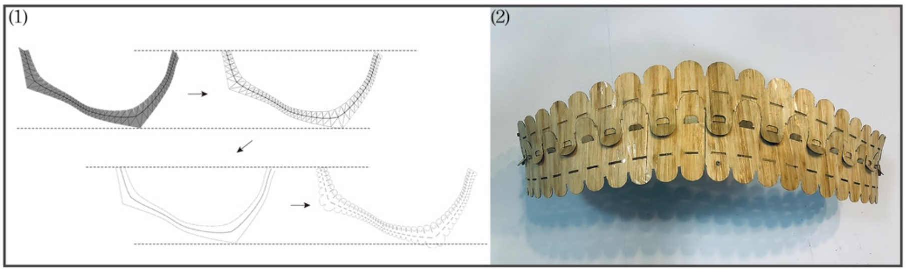

Figure 9. (1) Generation of snap-fit joints based on 2D planar strips. (2) Physical model of joints. (ratio 1:3)

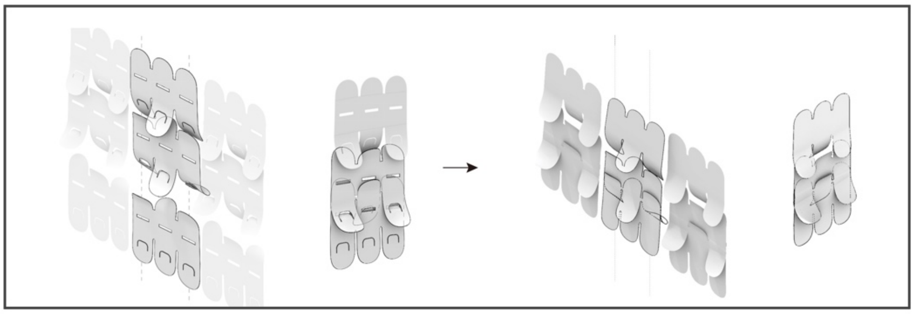

Figure 10. Joint design.

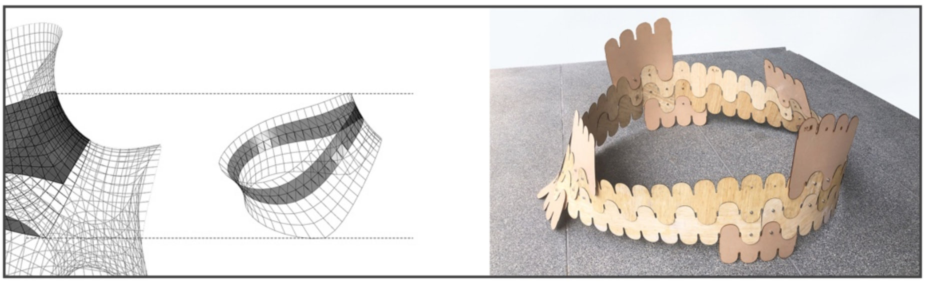

Figure 11. 1:1 a part of model test result.

5 Conclusion and Future Steps

In this paper, we first presented the material properties of laminated bamboo and its current development achievements. The goal of this research was to put forward the ideas of adding GFRP to improve bamboo's structural performance and of designing snap-fit joints for the fabrication of a lightweight shell structure. In this paper, we also proposed a method for optimizing the complex form with structural analysis software to realize the possibility of large-scale fabrication. This study's main contributions are (1) proposing the addition of GFRP to improve bamboo veneer materials' poor bending strength. and (2) demonstrating the bamboo composite's mechanical structure on free-form surfaces; (3) designing a snap-fit method for the joints' connection; and (4) using bamboo composite to fabricate a piece of a shell structure that can be used for further research and applications.

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