Sustainable Structures
ISSN: 2789-3111 (Print); ISSN: 2789-312X (Online)
http://www.sustain-dpl.com/journal/sust
DOI: 10.54113/j.sust.2024.000062

CASE REPORT

Engineered bamboo bridge structure - Report on 3rd International Collaboration on Bamboo Construction

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Abstract: Engineered bamboo has attracted more and more scientists' and engineers' attention in construction field. In order to show the application in bridge structures, the 3rd International Collaboration on Bamboo Construction, jointly organized by Nanjing Forestry University, University College London and International Bamboo and Rattan Organization (INBAR), was held on the campus of Nanjing Forestry University. During the event, Chinese teachers and students as well as some experts from industry, together with international teachers and students, successfully constructed a 12-meter-long reciprocal bridge made of engineered bamboo without using any large mechanical equipment. The main structure of the bamboo bridge was made of laminated bamboo lumber (LBL), and then bamboo scrimber (BS) panels were laid to form the bridge deck. Traditional Chinese mortise and tenon connection was adopted to connect the components of the main structure instead of metal connections. The purpose of this construction event was to demonstrate the feasibility and stability of a large-span engineered bamboo structure as a practical engineering reference for the development of engineered bamboo in the field of construction engineering.

Keywords: Engineered bamboo; reciprocal structure; bamboo bridge; mortise and tenon structure; engineering case

1 Introduction

Bamboo is rich in resources and widely distributed in China, with the area of bamboo forests and the output of bamboo products ranking among the top in the world. The scale of bamboo industry is

Received: 24 December 2023; Received in revised form: 4 May 2024; Accepted: 8 August 2024

developing rapidly, and the level of processing and utilization of bamboo products is at the world's leading level [1]. It is expected that the total output value of China's bamboo industry will exceed RMB 700 billion by 2025, and RMB 1 trillion by 2035 [2]. As an environmentally friendly biomass material in line with the sustainable development strategy, bamboo has a short growth cycle and can be processed into structural elements within 3 to 6 years. Engineered bamboo structural elements have the characteristics of low carbon, excellent mechanical properties, easy processing, and renewability [3-6], and has been a hot spot in the field of construction engineering nowadays. Bamboo only produces gases including carbon dioxide during the process from planting to processing, with little negative impact on the environment. Promoting the use of bamboo can reduce the use of energy-consuming building materials such as cement, steel, sand and gravel, while playing an important role in promoting environmental protection and sustainable development.


(a) Stilted building (b) Dai bamboo building

Fig. 1. Raw bamboo structures (Adapted from https://www.sohu.com/a/241422624_742101).

At the beginning of the development of bamboo structure, most of the components were raw bamboo materials, which can be put into engineering after simple processes such as cutting, polishing and dehumidification. As shown in **Fig. 1**, as a bamboo-producing country, China has many bamboo structures made of raw bamboo since ancient times, such as the stilted building and the Dai bamboo building. Due to the long history of bamboo as a building material and its sustainability and mechanical excellence, scholars have shown great interest in bamboo as a natural fiber material. Through a series of studies, it was found that the microstructure of bamboo determines its macroscopic mechanical properties [7], and the selection of bamboo part, bamboo age, moisture content have a great influence on the mechanical properties of bamboo [8-10]. With a series of research on the connection forms of bamboo, such as bolted connections, steel plate connections, etc. [11-14], bamboo has also appeared in modern structures quite often. However, with the development of modern construction engineering industry, raw bamboo is gradually difficult to meet the requirements of modern structural materials because of the insurmountable natural defects including irregular cross-section and discontinuous mechanical properties, and hence engineered bamboo was produced. At present, laminated bamboo lumber (LBL) and bamboo scrimber (BS) have become the two research hotspots in the field of engineered bamboo by virtue of their high strength, stable mechanical properties; cross-section shape can be customized according to the project requirements and a series of other advantages [15-19], and are also the two most commonly used materials in the field of bamboo structure at present. As an innovative engineered bamboo product, LBL boasts exceptional mechanical properties and ease of processing, making it ideal for a diverse range of applications in the construction industry. Notable examples designed by Haitao Li’s team include Ganzhou Sentai Bamboo Experimental Building [20], Ganzhou Sentai Bamboo R&D Center Building [21], and Wuyi ' Bamboo Cubic' Ecological Science and Technology Museum [22], all of which utilize LBL as their primary building material. These projects demonstrate the versatility and potential of LBL in the construction field, as illustrated in **Fig. 2**.

Since 2019, the International Collaboration on Bamboo Construction, jointly organized by Nanjing Forestry University, University College London and International Bamboo and Rattan Organization (INBAR), has been successfully held on two occasions, aiming to enhance international cooperation, strengthen academic and technical exchanges, promote talent cultivation, and to promote the development of bamboo and wood structure research around the world. During the previous two

International Collaboration on Bamboo Construction events, as shown in **Fig. 3**, wide variety of raw bamboo products were used in building some structures in the campus of Nanjing Forestry University. Based on those events, relevant researchers published reports [23, 24] and the structures have attracted attention to promote lightweight bamboo structure in the field of construction engineering.

(a) Sentai Bamboo Experimental Building [20]
(b) Sentai Bamboo R&D Center Building [21]
(c) Bamboo Cubic [22]

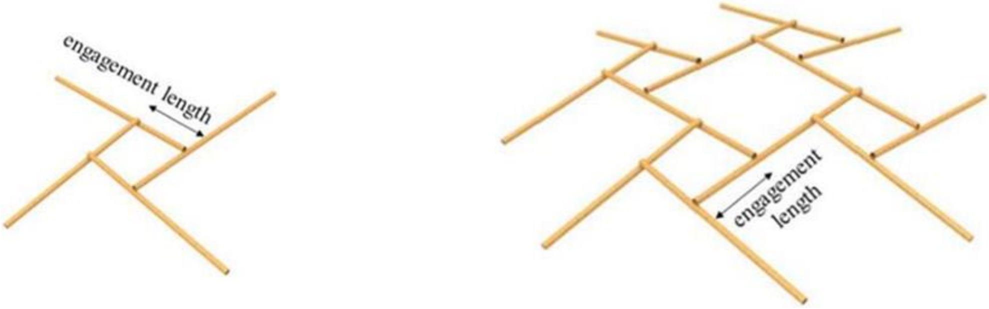
Fig. 2. LBL construction projects.

(a) Structure built in 2019
(b) Structures built in 2021

Fig. 3. The Projects of the 1st and 2nd International Collaboration on Bamboo Construction.

After two bamboo construction events using raw bamboo as the material, the 3rd International Collaboration on Bamboo Construction took place on November 22th, 2022, in which engineered bamboo was used to build a bamboo bridge structure based on the experience and foundation of the previous two events. More than 30 Chinese and international attendants participated in the whole construction process. No large mechanical equipment or metal connections were used during the construction period, and it took around eight hours to complete the construction, which successfully proved the feasibility of completing a construction of engineered bamboo structure in a short period of time through reasonable design and construction planning, and provided a case study reference for the green development of engineered bamboo structures.

2 Reciprocal Structure



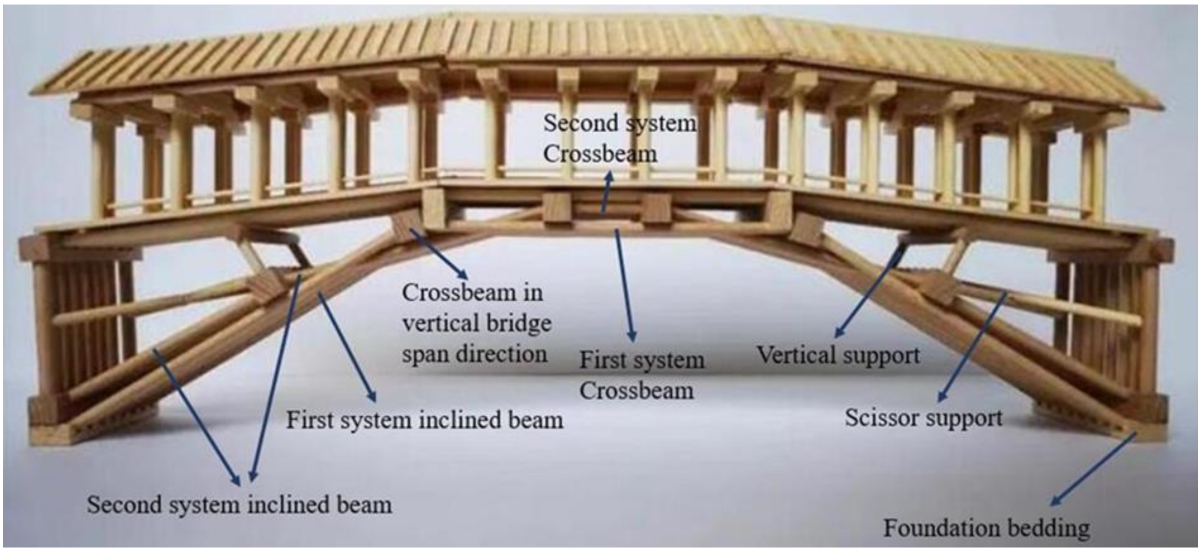
(a) Reciprocal unit
(b) Reciprocal structure

Fig. 4. Typical reciprocal structure (adapted from [27]).

Reciprocal structure, namely mutual bearing structure, is a special structural form, in which the members support each other. Each load-bearing member in the structure is supported by the nearby members, and itself at the same time supports other members of the structure, thus forming a stable structural system as a whole [25, 26], which can be interpreted as a mutual load-bearing and self-lapping leveraged structure, and its typical form is shown in **Fig. 4**. This type of structure appeared early in history and has been used in the architectural structures of various civilizations, but it was not until modern times that it was carefully studied [27-30].

With the advancement of analytical research methods, various scholars have studied the force mechanism and structural performance of reciprocal structures with great interest. Rizzuto et al. [31] listed several joint connection methods commonly used in reciprocal structures and analyzed the advantages and shortcomings of each method by discussing examples of completed reciprocal structures. Kohlhammer et al. [30] studied the structural components in a reciprocal structure by analyzing different bars and units in the structure, and mathematically resolved the force transmission mode between bars. Fan et al. [32] carried out a static-dynamic analysis on reciprocal reticulated cylindrical shell structure, but did not conduct a further study on other reticulated cylindrical shell structures or other curved surface structures. Gelez et al. [33] conducted a comprehensive study on planar reciprocal structures and proposed two methods to calculate the flexural strength and stiffness of the bars. Based on the low strength and low stiffness of single-layer reciprocal structure, Zhang et al. [34] designed a double-layer reciprocal timber member and conducted static tests on the model. A finite element model of the same size was established using ABAQUS, and the finite element simulation results were compared with the test values which produced comparable results. Garavaglia et al. [35] used the finite element method to analyze and numerically study the collapse behavior of the reciprocal structure. However, most of the finite element modelling packages require special subroutines to simulate the reciprocal structure, and further research is required in this field.

(a) Hong Bridge (b) Lounge bridge



(c) Detailed structure of lounge bridge

Fig. 5. Wooden reciprocal structure bridges.

(Adapted from https://www.163.com/dy/article/HEGL9VPF0550AXYG.html)

Reciprocal structures are characterized by the fact that the structural members are connected to each other, and the members can support each other to form bending moments and transfer loads. This characteristic makes construction simple and enables the use of various small-sized members to construct large-span structures.

China, with its many mountains and rivers, had an early start in bridge construction and has many bridges with different structures. Throughout the forms of traditional Chinese bridges, several bridges adopted the concept of reciprocal structure, dating as far back as the Hong Bridge in the Song Dynasty. The Hong Bridge is a wooden reciprocal structure arch bridge that utilizes the reciprocal principle to accomplish the construction of a large-span bridge with small-sized members [36]. **Fig. 5(a)** shows a depiction of the Hong Bridge in a scroll from Song Dynasty. At present, the most primitive structure of the Hong Bridge is almost extinct due to its inability to meet the demands of modern use, but there still exists a number of wooden arch lounge bridges developed on the basis of the Hong bridge in Zhejiang and Fujian, China, as shown in **Fig. 5(b)**. These wooden arch bridges are improved from the traditional wooden reciprocal structure arch bridge, with a unique bridge deck system, which improves the load bearing capacity and stability of the bridges. **Fig. 5(c)** shows the detailed structure of lounge bridge. All components are wooden, to meet the requirements of stability and aesthetic, making it one of the best wooden bridge structures. As can be seen from the structural diagram, lounge bridge has two force systems. By tightly weaving the two systems, structures that cannot be stabilized individually can be combined into a statically indeterminate structure, thus improving the load-bearing capacity of the bridge. Members in wooden reciprocal structure arch bridges were often connected using traditional Chinese mortise and tenon technique, in which two wooden members use a kind of concave-convex combination of connections, letting mortise and tenon bite, resulting in a tightly connected structural joint. In the course of history, many different forms of mortise and tenon connection have evolved, such as dovetail tenon, half tenon, and oblique tenon. The mortise and tenon connection is semi-rigid, which not only has a certain load-bearing capacity and good mechanical properties, but also has a certain deformation capacity [37, 38]. Due to the hollow nature of raw bamboo, mortise and tenon connection was rarely used in traditional Chinese bamboo structures. However, with the emergence of a wide range of engineered bamboo components, mortise and tenon connection can be adopted in bamboo structures.

Due to the similarities shared by bamboo and wood, the study of Chinese wooden reciprocal structure arch bridges inspired the design of the 3rd International Collaboration on Bamboo Construction event. Based on the study and analysis of wooden reciprocal structure arch bridges and mortise and tenon connection, Sketchup software was used to preliminarily design an engineered bamboo bridge. The designed bridge consisted of LBL structural components and BS panels, and experimental slots were made on the LBL components to form simple mortise and tenon connections. Design of the engineered bamboo bridge is shown in **Fig. 6**, and its detailed geometric information is listed in **Table 1**.

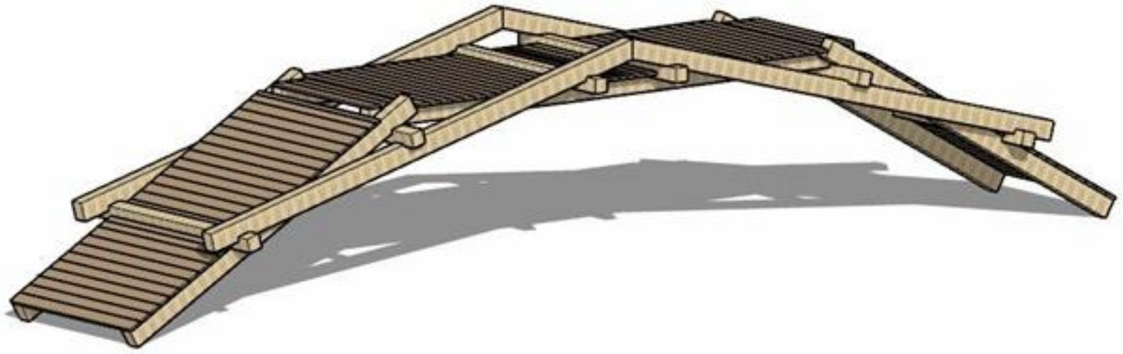


Fig. 6. Design of the engineered bamboo bridge.

Table 1. Geometric information of the engineered bamboo bridge

Length (m)	Width (m)	Height (m)	Grounding angle (°)
12.0	2.6	2.0	30.0

3 Materials

A total of 16 LBL components with different lengths and shapes were used to build the main structure of the bridge in this event, all of which were produced by Ganzhou Sentai Bamboo Co., Ltd. Their specific mechanical properties and dimensions are listed in **Table 2** and **Table 3**, respectively. A total of 95 pieces of 30 mm thick BS panels produced by Zhejiang Runzhu Technology Co., Ltd were selected for the bridge deck, with their specific mechanical properties and dimensions listed in **Table 2** and **Table 4**, respectively. In addition, glass fiber reinforced polymer (GFRP) sheet produced by Nantong Shirui Plastic Products Co., Ltd was also used in this event to wrap the weakened components for reinforcement, and its mechanical properties are listed in **Table 2**.

Table 2. Mechanical properties of materials

Category	f_b (MPa)	E_b (MPa)	f_t (MPa)	E_t (MPa)	f_c (MPa)	E_c (MPa)	f_s (MPa)
LBL	84.08	6201	62.58	5769	68.90	11090	1017
BS	144.33	9919	151.63	15895	98.81	13988	6295
GFRP	-	-	2313	10028	-	-	-

Note: f_b , f_t , f_c , f_s are the flexural, tensile, compressive, and shear strengths of the material; E_b , E_t , E_c are the elasticity moduli of the material in bending, tension, and compression modes, respectively.

Table 3. Geometric information of LBL components

Component	Section size (mm×mm)	Length (mm)	Number
B1	150×200	5408	4
B2	150×200	4000	4
B3	150×200	6000	2
B4	150×150	2600	2
B5	150×150	2600	2
B6	150×150	2600	2

Table 4. Geometric information of BS panels

Panel	Section size (mm×mm)	Length (mm)	Number
P1	45×30	1600	2
P2	140×30	1600	6
P3	60×30	1990	2
P4	82×30	1990	2
P5	90×30	1990	1
P6	100×30	1990	6
P7	132×30	1990	2
P8	140×30	1990	74

4 Finite element analyses

In this report, finite element analysis software was used for analyzing the engineered bamboo bridge. The real connections between the structural components were mortise and tenon connections, which were treated as hinge connections in the finite element analysis software. The connections between the four abutments of the bridge and the ground were also set as hinge connections. The model of the overall structure is shown in **Fig. 7**.

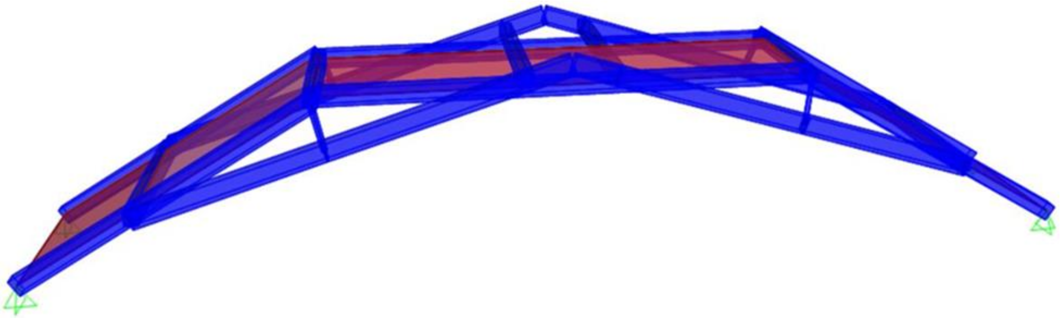


Fig. 7. Finite element structure model.

4.1 Material and load definition

LBL is an anisotropic material. By reviewing relevant literature, the material parameters of LBL required in the finite element analysis software were defined, as listed in **Table 5**. Dead load, live load and seismic load were all considered, in which the live load was determined as 3.5 kN/m^2 and the seismic coefficient was referred to the China Seismic Precautionary Intensity Table (mentioned in Code for seismic design of buildings (GB 50011-2010)). Three combination modes of loads are detailed in **Table 6**.

Table 5. Material definition

Material	E (MPa)			v			G (MPa)			ρ (g/mm^3)
	E_1	E_2	E_3	v_{12}	v_{13}	v_{23}	G_{12}	G_{13}	G_{23}	
LBL	11000	2100	3200	0.24	0.42	0.46	1000	1000	500	6.50E-05
BS	12000	4300	4300	0.40	0.11	0.50	2100	2100	700	7.50E-05

Note: E - Elastic modulus; v - Poisson's ratio; G - Shear modulus; ρ - Density.

Table 6. Load combination mode

Load combination list	Combination mode
Dead load	1.0 Dead load
Dead load + Live load	1.3 Dead load + 1.5 Live load
Seismic load	1.3 Dead load + 1.4 Seismic load

4.2 Beam analysis

By conducting finite element simulations on the structure under different load combination modes, the deformation and bending moment diagrams of bamboo beams under each load combination mode were obtained. The stiffness and strength of the structure were then checked.

4.2.1 Stiffness check

According to the provisions of Code for design of timber structures (GB 50005-2017) regarding the deflection limit of bending components, the top beam with a length of 6 meters was considered as a slab beam for deflection checking, and the deflection limit calculation formula is as follows:

$$\left[\omega\right] = l / 250 \tag{1}$$

Meanwhile, in the bridge design process, the empirical formula about the permissible limit of its mid-span deflection is as follows:

$$\left[\omega\right] = l / 600 \tag{2}$$

where ω is the deflection limit and l is the calculated length of the bending component.

By substituting the span into Formula (1) and (2), it was found that the calculation result of Formula (2) was relatively smaller, so the calculation result of Formula (2) was determined to be the maximum deflection allowed for the top beam. The maximum deflection of the top beam simulated by finite element analysis software under different load combination modes are presented in **Table 7** and were compared with the deflection limit calculated by Formula (2) to check the stiffness of the beam. The results showed that the stiffness of the beam met the code requirement.

Table 7. Stiffness check

Load combination list	Deflection simulated by software (mm)	Deflection limit (mm)	Result
Dead load	4.373	10.000	Qualified
Dead load + Live load	6.794	10.000	Qualified
Seismic load	7.816	10.000	Qualified

4.2.2 Strength check

According to the provisions of Code for design of timber structures (GB 50005-2017) regarding the flexural bearing capacity of bending components, when checking the strength of the beam, the empirical formula is as follows:

$$\frac{M}{W_\mathrm{n}} \le f_\mathrm{m} \qquad (1)$$

where f_m is the flexural strength of the beam, M is the bending moment of the bending component and W_n is the net section resistance moment of the bending component.

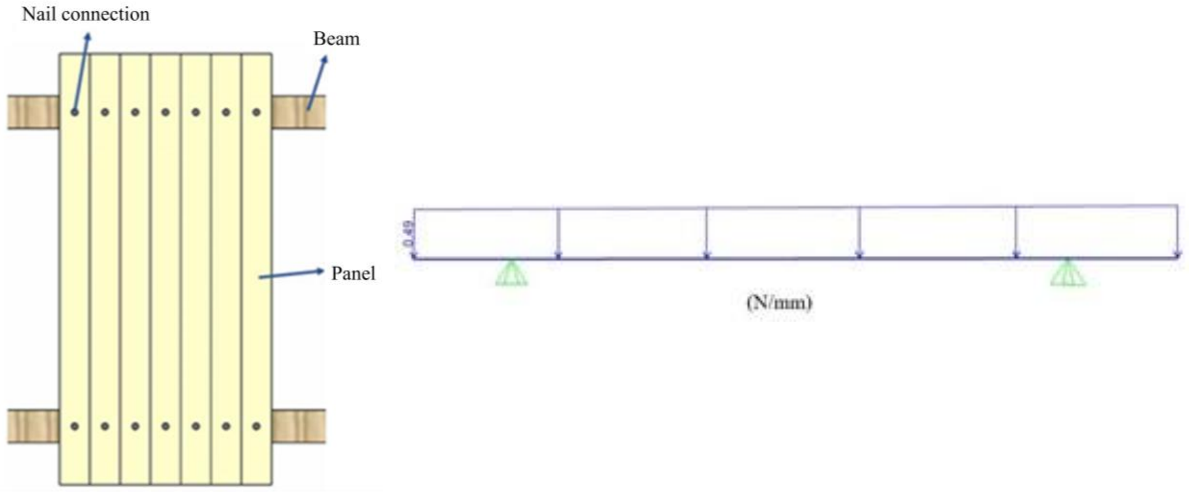
The maximum bending moment of the top beams under different load combination modes simulated by finite element analysis software are presented in **Table 8** and were substituted into Formula (3) for strength check. The results showed that the strength of the beam met the code requirement.

Table 8. Strength check

Load combination list	Bending moment simulated by software (N·mm)	Result
Dead load	15461222	Qualified
Dead load + Live load	27354470	Qualified
Seismic load	11893248	Qualified

4.3 Panel analysis

The bridge used 95 pieces of 30 mm thick BS panels to form the bridge deck, and the specific laying and connection method is shown in **Fig. 8(a)**. The BS panels and LBL beams were connected by nails. As for the analysis, a single panel was taken for checking, and it was regarded as a unidirectional bending component. The simplified model of the panel is shown in **Fig. 8(b)**, where the panel was considered simply supported, the nail connection between the panel and the beam was set as a hinge connection, and the surface load of 3.5 kN/m^2 was equivalently converted to a line load of 0.49 N/mm applied to the model. By conducting finite element simulations on the panel model under different load combination modes, the deformation and bending moment diagrams of the panel model under different load combination modes were obtained respectively. Thereby, the stiffness and strength of the panel were checked.



(a) Laying and connection of panel (b) Panel model

Fig. 8. Model building of panel.

4.3.1 Stiffness check

According to the provisions of Code for design of timber structures (GB 50005-2017) regarding the deflection limit of bending components, the deflection of the panel was checked, with the deflection limit calculation formula same as Formula (1).

The maximum deflection of the panel simulated by finite element analysis software under different load combination modes are presented in **Table 9** and were compared with the maximum deflection limit calculated by Formula (1) to check the stiffness of the panel. The results showed that the stiffness of the panel met the code requirement.

Table 9. Stiffness check

Load combination list	Deflection simulated by software (mm)	Deflection limit (mm)	Result
Dead load	0.599	8.000	Qualified
Dead load + Live load	4.312	8.000	Qualified
Seismic load	0.339	8.000	Qualified

4.3.2 Strength check

According to the provisions of Code for design of timber structures (GB 50005-2017) regarding the flexural bearing capacity of bending components, when checking the strength of the panel, the empirical formula is as Formula (3).

The maximum bending moment of the top panels under different load combination modes simulated by finite element analysis software are presented in **Table 10** and were substituted into Formula (3) for strength check. The results showed that the strength of the panels met the code requirement.

Table 10. Strength check

Load combination list	Bending moment simulated by software (N·mm)	Result
Dead load	14824	Qualified
Dead load + Live load	102819	Qualified
Seismic load	8073	Qualified

5 Building process

When planning the construction scheme, a detailed schematic diagram of the bamboo bridge was drawn, and each connection of the structure was dismantled and analyzed in order to develop the most reasonable construction scheme by easiest way. The final construction scheme roughly dismantled the bridge into three parts, as shown in **Fig. 9**. In order to facilitate the description and understanding of the subsequent construction process, the same components were grouped into one category, and each category of components was numbered in **Fig. 9**. Then, the component numbers are used to refer to the beam components at specific positions in the subsequent subsections. Based on the schematic diagram of structure dismantling, the participants were similarly divided into three teams, each of which constructed its responsible part at a designated location on the site. Once the three parts were prepared, they were assembled through pre-defined slots, and the interlocking of all the connections represented the end of the construction process. The entire construction flow diagram is shown in **Fig. 10**.

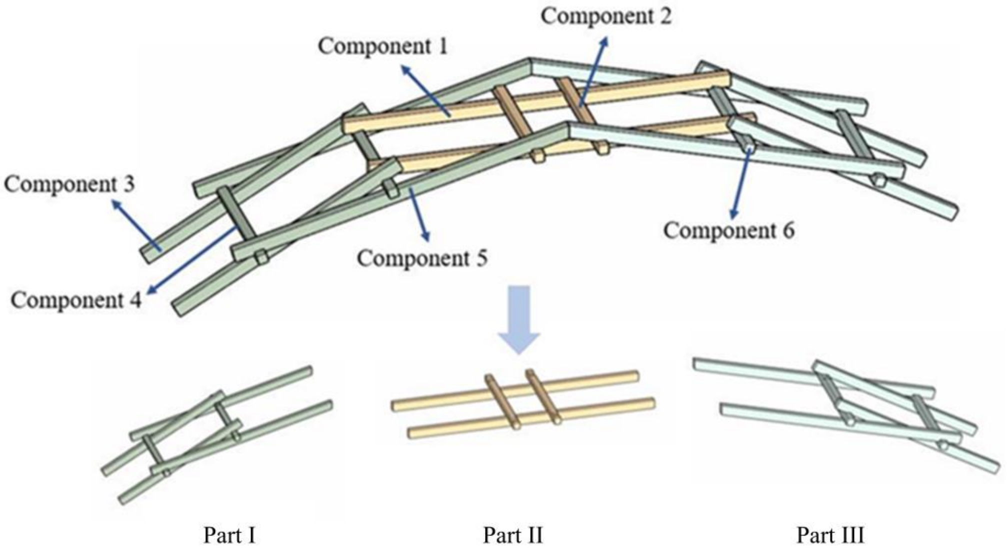


Fig. 9. Components numbering and structure dismantling.

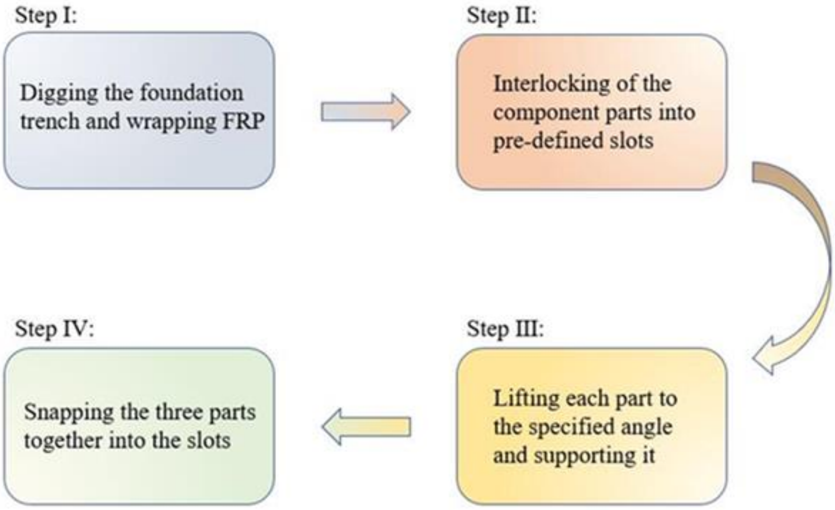
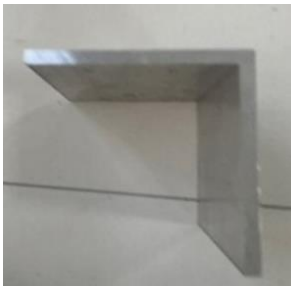


Fig. 10. Flow diagram of the bamboo bridge construction.

5.1 Digging the foundation trench and wrapping FRP

The construction site was chosen on the lawn in front of the College of Civil Engineering Nanjing Forestry University. There were various kinds of vegetation and plants on the lawn, and the bamboo bridge needed a considerable area of land, as it had a span of 12 meters and a width of 2.6 meters. Thus, before the construction, it is necessary to conduct surveys and measurements, in order to select a suitable area that can meet the conditions for the bamboo bridge construction. Moreover, it is also necessary to dig the foundation trench for placing the bridge abutments beforehand with reference to the span and width of the bamboo bridge, in order to limit the horizontal displacement of the bridge abutments. Carefully inspecting the length, cross-sectional dimensions, slot positions, and other parameters of each component was needed as well, to ensure the smooth assembly.



(a) Aluminum alloy base plate

(b) Placement diagram

(c) Final real placement

Fig. 11. Aluminum alloy base plate and its placement.

Due to the outdoor environment, the LBL components would definitely be affected by rain, temperature and other complex factors, leading to a decline in the durability. In order to strengthen the abutments, and to improve the durability of LBL, aluminum alloy plates were buried as the foundation base plates and fixed on the bottom of LBL components with wires, avoiding direct contact between LBL and the soil of the lawn. **Fig. 11(a)** shows an aluminum alloy base plate used in this construction event. According to the design of the bamboo bridge, the bottom oblique beam was at an angle of 30 ° with the ground, so it is necessary to dig a 30 ° trench in the lawn and put the aluminum alloy base plates inside. **Fig. 11(b)** demonstrates a schematic diagram of the placement of an aluminum alloy base plate, and the final real placement is shown in **Fig. 11(c)**.

In preliminary preparations, in addition to the aluminum alloy base plates, several layers of GFRP sheets were wrapped at the ends and near the connection joints of each LBL component for protection. Before wrapping, GFRP sheets with equal length should be prepared, and evenly coated with glue. The GFRP sheets were then wrapped layer by layer at the predetermined positions of the LBL components. On the one hand, this helped to improve the corrosion resistance of LBL components and ensure their service life. On the other hand, the slotted area of LBL components resulted in a decrease in mechanical properties due to weakened cross-section and was prone to stress concentration, while wrapping GFRP sheets could effectively prevent the splitting of LBL. **Fig. 12** shows the GFRP wrapping at the predetermined positions.

(a) GFRP wrapped at an end (b) GFRP wrapped near a connection joint

Fig. 12. GFRP wrapping.

5.2 Interlocking of the component parts into pre-defined slots

According to the construction scheme, the bamboo bridge was dismantled into three parts. The positioning and fixation of Part II could provide support for the subsequent assembly of Parts I and III, so the construction of Part II had higher priority than Parts I and III. The construction process of Part II is shown in **Fig. 13**, where the height of horse stools was adjusted to 2.2 meters. The height of horse stools was set higher than that of Part I or III in the design, to ensure the feasibility of the subsequent assembly process. Once the horse stools had been adjusted and fixed, the two beams of Component 1 were placed on the horse stools according to the designed spacing and the two beams of Component 2 were subsequently embedded in the slots of Component 1. In order to prevent accidental injuries to construction participants due to unstable assembly during the subsequent construction process, twines were used to secure the connections.

(a) Assembly of Components 1 and 2 (b) Twine fixing

Fig. 13. Construction process of Part II.

The structure of Parts I and III on both sides of the bamboo bridge was the same. Six beams of each part were placed on the aluminum alloy base plates for interlocking, and the process is shown in **Fig. 14**. As the foundation beams, the two beams of Component 3 were laid flat on the lawn, and the beam of Component 4 was embedded in the slots and secured with twines. The three beams were then lifted and rotated as a whole, and a table was put under them to provide temporary support.

(a) Assembly of Components 3 and 4
(b) Assembly of Component 5

(c) Assembly of Component 6
(d) Lifting Part I as a whole

Fig. 14. Construction process of Parts I and III.

5.3 Lifting each part to the specified angle and supporting it

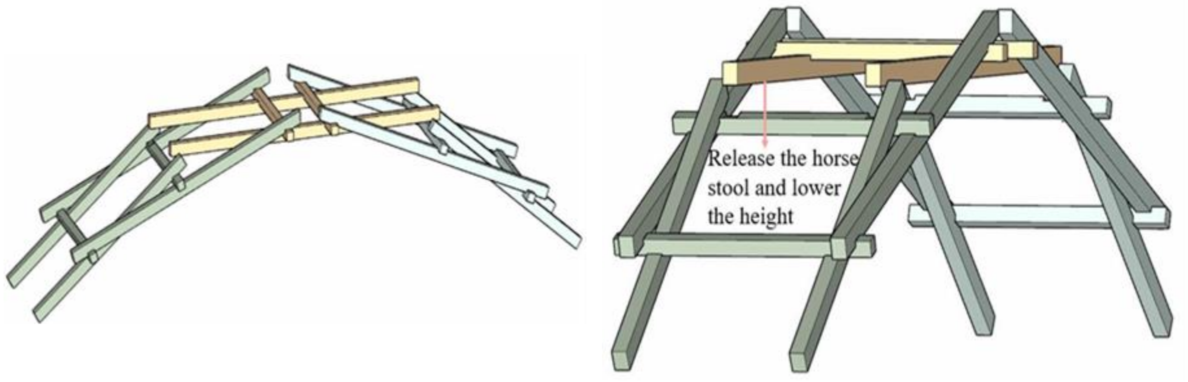
By the end of the previous construction process, the respective six beams of Parts I and III were mutually constrained, but they were still unable to remain stable as a whole. At the same time, the pressure given to Component 2 by these two parts might cause the instability of Part II. Therefore, the participants immediately inserted bamboo tubes under the oblique parts to provide support, as shown in **Fig. 15(a)**. Once a sufficient number of bamboo tubes had been inserted, each part could remain stable, the previously inserted table was withdrawn to provide more space for the subsequent construction process. After this step was completed, the three parts reached stability independently under their respective supports, as shown in **Fig. 15(b)**, and then the last assembly step could be performed.

(a) Bamboo tube support
(b) Reaching respective stability

Fig. 15. Three parts remaining stable individually.

5.4 Snapping the three parts together into the slots

Fig. 16(a) shows the overall state before the start of the last assembly step. The height of horse stools was higher than the design height of Component 2 during the construction of Part II, resulting in the grounding angles of both Part I and Part III being greater than 30 °, and there was no contact between the tops of the two parts. Therefore, in the last assembly step, the height of horse stools was lowered so that Component 2 could be embedded in the slots of Component 6 on both sides. Then, the grounding angle of Parts I and III became 30 °, and the tops of the two parts touched each other.



(a) State before the start of the last assembly step (b) Scheme diagram of the last assembly step

Fig. 16. Last assembly step (assembly scheme).

So far, the whole structure was mutually constrained without external support, and reached a stable state. After confirming the overall stability of the structure, the horse stools under Part II were removed. The scheme diagram of the last assembly step and the actual operation picture are shown in **Fig. 16(b)** and **Fig. 17**, respectively. Moreover, when lowering the height of horse stools, it was necessary to lower gradually instead of removing directly, to avoid the impact load caused by the fall of Part II having a destructive effect on the beams on both sides.

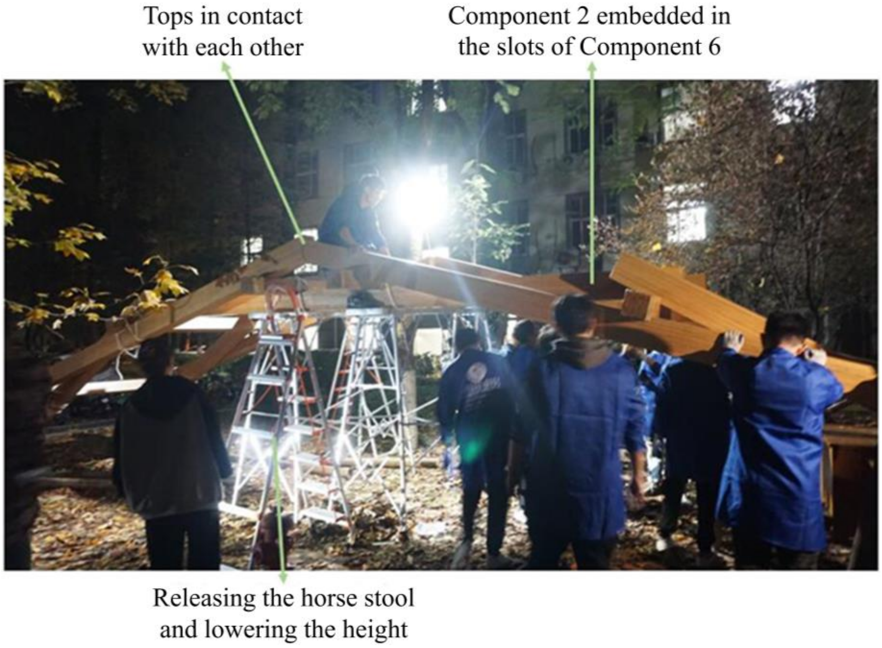


Fig. 17. Last assembly step (actual operation).

Fig. 18. Overall structure of final product.

The removing of horse stools represented the completion of the main structure construction. The entire construction process lasted around eight hours and was jointly participated by three groups of more than 30 construction participants. The final structure and connection details of the bamboo bridge are shown in **Fig. 18** and **Fig. 19**, respectively.

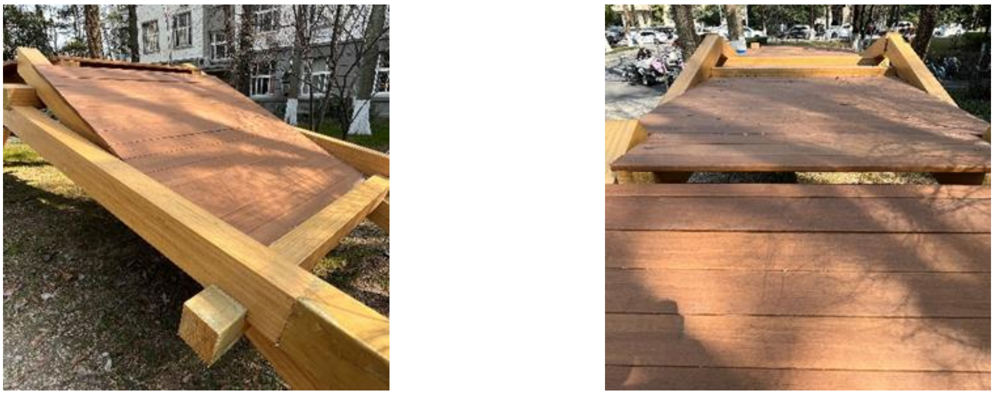
(a) Connection joints of Components 3,5,6

(b) Connection joint of Components 4,5

(c) Connection joints of Components 1,2,5

Fig. 19. Connection details.

After the completion of the main structure, the finishing work was carried out by several participants the next day. BS panels were fixed to the main structure with nails, to form an accessible bridge deck. The final product of the bridge deck is shown in **Fig. 20**.



(a) Sloping bridge deck

(b) Top horizontal bridge deck

Fig. 20. Bridge deck.

6 Conclusion

As green, low-carbon, sustainable structural materials, engineered bamboo will have a bright future in construction field. More and more application cases appeared. On November 12th, 2022, the 3rd International Collaboration on Bamboo Construction, jointly organized by Nanjing Forestry University, University College London and INBAR, was held on the campus of Nanjing Forestry University. The main purpose of this event was to strengthen academic and technical exchanges in the bamboo structure field and to demonstrate the feasibility and stability of using engineered bamboo to build large-span structures through a practical case. Sketchup and finite element analysis software were used for the design and verification of the bamboo bridge structure, to ensure its operability and stability. More than 30 attendants from all over the world participated in the construction of the bamboo bridge, which took around eight hours to build, and the main structure was completed later that day. Throughout the construction process, no metal connections were used, only mortise and tenon connections were adopted to connect the components. In addition, no large mechanical equipment was used during the construction process, and all construction work was completed with manpower and portable support. This practical case proved that the mortise and tenon connections commonly used in wooden structures can also be used in engineered bamboo structures. It also demonstrated the feasibility of using fewer resources to complete the construction of engineered bamboo structures in a short period of time through reasonable design and construction scheme. Apart from providing a practical engineering reference for the development of engineered bamboo structures, this event also had teaching significance in enhancing students' understanding of engineered bamboo and bamboo structures, and in cultivating their ability to deal with problems in the construction process.

Acknowledgement

The writers gratefully acknowledge Usama Sayed, Ziang Wang, Jinglong Zhang, Patrick Adjei, Mahdi Hosseini and others from Nanjing Forestry University for helping. Thanks for the support from Joint International Research Laboratory of Bio-composite Building Materials and Structures (JIRLBBMS).

Funding Statement

The research work presented in this paper is supported by the National Natural Science Foundation of China (Nos. 51878354 & 51308301), the Ministry of Housing and Urban-Rural science project of Jiangsu Province under Grant No. 2021ZD10, 333 Talent High-Level Project of Jiangsu Province, Forestry Science and Technology Innovation and Promotion Project of Jiangsu Province (No. LYKJ[2024]08) and Qinglan Project of Jiangsu Higher Education Institutions. Any research results expressed in this paper are those of the writers and do not necessarily reflect the views of the foundations.

CRediT authorship contribution statement

Haitao Li: Conceptualization, Funding acquisition, Supervision, Investigation, Formal analysis, Writing – original draft. **Zixian Feng**: Investigation, Formal analysis, Construction, Writing – original draft. **Xinqi Shen**: Investigation, Formal analysis, Construction, Writing – original draft. **Yifan Wang**: Investigation, Formal analysis, Writing – original draft. **Xin Xue**: Investigation, Formal analysis, Construction. **Rodolfo Lorenzo**: Supervision, Investigation. **Mahmud Ashraf**: Supervision, Writing – review & editing. **Zhenhua Xiong**: Supervision, Investigation. **Chungui Zhou**: Supervision, Investigation. **Ningjun Chen**: Supervision, Investigation. **Jian Zhang**: Supervision, Investigation. **Kewei Liu**: Supervision, Investigation. **Edwin Zea Escamilla**: Supervision, Investigation.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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