# Design and Construction of Modern Bamboo Bridges

Yan Xiao, M.ASCE[1]; Quan Zhou[2]; and Bo Shan[3]

**Abstract:** The writers are conducting a comprehensive research program, with the goal to develop modern bamboo structures for buildings and bridges. This paper reports the design, construction, and testing of modern bamboo bridges. Laminated bamboo girders or glubam were developed and verified for satisfactory mechanical performance through full-scale testing. It was demonstrated that the laminated bamboo girders have satisfactory stiffness and load carrying capacity. The use of carbon fiber-reinforced plastics can further enhance the stiffness and capacity of the bamboo girders. Based on the test results and analysis, a 10-m long single lane roadway bridge was designed and constructed, which was the first of its kind in the world. The field tests were carried out using an over loaded two-axel truck with a total weight of 8.6 t which exceeded the given design truckload of 8.0 t. The bridge performed satisfactorily with the midspan deflection corresponding to the critical service loading condition being much smaller than the code required limit. Computer simulation of the field tests shows that the trend of the measured midspan deflection can be reasonably well captured. Examples of other bridge applications are also reported in this paper.

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## Introduction

With social progress and economical development, the demand and consumptions of conventional construction materials such as steel and concrete are at an unprecedented level throughout the world. Meanwhile, it is becoming increasingly obvious that conventional construction materials are causing a significant environmental burden to the modern society. Particularly in developing countries, both steel and cement are high energy consuming and high pollution industrial products because their production processes consume a large amount of energy, generating considerable wastes of water, gas, and residues, which gradually and seriously affect the ecological environment of the globe. Sustainable development has become a major theme of today's international community and the concept of "green building" is its inevitable choice. It is important to develop environmentally friendly new materials and innovative structures, to gradually reduce and even replace a certain portion of the use of conventional steel and concrete as major forms of building materials. This has become the new challenge of the 21st century civil engineering.

Bamboo, as a natural resource, has been used by mankind for thousands of years (Janssen 2000). However, modern structures using bamboo as basic material can well become a new breakthrough in the civil engineering field. There are several key characteristics in bamboo-based structures. First, the source of raw bamboo materials is widely available in many parts of the world, particularly in developing countries, most notably, China and India. Bamboo is essentially giant grass and grows much faster than trees. Bamboo typically can be harvested in less than 4 years, and they can regrow. Second, bamboo has good mechanical properties and is relatively easy to process for different purposes. Third, but definitely not last, the manufacturing process of bamboo products can be essentially environmentally friendly, pollution free, and suitable for sustainable development.

Bamboo is not fully used in modern structures, due largely to the lack of validation based on the theory of mechanics, material science, structural design, and testing. Structures thus developed with bamboo as the main structural material can improve the level of value-added bamboo usage, elevating the livelihood of farmers and contributing to the realization of a sustainable construction industry. Bamboo reinforced concrete is a topic of bamboo usage in modern structures and has a reasonably long history of research and applications (Brink and Rush 1966; Ghavami 1995; Rong 2008). However, such usage becomes somewhat obsolete due to the fact that bamboo cannot offer the required strength and deformability as reinforcing steel bars for today's reinforced concrete structures. The laminated bamboo, or so-called bamboo made plywood, or plybamboo is an industrialized product that has the potential for building modern structures.

In North America and many industrialized countries, timber has been widely used in bridges and buildings (for example, Ritter 1990; Forest Products Laboratory 1999; Davids et al. 2008). Despite the fact that North America has significant cover-

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**Table 1.** Basic Material Properties of Laminated Bamboo

| Materials | In-plane compressive strength (MPa) | In-plane tensile strength (MPa) | Bending strength (MPa) | Elastic modulus (GPa) | Density $(kg/m^3)$ |
|---|---|---|---|---|---|
| Plybamboo | 54 | 20 | 75 | 9.4 | 880 |
| Typical bamboo culm | 55 | 124 | — | 17 | 650–800 |
| Douglas-fir[a] | 48 | — | 83[b] | 12 | 497 |
| West white pine[a] | 35 | — | 64[b] | 10 | 398 |

[a]Average values taken from *Wood Handbook* (Forest Products Laboratory 1999).

[b]Modulus of rupture.

age by trees and is rich in forest resources, preserving them for future generations is still an urgent task facing the society. Developing and using modern bamboo materials may provide an alternative in bridge and building construction in North America. As a direct return, the development of modern bamboo structures will not only benefit the bamboo-rich developing countries but will lead to the promotion of the fast-growing and fast maturing bamboo forests in other parts of the world, contributing to a greener environment. This paper presents the research, design, and testing of the world's first modern bamboo bridge to carry traffic truckload along with a report of the writers' efforts in developing modern bamboo structures.

## Development of Laminated Bamboo Girders—GluBam

The main components intended for making the main load-bearing components of bridges or other types of structures were laminated bamboo elements, trademarked as GluBam (Xiao et al. 2008), made from 28-mm thick bamboo veneer sheets with a planner dimension of 2,440 mm long and 1,220 mm wide, using a processing method invented by the writers. The process involves finger-jointing the sheets, surface preparations, painting with two-part epoxy adhesive, and pressure hardening for 24 h.

Because that the bamboo veneer sheet is relatively new to construction industry in North America, some descriptions are provided herein. Bamboo veneer sheets or plybamboo sheets (Janssen 2000) are similar to plywood except using bamboo as basic materials, and are well established industrial products in China. There are two typical types of bamboo veneer sheets, which the writers categorize as the thin layer lamination and thick layer lamination. The thick layer laminated bamboo sheets are made by pressure gluing a few layers (typically three layers) of relatively thicker bamboo strips (Wahab et al. 2006; Li et al. 2002). The top of the line products can make floor plates, which became available in North America market recently. The thin layer laminated bamboo sheets typically have a thickness of about 10–15 mm, and are made by laminating approximately 2-mm thick bamboo strip mats. They are mass produced and mainly used as concrete formwork in China. Based on extensive review of the existing bamboo products available in China and careful comparison of their costs and known properties, the writers adopted the thin layer laminated veneer bamboo sheets with modifications of the configuration of thickness and orientation. The 28-mm thick bamboo veneer sheets used in this study were manufactured at a facility in Hunan Province, China, based on the specification developed by the writers. The sheets contain the same amount of bamboo strips oriented in the longitudinal and the transverse directions. The strips were weaved into mats and prepared by local farmers before bringing to the factory. At the factory, the mats were cleaned and dried in a kiln. Then the mats were saturated in phenol formaldehyde resin. The resin saturated bamboo strip mats were finally stacked and pressed under a temperature of 150°C, using a procedure similar to manufacturing plywood (Forest Products Laboratory 1999).

Basic material properties shown in Table 1 were obtained by conducting significant amount of material tests following conventional testing methods for timber materials. The tests were conducted according to the Chinese standards (Ministry of Construction of China 2009, 2002), which are identical to the methods used in the United States [ASTM-D143 (ASTM 2007)]. Comparison of the main mechanical properties between the laminated bamboo and values of typical fir or pine woods from the Wood Handbook by Forest Products Laboratory (1999) is also given in Table 1. Generally, bamboo and laminated bamboo have identical mechanical properties as common woods, however, they are heavier than wood and wood products. Table 1 also indicates that the modulus of elasticity of the laminated bamboo used in this study was not particularly high, due primarily to the equal configuration of bamboo strips in the longitudinal and the transverse directions. Fig. 1 shows a 10-m long girder beam manufactured at the laboratory of the Institute of Modern Bamboo, Timber, and Composite Structures (IBTCS) at the Hunan University. It should be pointed out that the glubam material is essentially a bidirectional bamboo fiber matrix, however, the full quantification and the definition of its constitutive law need to be addressed in future.


**Fig. 1.** Laminated bamboo girder



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**Table 2.** Mechanical Properties of FRP Sheets

| | Elastic modulus (GPa) | Tensile strength (MPa) | Strain at failure |
|---|---|---|---|
| CFRP | 220 | 2,600 | 0.0118 |

## Experimental Program

### *Specimen and Test Design*

In order to study the load carrying capacity and deformability of laminated bamboo girders, the writers tested six full-scale specimens. All model girder specimens had a cross section of 600 mm deep and 110 mm wide with a length of 9.6–10.0 m between the two end supports. The materials and processing methods for the laminated bamboo girders were the same. Specimen B6 was further strengthened at the bottom with two layers of 0.22-mm thick carbon fiber strips bonded by epoxy, making it into a carbon fiber-reinforced polymer (CFRP) and laminated bamboo composite beam. Testing of the CFRP enhanced glubam girder B6 was intrigued by recent promising development of fiber-reinforced polymer (FRP) enhanced wood structures (Tingley et al. 1996; Hernandez et al. 1997; Qiao et al. 1998; Trimble et al. 2000a,b; Weaver et al. 2004; Dagher 2005; Fiorellia and Diasb 2006). Another reason for the use of CFRP enhancement was to increase the elastic modulus of the glubam used in this study. Mechanical properties of the CFRP sheet are shown in Table 2.

The specimens were tested in a condition of a simply supported beam with a concentric load applied at the midspan, as shown in Fig. 2. Before the tests, the writers reviewed the truck load given for designing the road bridge. The most critical loading condition is when the rear axle, which carries most of the truck load, positions near the midspan. For simplicity, three point loading shown in Fig. 3 was adopted. The writers recently started a new research program for testing glubam girders with more loading conditions. In order to prevent out-of-plane instability during the testing, lateral supports were provided using steel frames and ball-bearing contacts. The test was conducted by monotonically increasing the applied load at the midspan of the girder specimen until failure. The increment of the load was 2.5–5 kN. Instrumentation included measurement of the applied force, deflections at midspan and points of quarter-span, and strains of the midspan section.

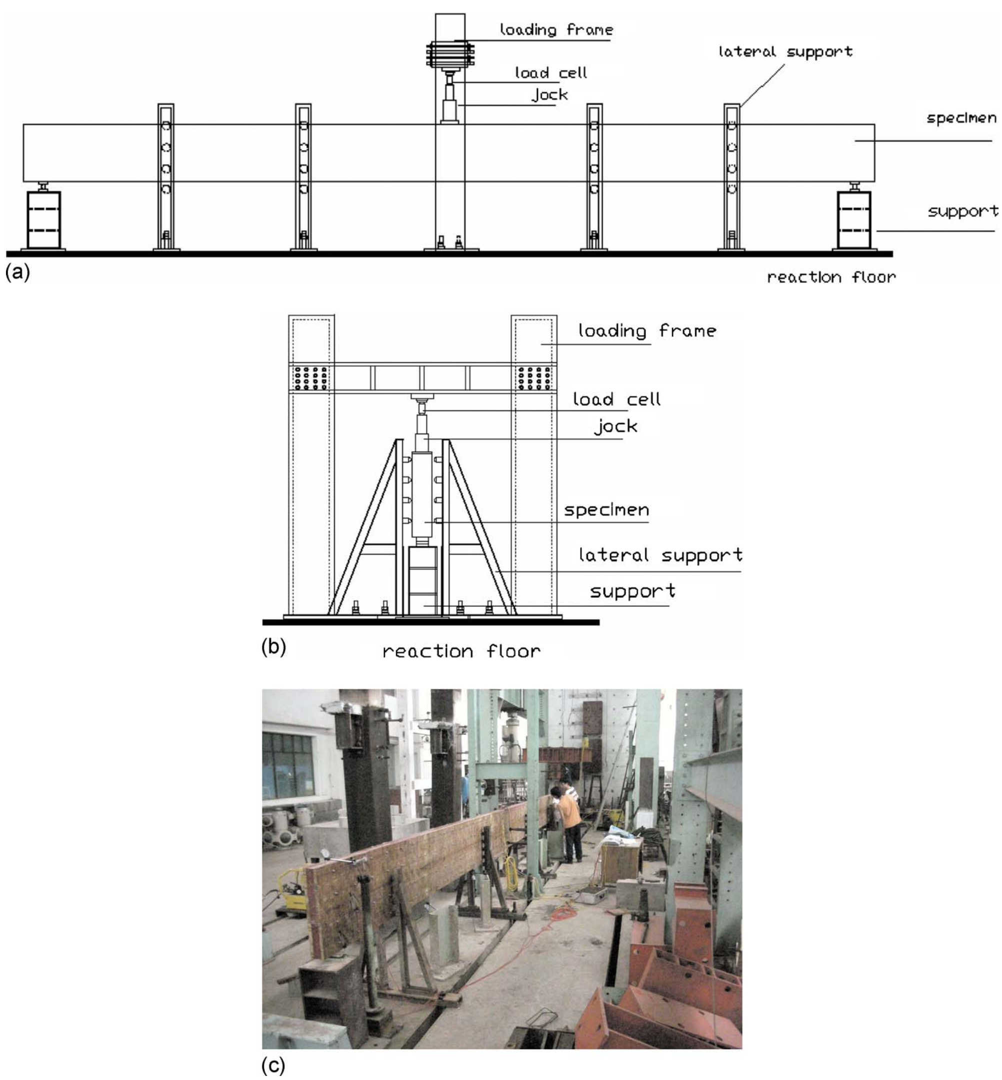


**Fig. 2.** Test setup: (a) front view; (b) cross-sectional view; and (c) test in progress



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(a)

(b)

**Fig. 3.** Final failure patterns: (a) fracture of midspan section of specimen B1; (b) rupture of CFRP of specimen B6

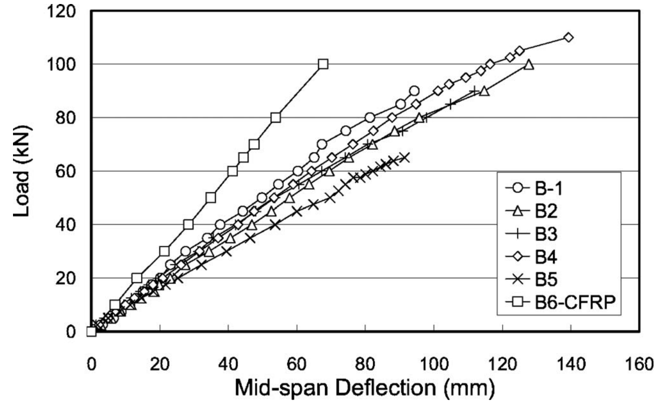


**Fig. 4.** Load and midspan deflection relationships for full-scale bamboo girder specimens

### Experimental Results—General Observations

Details of all specimens and the main test results are summarized in Table 3. For bamboo girder specimens without any additional enhancement, the initial increase of deflection was essentially linear corresponding to the increase of the applied midspan load. The deflection increment corresponding to the same load increment became apparently larger when the load exceeded 55–65 kN. When the load exceeded 80 kN, sounds indicating the cracking development in the beam were generally audible for all the specimens. All the specimens exhibited an essentially elasto-brittle behavior. Girder specimen B1 failed due to the fracture of the lower part and the crush of the compression side at the midspan when the load approached to its ultimate load carrying capacity. Failure load for specimen B2 exceeded 100 kN when the capacity suddenly dropped, however, the girder specimen did not suffer a total section failure. At a load exceeding 90 kN, girder specimen B3 lost the lateral stability with buckling of the compression zone near the midspan of the girder. Specimen B4 had the highest load carrying capacity of about 110 kN, and a failure pattern similar to that of B1. Specimen B5 had the lowest load carrying capacity of 65 kN, due mainly to an undesirable failure pattern of partial delamination.

For CFRP strengthened bamboo girder B6, there was little noticeable phenomena throughout the testing process, until the final stage of failure. The cracking sounds started to be audible when the applied load was increased close to the maximum value of about 100 kN. The specimen fractured near midspan following the rupture of the CFRP glued at the bottom of the girder section. Fig. 3 shows the final failure patterns of a typical girder specimen without CFRP enhancement and the specimen with CFRP enhancement.

### Load and Deflection Relationships

Fig. 4 exhibits the applied load and the midspan deflection relationships of the six full-scale laminated bamboo girder specimens. Linear elastic responses can be seen from the load and deflection relationships for laminated bamboo girders B1 to B5 when the

**Table 3.** Full-Scale Girder Test Specimens and Main Test Results

| Specimen name | Length (mm) | Initial stiffness (kN/mm) | Theoretical initial stiffness (kN/mm) | Ultimate load (kN) | Ultimate displacement (mm) | BE[a] (GPa) | MOR[b] (MPa) |
|---|---|---|---|---|---|---|---|
| B1 | 9,600 | 0.949 | 0.918 | 90 | 94.3 | 9.7 | 36.0 |
| B2 | 10,000 | 0.868 | 0.812 | 100 | 127.7 | 10.0 | 41.7 |
| B3 | 10,000 | 1.026 | 0.812 | 90 | 111.8 | 11.9 | 37.5 |
| B4 | 10,000 | 0.946 | 0.812 | 110 | 139.3 | 10.9 | 45.8 |
| B5 | 10,000 | 0.794 | 0.812 | 65 | 94.1 | 9.2 | 27.1 |
| B6-CFRP | 9,600 | 1.404 | 0.942 | 100 | 67.7 | 14.4 | 40.0 |

[a]BE=experimentally obtained bending modulus and is calculated as, $BE=K_oL^3/48I$, here, $K_o$=initial bending stiffness and $I$=moment of inertia of girder section.

[b]MOR=experimentally obtained modulus of rupture and is calculated as, $MOR=M_u/S$, here, $M_u$=ultimate moment and $S$=section modulus.



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load is below approximately 30 kN. After this stage, the stiffness of the girder specimens reduced slightly until reaching their ultimate load carrying capacities.

As shown in Fig. 4, the stiffness of specimen B6-CFRP is apparently higher than those of laminated bamboo girders without CFRP enhancement, indicating the further reinforcing effect by using CFRP. Specimen B6-CFRP behaved essentially in a linear elastobrittle fashion and failed at an ultimate load carrying capacity of 100 kN, marginally higher than those of bamboo girders without CFRP.

### Stiffness and Capacity Analyses

Analyses are performed based on theory of elasticity with the straight line assumptions for stresses and strains along the height of the section. The stress in the laminated bamboo girder is assumed to have a linear distribution proportional to the distance from the neutral axis. For CFRP strengthened girder B6-CFRP, the strain is assumed to be linearly distributed in the section for the calculation of the stresses in the bamboo girder and the CFRP strip affixed at the bottom of the section. The actual analysis for B6-CFRP could be based on transform section, using the experimentally obtained elastic modulus of the materials.

Based on elastic analysis, the initial stiffness of the girders was estimated and shown in Table 3. The calculated stiffness values for the bamboo girders without CFRP range about 79% to 94% of the experimental results. As also shown in Table 3, the calculated initial stiffness for the bamboo girder with CFRP strengthening B6-CFRP is underestimative to the test result with a relatively large margin. Previous studies on FRP enhanced glulam beams indicate that with FRP reinforcement can result in large increases in strength and ductility because of the delay of tensile rupture in the wood and the onset of plastic deformation of the wood in compression. Such effects were not identified in current studies with the limited number of testing, and should be addressed in future with increased testing numbers and testing parameters.

The experimental results of the ultimate load carrying capacity of the bamboo girders without CFRP strengthening ranged between 65 and 110 kN. Using theory of elasticity and a material tensile strength of 20 MPa, the calculated load carrying capacity was estimated as 53 kN, which was quite conservative compared with the test results. The estimation of the ultimate load carrying capacity based on tensile strength of the extreme tensile fibers might not be appropriate.

It is of particular interest to compare the test results in this study with those of well-known glulams. Moody et al. (1990) summarized a significant number of Douglas-fir glulam beam test results conducted in the United States. Two groups of specimens had spans and section sizes larger but comparable with the specimens tested in this study. Group II consisted of 30 beams of 610 mm deep and 130 mm wide with a span of 11.6 m, and Group III consisted of 15 beams of 1.22 m deep and 222 mm wide with a span of 19.5 m. The tests were conducted under four-point loading with a pure bending portion. The reported average modulus of elasticity or MOE values were 14.2 and 11.9 GPa, whereas the average values of modulus of rupture or MOR were 41.7 and 33.4 MPa, for Group II and Group III Douglas-fir beams, respectively. Despite of the difference in the loading method used in this study, the values of MOE and MOR from the glubam girder specimens were calculated and shown in Table 3. The average MOE value of the glubam girders without CFRP was 10.4 GPa, slightly smaller than those for Douglas-fir glulam beams. However, the average MOR of the glubam girders was 37.6 MPa, close to the average values of Douglas-fir glulam beams reported by Moody et al. (1990). The experimentally estimated values of MOE and MOR for the CFRP enhanced laminated bamboo girder B6-CFRP are 14.4 and 40.0 MPa, respectively, however does not have any statistical meaning as only one specimen was tested.

**Fig. 5.** Modern bamboo pedestrian bridge

## Modern Bamboo Bridges

### Application in a Pedestrian Bridge

In November 2006, the writers designed and built the first modern bamboo bridge as an initial trial of the laminated bamboo technology (Xiao et al. 2008). Based on experimental testing of prototype girder specimens, the writers adopted a modular design concept, enabling the efficiency of construction. Column and girder elements were all manufactured using bamboo veneer sheets. The 1.5-m wide, 5-m long pedestrian bridge was supported on six laminated bamboo girders. The size of the laminated bamboo girders was 300 mm deep and 84 mm wide. Two stairways were attached to the pedestrian bridge. The surface of the bridge was covered with bamboo strip reinforced precast concrete panels. Fig. 5 shows the completed modern bamboo pedestrian bridge. The bridge is functioning well for over 3 years after it was opened to usage.

### Design Considerations for a Truck Load Bridge

After the successful completion of the first modern bamboo pedestrian bridge in 2006, the writers were given the opportunity to design and construct a truck-safe 10-m long bridge in the village of Daozi, Leiyang City, Hunan Province, China. The bridge was a single lane bridge to cross the Xunjiang river and connect the rural roadway network in the local region, as a part of the agriculture infrastructure development by the local government.

The field survey revealed that there was a 1.0-m wide old stone bridge at the site, however, neither capable of carrying truck transportation, nor safe for pedestrians, particularly in the rainy days. The requirement for the new bridge design was to increase the width to 3.5 m to enable single lane truck traffic. Based on the assessment of the existing piers and discussions with the local authority, a decision was made to build the new bridge using the existing stone piers. As shown in Fig. 6, the new bridge had a total length of 22.8 m consisting of four simple spans. The center



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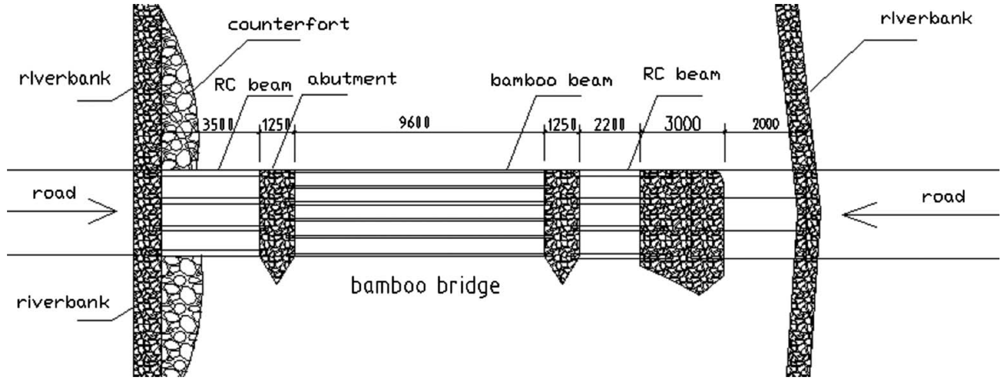


**Fig. 6.** Layout of Leiyang Bridge

10-m long span was designed and constructed using the laminated bamboo girders and the remaining shorter spans were constructed using conventional reinforced concrete beams and slabs.

The design truckload was two-axel 8-t truck. Based on initial analysis, nine 600-mm deep by 100-mm wide laminated bamboo girders were used to carry the 10-m long span. As shown in Fig. 7, the girders were interconnected by bolting bamboo veneer plates between and on top of the girders to provide the overall integrity. Waterproof asphalt sheets were laid on top of the cover plates before placing the 200-mm thick, 3.5-m long, and 1.0-m wide precast concrete pavement panels. For simplicity, the writers designed the bridge assuming a 16-t truckload applied at the midspan of the bridge. The final design was based on limiting the midspan deflection below the value of 1/600 of the span length, required by the Chinese bridge design code (People's Transportation Press 2004). Also for simplicity and safety, the CFRP layers were provided but were neglected in the design.

The ultimate design condition is checked based on the following simple procedure:

- Design dead load of precast concrete deck: 1.68 t/m;
- Design dead load of nine glubam girders: 2.16 t/m;
- Dead load moment: $M_D=(1.68+2.16)\times 10^2/8=26.9$ t-m;
- Live load moment: $M_L=16\times 10/4=40$ t-m; and
- Design ultimate moment: $M_u=1.4M_D+1.6M_L=101.7$ t-m.

Assuming the lowest capacity of 65 kN shown in Table 3 as the representative ultimate loading capacity, the nominal design moment of the nine girders is then calculated as

$$M_n = 9 \times 6.5 \times 10/4 = 146.3 \text{ t-m}$$

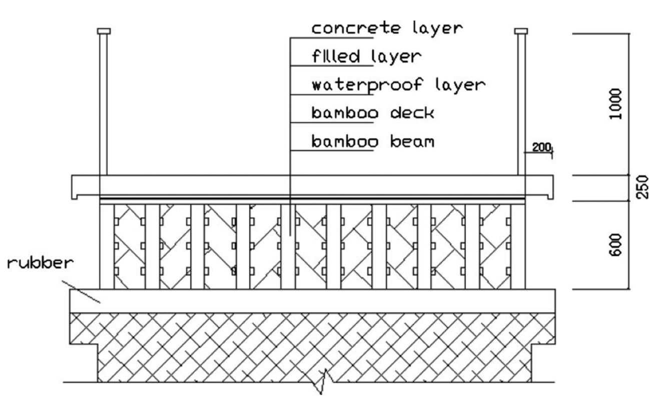


**Fig. 7.** Section sketch of bamboo bridge

Considering a strength reduction factor of $\varphi=0.9$, then

$$\varphi M_n = 131.6 \text{ t-m} > M_u = 1.4M_D + 1.6M_L = 101.7 \text{ t-m}$$

Apparently, the bridge has sufficient ultimate capacity with enough safety margin. The bridge could essentially be designed with only seven glubam girders instead of nine girders. The reason to adopt a conservative design was mainly from the concern of possible passage of excessively overloaded trucks or tractors by the local farmers, particularly in harvest seasons.

(a)

(b)

**Fig. 8.** Construction stages: (a) installation of bamboo girders; (b) installation of water proof materials



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**Fig. 9.** Truck loading test of Leiyang Bridge

### *Construction of Bamboo Bridge*

The bamboo bridge under construction is shown in Fig. 8. Reinforcement cages were made with vertical bars anchored in the drilled holes on top surfaces of the existing stone piers. Then 400-mm thick concrete layer with design strength of 30 MPa was cast. Fiber-reinforced rubber pads with a thickness of 20 mm were placed between the laminated bamboo girder ends and the concrete seat on top of the piers to reduce the effect of impact under traffic loads. All bamboo girder components were manufactured at the IBTCS laboratory and transported to the construction site. Components were installed on the piers and fastened using bolts. The site installation of the bamboo bridge was completed within 10 days by a team of four to eight workers daily without the need of heavy equipment.

In an earlier trial test, the writers made samples of glubam elements for natural weathering exposure. The preliminary observations suggested that the direct exposure of the laminated bamboo girders to rainwater may cause splitting cracks. Previous studies on different bamboo laminated composites by Li et al. also observed the delamination of bamboo layers if subjected to water (Li et al. 2002). The two exterior girders were wrapped in waterproof rubber sheets. Two layers of waterproof asphalt sheets were also used between the precast concrete surface panels and the veneer deck plates on top of the girders. The precast plates were fixed to the girders using bolts for preventing them from sliding off. The slits between the precast concrete panels were sealed by waterproof sealant. Steel railings were installed at last to provide safety for pedestrians.

## Field Loading Test

In order to understand the actual behavior of the world's first truck-safe modern bamboo bridge, field tests were carried out, 30 days after the completion of the overall bridge, as shown in Fig. 9. The loading was carried out using a truck loaded with stone blocks, which represented the possible overloaded truck in the area. The wheel-lane distance was 1.5 m and the distance between the front and the rear wheel axles was 3.0 m. The weight of the loaded truck was about 8.6 t, with the measured weight for the front wheels was approximately 1.6 t, whereas about 7.0 t for the rear wheels. Based on influence line analysis, the critical midspan moment was generated in the condition where the rear axle wheels were positioned close to the midspan. Two types of loading cases shown in Fig. 10 were carried out. As shown in Fig. 10,

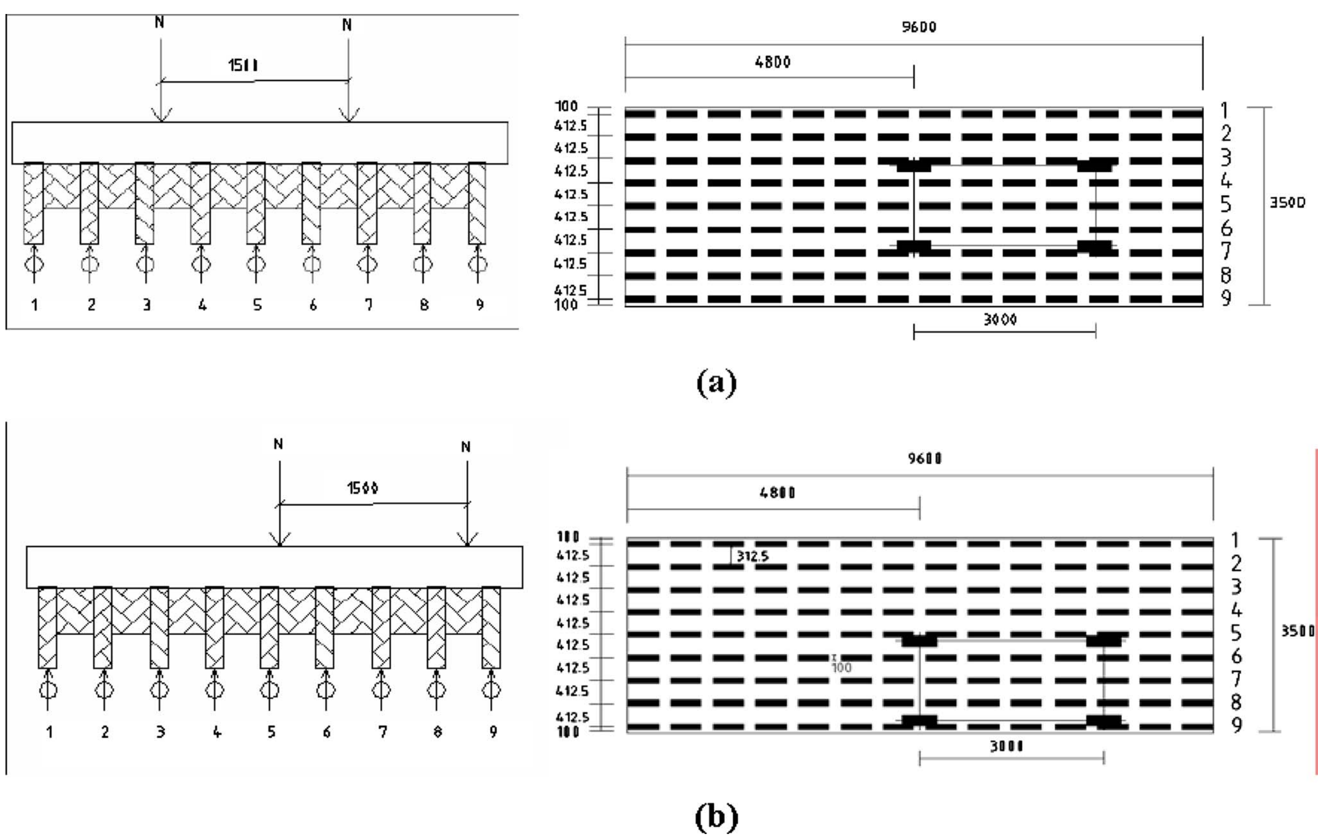


**Fig. 10.** Loading and instrumentation conditions: (a) loading Case 1 for centerline loading; (b) loading Case 2 for eccentric loading



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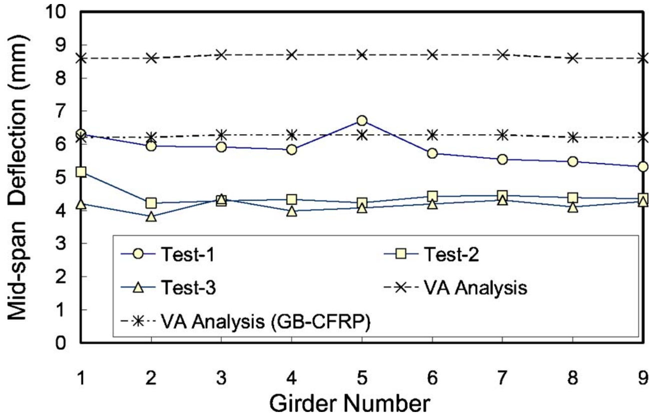


**Fig. 11.** Midspan deflection of bamboo girders corresponding to 8.6-t truckload Case 1

dial gauges were installed under each of the nine girders at the midspan for measuring their deflections.

Fig. 11 shows three test results of midspan deflections measured for the nine girders in critical loading Case 1. All the midspan deflections of the girders were below the limit of 16.7 mm (1/600 of the span length) per the requirement of the Chinese design code (People's Transportation Press 2004). Critical deflections were also below the limit value when the truck was positioned away from the bridge centerline and close to one edge, as shown in Fig. 12.

The field truckload tests were simulated using computer program VisualAnalysis. The glubam girders and the top precast concrete slabs are treated as grid girders and beams forming a single story space frame. A vertical connecting element model at the interfaces of the concrete slab grid beams and the glubam girders is designed as a rigid element without moment restraints at top, therefore the transverse concrete slab beams are treated as placed on top of the glubam girders with pin connection to reflect the actual interface. Along the longitudinal direction of the girders, no composite effect between the concrete slab and the girders is considered. Fig. 13 shows the schematic view of the computer model, which is formed with 537 members and 378 nodes. The analytical results for the Case 1 and Case 2 truckloads are also shown in Fig. 11 and Fig. 12, respectively. In the analysis, two types of modulus of elasticity for the girders are used, one is the average MOE values of 10.4 GPa obtained from testing of specimens B1

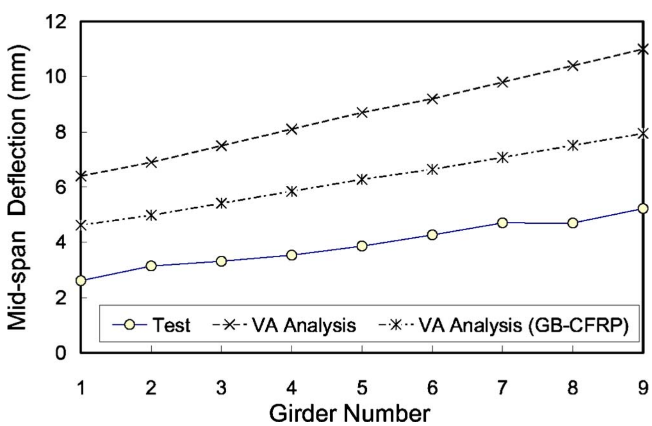


**Fig. 12.** Midspan deflection of bamboo girders corresponding to 8.6-t truckload Case 2

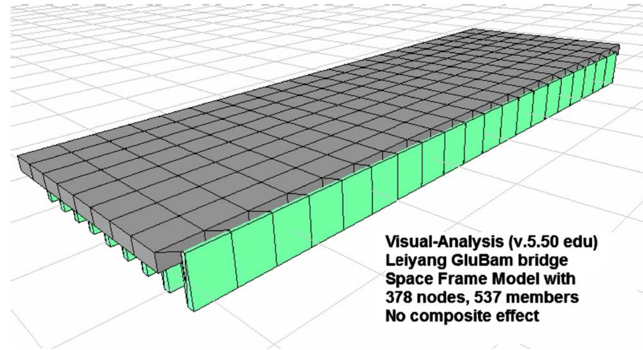


**Fig. 13.** Analytical model of Leiyang glubam bridge using Visual-Analysis

to B5, whereas the other is the value of 14.4 GPa obtained from the testing of specimen B6-CFRP, shown in Table 3. The comparisons shown in Figs. 11 and 12 indicate that the analyses capture the trend of the bridge midspan deflections during the field loading tests reasonably well, however, overestimate the deflection values for about 100%, if using the modulus of elasticity from the test results of girders without CFRP enhancement. Considering the CFRP enhancement effect by using the modulus of elasticity obtained from testing of B6-CFRP in this study can have a better estimation of the field test results, however, still conservatively predict the measured values. Assumptions of no

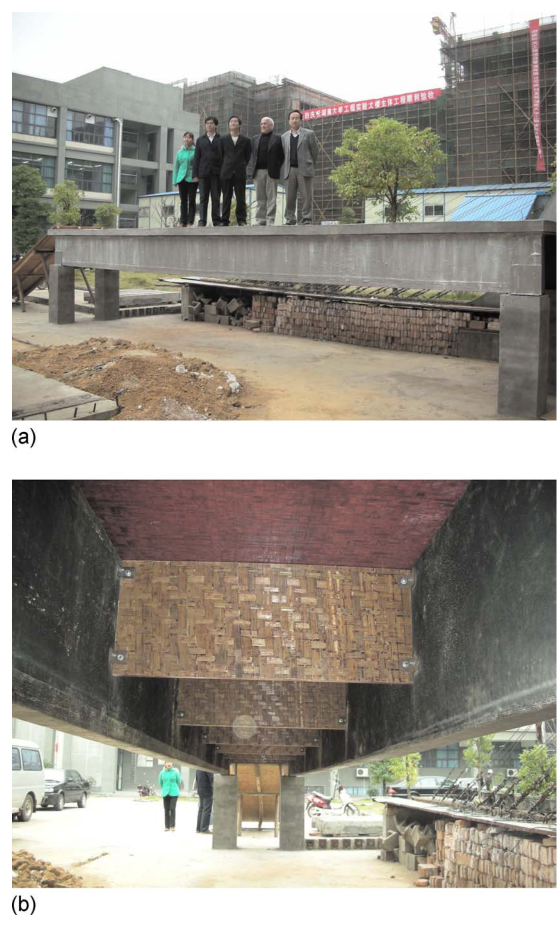


**Fig. 14.** Long-term loading test bridge at IBTCS laboratory: (a) overall bridge; (b) underneath view of two laminated bamboo girders



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composite effects between the concrete deck slab and the girders, and simple supports at the bridge ends in the analytical modeling are possible reasons for the overestimation of the field test results.

The bridge was certified for satisfying design load conditions and was officially opened to traffic on December 12, 2007. The modern bamboo bridge in Leiyang, China is being monitored regularly to obtain data for its long-term performance. Meanwhile, as shown in Fig. 14, another 10-m long but 1.5-m wide bridge supported on two laminated bamboo girders was constructed at the IBTCS laboratory at the Hunan University. This bridge is currently subjected to long-term loading for a research program to obtain creep data.

## Conclusions

Large size laminated bamboo girders, or GluBam girders, were developed and tested successfully. The newly developed bamboo structural elements have several design and construction merits such as being lightweight with sufficient load carrying capacity and stiffness, suitable to be used for carrying load, as demonstrated by testing of six full-scale girder specimens. Although limited in specimen number, the results also indicated that the use of FRP can further enhance the stiffness and increase the strength of the laminated bamboo girder. Installation procedures similar to those practiced in wood frame construction can be adopted for the construction of structures using laminated bamboo elements.

Based on the theory of mechanics, design and experiment, the world's first truck-safe modern bamboo bridge was designed and constructed. Field truckload tests indicated that the bridge performed well.

The writers are currently conducting a series of testing on modern bamboo bridges built to date in order to further study the long-term performance and fatigue behavior of laminated bamboo girders. In addition, significant research progress has also been made in mobile and permanent houses using laminated bamboo elements.

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