# MODERN BAMBOO STRUCTURES

Y. XIAO, M. INOUE & S.K. PAUDEL
EDITORS

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MODERN BAMBOO STRUCTURES

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# Modern Bamboo Structures

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# Preface

In October of 2007, the First International Conference on Modern Bamboo Structures (ICBS-2007) was held at the Hunan University, Changsha, China. The conference was co-organized by Hunan University of China, University of Southern California of USA, Oita University of Japan and the International Network of Bamboo and Rattan (INBAR). The sponsors for this conference include:

> National Natural Science Foundation of China (NSFC); Chinese Academy of Forestry (CAF); China Youth Center for International Exchange; World Bamboo Organization (WBO); American Society of Civil Engineers (ASCE); Architectural Institute of Japan (AIJ) American Bamboo Society, USA; Southern California chapter of the American Bamboo Society, USA; Bamboo Society of Australia; Bambu Brasileiro, Brazil; National Mission for Bamboo Application, India; Brazilian Association of Non-Conventional Materials and Technologies, Brazil; Bamboo Technologies, USA; TRADA international, UK.

The objective of the conference was to provide an open forum for experts around the world to exchange information and to thoroughly discuss topics related to design, analysis, testing, manufacturing, construction of modern bamboo structures and other natural or non-conventional construction materials. More than fifty presentations have been made by participants from more than twelve countries. The proceedings of the ICBS-2007 include thirty-three papers selected from the final submissions of the conference. The editors are pleased and believe that these papers provide the-state-of-the-art about the research and applications of bamboo in structures. We believe the conference and the proceedings contribute to our knowledge towards the utilization of bamboo in the eco-friendly and sustainable construction.

The editors would like to thank all the participants and authors for their contribution. The guidance and assistance of Taylor & Francis staff, particularly, Mr. Léon Bijnsdorp, in finalizing the proceedings are gratefully acknowledged. Particular appreciation is extended to the Hunan University for hosting the conference, and to the University of Southern California, the Oita University and the International Network for Bamboo and Rattan for co-organizing the Conference.

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# Photo of ICBS-2007 participants

*Theme papers*

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# Opening speech

B.S. Rong
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*Architectural Design and Research Institute of Guangdong Province, Guangzhou, Guangdong, China*

Distinguished Participants, Ladies and Gentlemen: Good morning!

It is my pleasure to have been invited to join the opening ceremony by Professor Xiao, chairman of the International Conference on Modern Bamboo Structures. Here, I would like to congratulate the organizers and all the participants for holding this important international conference, which is the first of its kind.

Bamboo is available everywhere around the world and is an abundant natural resource. It has been a conventional construction material since ancient times. As the development of modern material science progresses, a large amount of masonry, concrete and steel are used in the building structure, but bamboo and some other non-conventional natural materials still exist and are being used due to their natural characteristics and good mechanical properties. As a matter of fact, some regions in the world continue to use bamboo structures to this day. Therefore, should we transform the conventional structure to modern structure member or system by means of the modern technologies, the bamboo structure will possess a certain position and developmental perspective in the modern building and bridge constructions

Chairman of the conference and professor of Hunan University and University of Southern California, Dr. Xiao Yan has done a lot of research work on modern bamboo structures. I congratulate him and his team for having successfully built two bamboo structural bridges. His research achievements have provided beneficial reference for this research area.

Taking this opportunity, I would like to share a true story about the utilization of bamboo. In the fifties of the last century, the Architectural Design and Research Institute of Guangdong Province where I work built a five story office building making use of bamboo. The building was initially designed with a brick wall and pre-cast reinforced concrete slabs. However, at the time, our government called for saving steel as much as possible, so we used bamboo bars instead of steel bars in the pre-cast slabs. The bamboo bars were made of so-called moso bamboo strips with simple anti- corrosion treatments. After more than fifty years of usage, all the building slabs are still intact and function well, and I and my colleagues are working there everyday. Of course, it does not mean that these slabs are modern bamboo structures, but it has proved that bamboo can be the replacement of steel and also has a good durability.

At this conference, experts and researchers will gather to exchange the research information and discuss on many of technical aspects, such as the composition and characteristics of bamboo, test and analysis of bamboo members and structures, modern bamboo buildings and bridges, industrialization of bamboo products and so on. I believe it would contribute greatly to further research and development of modern bamboo structures.

I regret that I have to go to Beijing this afternoon for the annual meeting of the Chinese Academy of Engineering, so I cannot attend the entire conference. However, I look forward to learning more research findings from the proceedings of this conference.

Congratulations to the success of the conference in advance!

Thank you!

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# Bamboo: Low cost and energy saving construction materials

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ABSTRACT: In order to use bamboo on a large scale as an engineering material, economically feasible, with a possible industrialization, it becomes necessary to study scientifically the plantation, harvesting, curing and treatment processes. After this initial stage, a complete statistical and probabilistic analysis of the physical, mechanical and micro-structural properties of whole bamboo culms of different species should be carried out. Since 1979, the research programs at PUC-Rio, supervised by the author, were mainly concerned with establishing the engineering properties of some of the existing bamboo in Brazil and creating new structural elements using bamboo for civil and rural construction. The present paper has as its main objective to present the physical and mechanical properties of whole bamboo culms in addition to determining the functionally graded composite properties using data processing imagine of the studied bamboo. The bamboo species studied were Dendrocalamus giganteus take from the PUC-Rio and Guadua angustifolia, take from the Botanical Garden of Rio de Janeiro, Guadua tagoara and Guadua angustifolia taken from of Guarulhos in the state of São Paulo and Phyllostachys heterocycla pubescens (Mosó) and Phyllostachys bambusoides (Matake) from the city of Presidente Prudente in the state of São Paulo. A concise report about the structural elements such as bamboo space structure and different structural concrete elements reinforced with bamboo in addition to the several successful constructions built in Rio and Sao Paulo is given.

## 1 INTRODUCTION

In the era of industrialization the choice of the material has come to be determined mainly by the price and the facility of production or processing. Industrialized materials, such as Ordinary Portland Cement (OPC) and steel, find application in all sectors and any part of the world to which a road leads. In the last half of the 20th century advanced materials, constituents of synthetic polymers such as Rayon, Nylon, Polyester, Kevlar, new alloy metals and carbon fibers, among others, are being developed and are introduced in places where locally produced materials exist in abundance, especially in developing countries. In developing countries due to the educational system, which is mainly based on programs from industrialized nations, there is still no formal education or research program concerning the traditional and locally available materials and technologies. Lack of reliable technical information about the local materials leads the inhabitants and specialists to use mainly industrialized materials for which the information is freely available (Ghavami, 1995, 1985).

The construction industry is one of the most polluting on earth. On the one hand housing is still urgently needed as there are millions, alone in the developing world, without homes cities have grown beyond their limits, have sprawled in all directions, which not only create problems with transport, energy, different wastes and water-supply but as well have invaded eco-systems and valuable green space necessary for agricultural use. Nature has suffered irreparable damage. The consequences become more and more evident: droughts, heat waves, forest fires, polluted air and waters, which together result in human sacrifices. Crops fail; there is a lack of drinking water, lack of water in the reservoirs for energy generation etc. Armed conflicts around the world contribute even more to the human misery. At this point it does not lead anywhere blaming the industrial countries because they cause more pollution in the nature of their activities. Waiting for them to clean up, thinking that they have the means to do so, does not resolve the problems either. Everywhere, actions need to be taken to try to reverse the present state. Rio 92 and Rio+10, Kyoto agreement, Bali conference, had created a forum where the environmental problems were presented and discussed. Various other national and international events disseminated on-going research projects. Now steps need to be taken to implement the results of the research investigations which have been ignored for years for not being agreeable to centralized multinational industries (Ghavami and Rodrigues 2000, Ghavami and Zielinski 1988).

The whole construction process has to be revised starting with the location and the choice of materials to the different production processes. The answers are there already but they are followed by only a few. The few research centers make hardly a difference. These topics need to be taken up and supported by governmental agencies, NGOs, private enterprises industries and especially multi-national industries. Non-conventional Materials and Technologies (NOCMAT) and infrastructure need to be part of regular university courses. Before starting to build new houses one should look at the existing already. It has been a trend recently, and this worldwide, to abandon the old city centre and build at the periphery of the city getting further away from the centre and its commercial activities (Swamy, 2000).

To overcome the serious housing problem in Brazil and in other developing countries around the world, the author of this paper has been carrying out several successful research program since 1979 using indigenously available local materials such as bamboo, vegetables fibers, soil, quick lime, and cement mortars in the production of new structural elements such as bamboo space structures, corrugated sheets made of cement mortar composites reinforced with sisal, curaua and coconut fibers, soil-fibers composite for load bearing walls and concrete elements reinforced with bamboo beside the study of traditional construction (Ghavami and Hombeck 1981, Ghavami and Culzoni 1987, Ghavami and Villela 2000, Moreira, 1997). The main problem with the ample application of the structural elements developed is still the lack of sufficient information concerning each constituent of the composite and its durability besides sufficient financial support. The focus of this paper is to present a summary of information about the mechanical, physical at meso structure of bamboo and its application as a low cost energy saving material, which is locally available for producing the space structure concrete structural elements reinforced with bamboo. Some successful examples of the application of the results in practice also reported.

## 2 BAMBOO AS CONSTRUCTION MATERIAL

In South American countries the natives used bamboo intensively before the arrival of the European invaders who never knew how to use bamboo (Culzoni, 1986, Lopes, 1974). Up to the eighties of the last century its use was limited to the construction of some scaffolding and simple dwellings. In Brazil systematic studies were carried out on bamboo since 1979, of which the greater part was dedicated to the development of a methodology for its application in space structures and as reinforcement in concrete. The energy necessary to produce 1 $m^3$ per unit of stress projected in practice for materials commonly used in civil construction has been compared with that of bamboo. It was found that for steel it is necessary to spend 50 times more energy than for bamboo (Janssen, 1981). In the production of one tone steel two tons of $CO_2$ is produced. In contrast bamboo plant absorbs $CO_2$ besides producing oxygen. The tensile strength of bamboo is relatively high and can reach 370 MPa (Dunkelberg, 1985, Liese, 1992, Lopes, 1974), this turns the use of bamboo attractive as substitute of steel, especially when considering the relation between tensile resistance and specific weight of bamboo which is six times greater than that for steel (Ashby, 1992, Wgst, et al.,1993).

### 2.1 *Basic characteristics of bamboo*

Bamboo as a Functionally Graded Composite-Bamboos are giant grass-like plants and not trees as commonly believed, belonging to the family of the Bambusoideae. The bamboo culm, in general, is a cylindrical shell, divided by transversal diaphragms at the nodes. Bamboo is an orthotropic material with high strength along and low strength transversal to its fibers. The structure of bamboo is a composite material, consisting of long and aligned cellulose fibers immersed in a ligneous matrix (Liese, 1992). A close-up of a cross-section of a bamboo culm shows that the distribution of the fibers is variable along its thickness. This presents a functionally graded material, produced according to the state of the stress distribution in its natural environment (Amada, 1996), As it can be seen in Fig. 1 the fibers are concentrated more as they approximate the outer skin, in a way that the culm could resist wind forces, to which it is constantly subjected during its life.

In establishing the mechanical properties of bamboo in the elastic range using the rule of mix for the composite materials, the properties of the fibers and matrix with their volumetric fractions should be taken into account. Equation 1 presents the calculation of the elasticity modulus, $E_c$, of the bamboo as a composite. In this equation $E_f$ and $E_m$ are elasticity modulus and $V_f$ and $V_m = (1 - V_f)$ are the volumetric fractions of the fibers and matrix respectively. The assumed hypotheses in the development of equation 1, beside the long and aligned fibers, consider also the perfect bonding between fibres and matrix as well as the uniform spacing between fibres (Ghavami and Rodrigues, 2000).

$$E_c = E_f V_f + E_m \left(1 - V_f\right) \tag{1}$$

To apply equation 1 for the analysis of bamboo, the fibers variation of the volumetric fraction, $V_f(x)$, in its thickness should be taken into account. Considering that the $V_f(x)$ distribution follows an axis $x$, originating in the internal wall thickness with the maximum limit at the outer wall of the bamboo culm, equation 2 can be written. The variation of the fibers along the thickness, $V_f(x)$, was determined using the digital image processing, DIP.

$$E_c = f(x) = E_f V_f(x) + E_m \left(1 - V_f(x)\right) \tag{2}$$

The developed methodology of DIP is being used to establish the variation of the fiber volume fraction of bamboo along their overall length of ten different bamboo species. For this purpose, three samples are taken from the bottom, middle and the top part of bamboo culm, as shown in Fig. 2a for bamboo Dendrocalamus giganteus (Ghavami and Rodrigues, 2000).

$$V_f(x) = 49.8x^2 - 0.49x + 20.01 \tag{3}$$

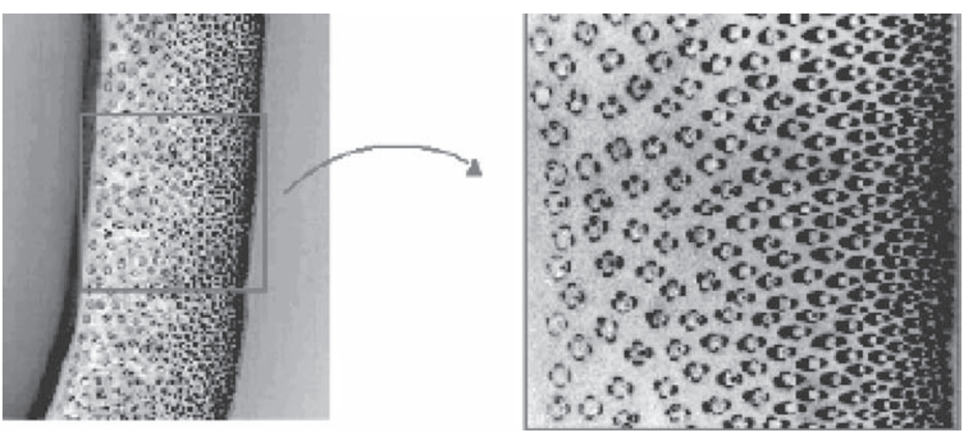
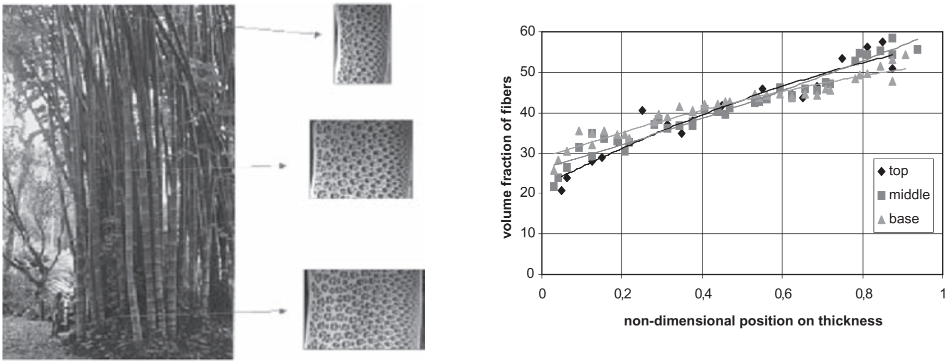


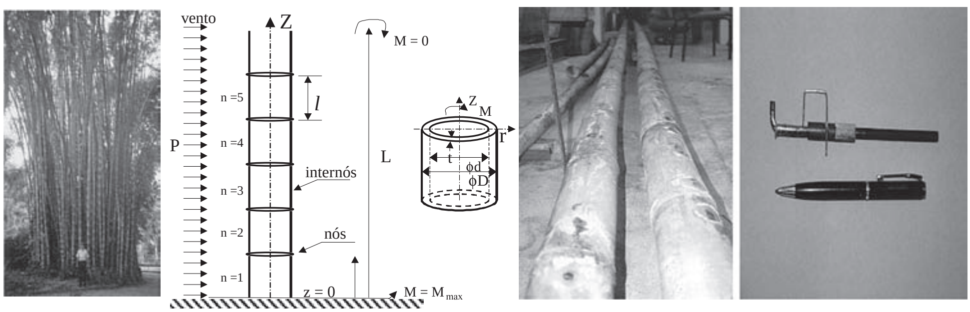
Figure 1. Non-uniform fiber distribution on cross section of bamboo.




(a) Location of samples for DIP along the length bamboo culm DG

(b) Fiber distribution across bamboo thickness at bottom, middle and top part of DG

Figure 2. Fiber distribution across the bamboo thickness using DIP method.




(a) Axis of the coordination

(b) Holes along the bamboo culm

(c) Instrument to measure the thickness

Figure 3. The bamboo DG in Botanical garden of Rio de Janeiro.

The variation of fiber volume fraction across the thickness of bamboo, $V_f(x)$, at the three parts for DG, are given in Fig. 2b. It is observed that the fiber distribution is more uniform at the bottom than at the top and the middle parts. This phenomenon could be explained knowing that the bamboo is subjected to maximum bending stress due to wind load and its own weight in the base. However, the differences between the distributions are not very significant. Therefore all the data presented in Fig. 2b were used to establish equation 3 where the mean volume fraction variation of fibers across the thickness of bamboo DG is presented by:

Physical property of whole bamboo culm-The variation of the wall thickness and internodal distance of entire bamboo culms of the species Dendrocalamus giganteus (DG), Moso, Matake, Guadua and Phylostaques pubensen have been measured as shown in Fig. 3, The results are presented in Fig. 4, where the variation of the geometric features of DG is given as an example and discussed in order to show how these data will help the bamboo user to choose the dimensions he would need for his designed project. The internodal length is larger in the middle part and the thickness decreases from the bottom to the top of the bamboo culm. Based on the obtained data a mathematical formula, which relates the thickness, $t$, to the position of the internode, $n$, is established for all species of bamboo studied. The relation for bamboo DG is given by equation 4. With the help of this equation the designer can choose the required thickness from the range of bamboo species.

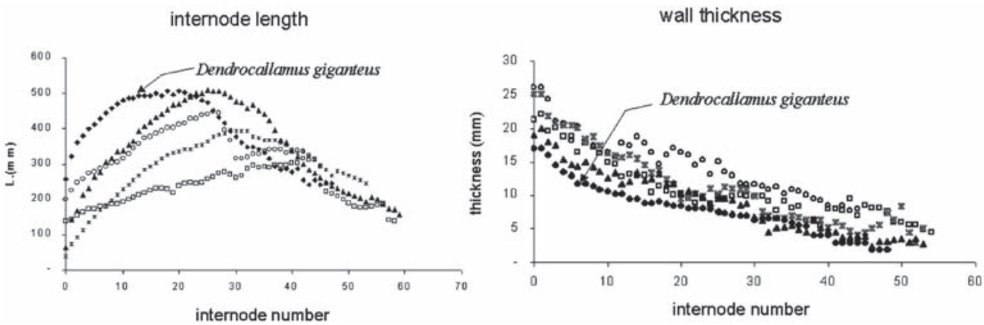
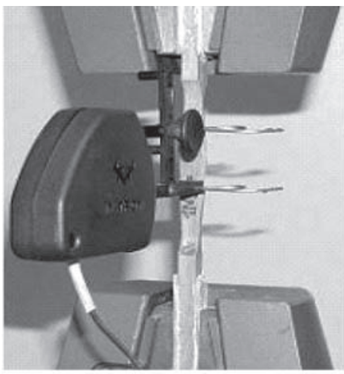
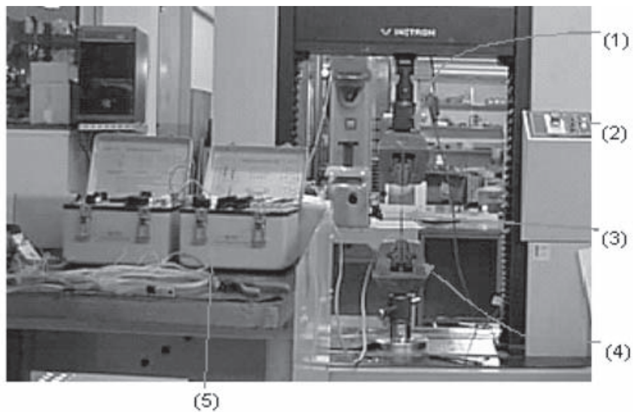



Figure 4. Variation of thickness and internodal length along the whole bamboo culm.



Measurement of the tensile strength using Clip gage




(1&4) application of the load. (2) control system. (3) tested specimen (5) Vischay instrument to register the deformation.

Figure 5. Tensile test set up.

Similar mathematical formulas are developed for diameter and internodal length of the bamboo. These results allow establishing easily the mechanical behavior of different types of bamboo.

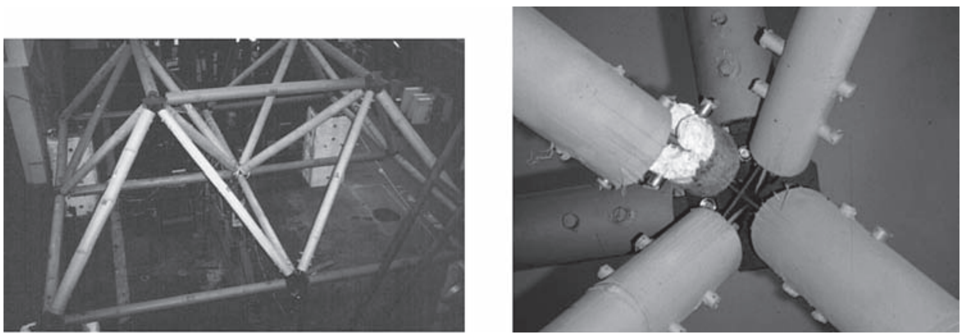
$$t = -0.0003n^3 + 0.025n^2 - 0.809n + 16.791 \qquad (4)$$

Mechanical Properties—As for any other material to be used safely its mechanical properties should be established through simple laboratory tests. The international norm on test procedure for the mechanical behavior of bamboo elaborated by the international Bamboo Committee of INBAR is being approved by ( ISO, 200) as shown in Fig. 5 and Fig. 6 have been used to establish mechanical properties of the studied bamboos. The results of the tensile and compression tests are given in Table 1.

## 2.2 *Bamboo space structure*

Having once tested the isolated elements for buckling, as well as the joints under axial loading, an experimental study of the global behavior of a double layer space structure using the results of the studied of the isolated elements was carried out. A full scale prototype of the Double Layer Grid, with 4 m × 4 m of free span, was carried out (Moreira, 1997). The prototype consisted of


Figure 6. Dimensions and position of the strain gauges in compression test.



a) Double Layer Bamboo structure during test

b) Shear failure of the bamboo joint

Figure 7. 4 m by 4 m developed bamboo space structure during test.

32 elements of bamboo poles of 2 m length with pin joint connections of bamboo elements using the metallic plates as shown in Fig. 7. The prototype was simply supported at four points and load was applied vertically at the centre of the structure, node 9, through a hydraulic jack with a capacity of 120 kN. The load of 0.5 kN, was applied at the interval of 20 second in order to establish the load displacement curves of the structure. The strains in the individual elements were measured by means of electrical strain gauges and the displacements of the nodes with electrical transducers of linear displacements, LVDT.

To verify the symmetrical behavior of the prototype, the reactions of the support were measured by load cells. The DLG prototype failed when the applied load at the centre of the structure was 32 kN. The failure occurred due to shearing stress of 11.18 kN at the hole where the pin was used at the connection. This failure shear value was lower in relation to the failure stress of the isolated tested connections, with had a mean value of 21,63 kN. The failure of the bamboo in the connection is shown in shown in Fig. 7b.

### 2.3 *Development of bamboo reinforced concrete elements*

One of the main shortcomings of bamboo when used as a reinforcement and/or permanent shutter form with concrete is the effect of water absorption. The capacity to absorb water was studied on several bamboo species. The obtained results have shown that the Dendrocalamus giganteus, DG, and Bambusa vulgaris schard, BVS, absorbed the least water in comparison with other species (Culzoni, 1986). The measurements of the dimensional variations of bamboo DG and

Table 1. Mechanical properties of five species of bamboo.

| Species/local | | Tensile Strength (MPa) node | No node | Modulus of Elasticity Et (GPa) node | No node | Compression Strength (MPa) node | No node | Modulus of Elasticity Ec (GPa) node | No node |
|---|---|---|---|---|---|---|---|---|---|
| Bambusa multiplex Disticha (RJ)* | Base | 68,80 | 98,00 | 11,11 | 14,08 | 20,60 | 30,00 | 3,05 | 4,15 |
| | Middle | – | – | – | – | – | – | – | – |
| | Top | 79,8 | 108,4 | 11,95 | 14,92 | 20,00 | 26,50 | 3,54 | 4,27 |
| | Average | 74,30 | 103,2 | 11,53 | 14,50 | 20,30 | 28,25 | 3,29 | 4,21 |
| Bambusa tuldoide (RJ)* | Base | 112,0 | 140,5 | 9,99 | 12,66 | 30,20 | 37,80 | 2,97 | 3,24 |
| | Middle | – | – | – | – | – | – | – | – |
| | Top | 95,80 | 98,00 | 8,55 | 11,19 | 30,00 | 38,3 | 2,83 | 2,78 |
| | Average | 103,9 | 119,2 | 9,27 | 11,92 | 30,10 | 38,05 | 2,90 | 3,01 |
| Guadua superba (RJ)* | Base | 108,8 | 142,6 | 8,33 | 10,48 | 36,40 | 50,60 | 2,46 | 3,12 |
| | Middle | – | – | – | – | – | – | – | – |
| | Top | 115,8 | 151,0 | 9,42 | 11,83 | 35,00 | 45,00 | 2,83 | 3,55 |
| | Average | 112,3 | 146,8 | 8,87 | 11,15 | 35,70 | 47,80 | 2,64 | 3,33 |
| Bambusa vulgaris Schard (RJ)* | Base | 131,6 | 176,4 | 8,46 | 10,02 | 37,50 | 53,00 | 2,59 | 2,86 |
| | Middle | 106,1 | 153,5 | 8,50 | 10,22 | 39,50 | 46,00 | 2,36 | 3,19 |
| | Top | 145,6 | 182,0 | 9,45 | 12,67 | 42,00 | 59,00 | 2,80 | 3,67 |
| | Average | 127,7 | 170,6 | 8,80 | 10,97 | 39,66 | 52,66 | 2,58 | 3,24 |
| Dendrocallamus giganteus | Base | 106,8 | 147,0 | 12,98 | 19,11 | 58,66 | 56,61 | 12,07 | 15,29 |
| | Middle | 143,6 | 188,1 | 16,73 | 15,70 | 53,96 | 63,77 | 15,15 | 11,26 |
| | Top | 114,0 | 157,6 | 13,44 | 10,71 | 54,04 | 72,87 | 9,79 | 10,41 |
| | Average | 121,5 | 164,2 | 14,38 | 15,17 | 55,55 | 64,42 | 12,34 | 12,32 |

BVS reached up to 6% of the transversal section after 7 days immersion in water. To produce an effective impermeability treatment three factors were considered: The adhesion properties of the applied substance to bamboo and concrete, water repellent property of the chosen substance and the creation of rough surface on bamboo. The bonding between bamboo and concrete considering twenty five types of products was established on pull-out test specimens. To isolate the secondary effects due to non-uniform shearing stress distribution in conventional tests, only the 100 mm middle part of the bar was subjected to bonding shear stress. The other two parts are prepared for zero shears (Culzoni, 1986, Ghavami and Culzoni, 1987). The application of SIKA32-Gel has produced the best results. The shear bond stress, $\tau b$, in N/mm$^2$, was calculated by equation 5 .

$$\tau_b = \frac{F}{L.S} \tag{5}$$

where F is the applied pulling load in Newtons and S is the perimeter of the bamboo in mm and $L$ = 100 mm is the length of bamboo with and without treatment. This treatment has improved the shearing bond strength by up to 400%.

### 2.3.1 *Bamboo reinforced concrete beams*

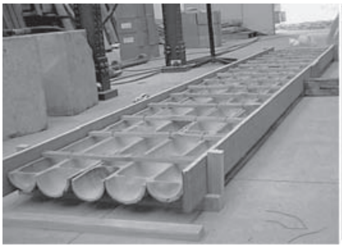
Several series of tests on simply supported bamboo reinforced concrete beams have been studied using normal, lightweight and laterite aggregates. The maximum size of aggregates was 20 mm. A beam reinforced with steel bars was always considered as reference. The lightweight aggregates were expanded clay commonly used in southeast of Brazil and fabricated in Sao Paulo. In the Northeast of Brazil the laterite aggregates which exist in abundance were considered. Throughout the research programs only ordinary Portland cement CP-32 and natural-washed river sand were used.

The concrete mix proportions for normal concrete were 1:1,4:2,4 and water cement ratio of 0,45 and for lightweight concrete were 1:3,22:0,78 of cement: fine and coarse aggregate with water cement ratio of 0,55; all measured by weight. The compressive strength of the concrete was established on 15 cm diameter and 30 cm high cylinders. The ultimate compressive strength, $f_{cc}$, modulus of elasticity in compression, $E_c$, varied between 20 MPa to 40 MPa and 12 GPa to 34 GPa respectively (Culzoni, 1987). The split bamboo culms were of 30 cm width rectangular sections. The smooth surface of the bamboo splints were cleaned and slightly roughened before a thin layer of the impermeable product was applied. Then the splints were allowed to dry before being fixed inside the form work.

The length of the beams was 340 cm with free span of 300 cm and their cross sections were 12 cm wide and 30 cm deep. The beams were fabricated by pouring the concrete into the form work in layers of 10 cm and then vibrating as recommended by the Brazilian Norms. All beams were cured for 28 days, using wet sawdust, before they were tested. The bamboo reinforcing ratio, ρ, varied between 0,75% to 5,00%. The tests were carried out in different laboratories at PUC-Rio showed that the, ρ, of 3% produces the best results.

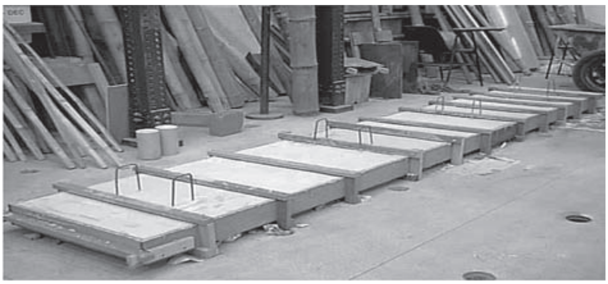
### 2.3.2 *Bamboo reinforced concrete slabs with permanent shutter forms*

Concrete slab reinforced with half bamboo section which works also as a permanent shutter form, is perhaps one of the best applications (Ghavami and Zielinski,1988). The same methodology and concrete as for bamboo reinforced concrete beams were applied to establish the mechanical and structural behavior of the slab of which the largest had a cross section of 80 cm width by 14 cm height with an overall length of 416 cm and a free span of 400 cm as shown in Fig. 8a, to Fig. 8c. A half split DG bamboo culm which works as a tensile reinforcing bar and also as permanent shutter form was filled with concrete as can be seen in Fig. 8c. For this investigation normal, lightweight and laterite concrete as for beams were used. The experimental results have been analyzed using conventional analytical methods and proved not to be sufficient enough as this type of structural element works as composite slab with the bamboo diaphragms acting as connectors. Therefore for the analysis of the slabs beside the normal semi-analytical method the layer-wise theory and Finite Element method were used to realize a parametric study considering different variables



(a) Permanent shutter bamboo working as tensile reinforcement

(b) Permanent shutter bamboo with full diaphragm shear connector



(C) Permanent shutter bamboo slab before testing

(d) Push-Out test

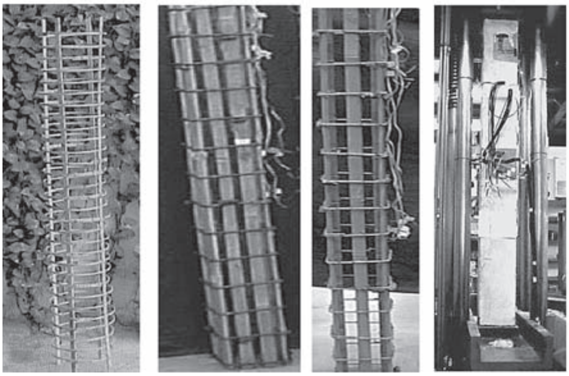
Figure 8. Concrete slabs reinforced with bamboo permanent shutter forms.

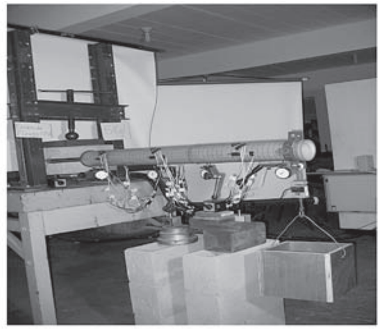
influencing the behavior of the composite slabs (Ghavami and Zielinski, 1988). One of the important factors which have a great influence on the ultimate load of the slab is the shearing resistance of the bamboo diaphragms which act as shear connectors.

The shearing resistance of whole and half bamboo diaphragms of specie DG have been studied. For the half bamboo its shearing strength has been found to be 10.89 MPa with a standard deviation of 2.56 MPa. Although the bamboo diaphragm creates a composite interaction between bamboo and concrete, its shear resistance is not sufficiently enough to prevent its shearing failure of the connector. Most of the tested slabs had first failed due to bonding and failure of the diaphragm then followed by concrete compression failure. To increase the shearing strength of half bamboo several alternatives have been considered. One of the simplest methods was to fix a strip of steel or bamboo rod close to the bamboo diaphragm passing through the bamboo diameter. This method almost doubled the shear strength of the diaphragm hence the ultimate load of the slabs. The full diaphragm as shown in Fig 8b also presented to be very effective. This type of slab is now used in Brazil. At present, studies are underway to improve the bonding between bamboo and concrete with new products such as Sika 32 in addition to the shearing behavior of the connectors see Fig. 8c.

### 2.3.3 *Bamboo reinforced concrete columns and torsion test*

The structural component being developed, analyzed and tested recently is a bamboo reinforced concrete column with permanent shutter form. The main reinforcement of this 30 cm diameter column is made entirely of treated 3 cm DG bamboo segments. The bamboo was treated with a new SIKA32 product which gave a very satisfactory bonding when compared with IGOL-T and Negroline see Fig. 9a. In this series of test beside the bamboo reinforcement the concrete form is also entirely made of bamboo. Bamboo can be left to work as a permanent shutter which besides having a pleasing aesthetic appearance can economize the finishing costs of the concrete (Ghavami and Villela, 200). The second series were the concrete columns of 20 cm by 20 cm and





(c) Torsion and Flexo-torsin expermential set up

(a) Cicular column

(b) Square bamboo

Treated bamboo

Reinforced concrete bamboo test

Figure 9. Bamboo reinforced concrete column with permanent shutter form.

the height of 220 cm as shown in Fig. 9b. The strips in this series made of 5 mm steel bars. In both series one conventional concrete column reinforced with steel was tested. Electrical strain gauges were fixed to the reinforcing bars of the column in order to compare the test results with those of the calculated ones. The test results have shown that the maximum load of bamboo reinforced concrete is the same as the one reinforced with steel. After four years the tested columns were broken to see the bamboo reinforcement's condition. The bounding was in a very good conditions. The bamboo segments were taken out and their tensile strength were verified. Surprisingly most of the bamboos have shown higher strength as compared with those measured four years earlier. Recently the torsion and flexo-torsion behaviour of bamboo culm of the species Moso, Dendrocalamus Giganteus and Guadua Angustifolia have been studied in detail. The experimental set up is shown in Fig. 9c.

2.3.4 *Analysis of bamboo reinforced concrete elements*

As for conventional steel reinforced concrete beams and slabs subjected to increasing bending load up to collapse, the bamboo reinforced elements also go through three characteristic stages of stress and strains in their cross sections as shown in Fig. 10. In this Figure D, d and b are the total, the effective depth and the width of the bending element respectively, $A_{bt}$ is the area of bamboo subjected to tension, $\varepsilon_c$ and $f_c$ are compression strain and stress of the concrete, $\varepsilon_{bt}$ and $f_{bt}$ are tensile strain and stress in bamboo. In stage 1 for a small load, the stress and strain are in linear elastic range. The normal compression and tension stresses in a section in concrete are triangular. With an increase of the applied load the internal stress diagram of concrete along the depth of the section becomes non-linear until the ultimate tensile strength of the concrete is reached.

In stage 2 the bamboo at the cracked points and in the concrete between the crack, in the tension zone resists the internal tensile stresses. The stress distribution in the bamboo in the un-cracked part is similar to the conventional pull out test i.e. the further from the crack point the higher the bonding shearing stress, as the bond between bamboo and concrete in this region is still almost intact. With the increase of the applied load the stress diagram in the compression zone of concrete continues to be non linear before its ultimate strength and bamboo in tension starts to break from its lower layer and hence, starting the third stage.

In stage 3 the diagram of normal compression zone of concrete is of parabolic shape. However for the development of formulas for the practical design a rectangular shape is adopted. Depending on the percentage of bamboo reinforcement three cases may occur: the case with under reinforcement where the failure of bamboo leads to the collapse of the bending element, with

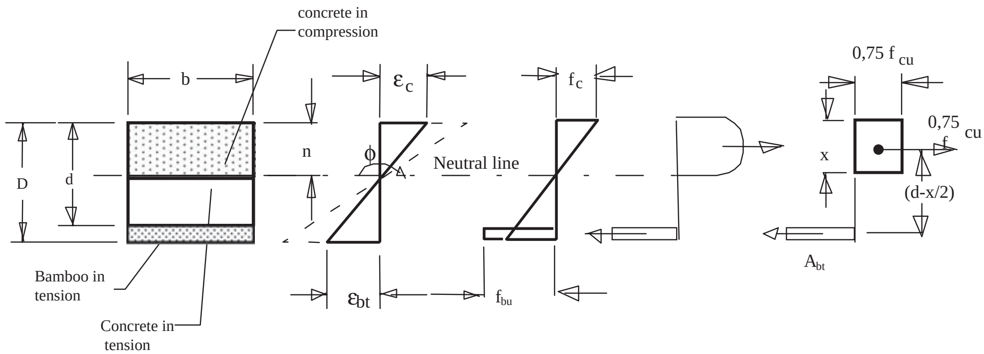



Figure 10. Stress and strain distribution in an element subjected to bending at different stages.

over reinforcement, where the collapse of the element occurs due to compression failure of concrete and the balanced case where both concrete and bamboo could fail simultaneously. Based on the obtained experimental data of the beams and one way composite slabs and the explained failure modes formulas for the design of these reinforced concrete elements have been developed.

In all the bamboo reinforced beam tests realized up to present the failure mostly occurred due to tensile failure of concrete and bamboo. Although in several cases the test beams were over-reinforced but no compression failure was provoked. This is mainly due to imperfect bonding between bamboo and concrete. With the advent of new products a research program is underway to overcome this. However, in the permanent bamboo shutter slabs with only a diaphragm as connector the collapse was mainly due to shear failure of connector.

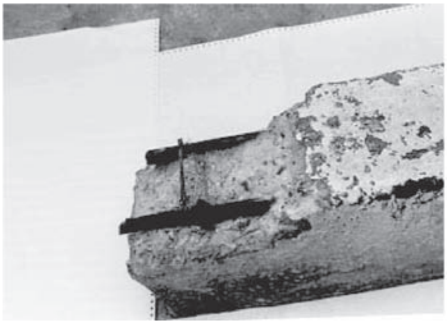
## 2.4 *Durability of bamboo as an engineering material*

Similar to timber bamboo is vulnerable to be attacked by environmental agents, insects and moulds. Its durability depends very much on the species, age, right conservation, treatment and curing which is initiated already when being cut in the bamboo grove. There is a strong relation between insect attacks, humidity content and starch of bamboo. In order to reduce the nutrition content, bamboo needs to pass through a curing process such as: curing on the spot, curing by immersion, curing by heating, curing by smoke.

Drying bamboo is fundamental for its conservation for various reasons. Bamboo with low humidity is less prone to mould attacks, with a very low risk when humidity content is less than 15%. Physical and mechanical properties increase when bamboo has a low humidity content. Bamboo to be treated needs to be dry to facilitate penetration and obtain a better result and reducing transport costs. Bamboo can be dried in air, green house, oven or by fire. The durability of bamboo depends strongly on the preservative treatment methods in accordance with basic requirements: its chemical composition should not have any effect on the bamboo fiber and once injected it must not be washed out by rain or humidity. The preservative can be applied using simple systems such as leave transpiration, immersion, impregnation, Modified Boucherie Method or sophisticated modern equipment of cauldrons and special chambers working with vacuum or pressure.

In engineering and architectural faculties the subject “Structural Analysis” emphases mainly on the strength of steel or steel reinforced concrete elements and little is taught about durability and performance of these structures during their life time. Many steel and concrete buildings constructed during the last 30 years reveal serious deterioration caused mainly by the corrosion of the steel reinforcement. Many on-going research programs are concerned about the rehabilitation of these conventional reinforced concrete structures for which millions of US dollars are spent.

In Fig. 11a comparison is made between the durability of conventional steel reinforced concrete columns after 10 year in service and the first bamboo reinforced concrete beam tested at PUC-Rio



(a) Bamboo reinforecment after 15 years in open air

(b) Steel reinforcement after 10 years in closed area

Figure 11. Durability of bamboo and steel concrete elements.

Figure 12. Front and lateral view of bamboo house in Itanhangá/Rio de Janeiro.

in 1979 (Ghavami and Hombeeck, 1981). The steel reinforced concrete columns are part of the tunnel structure of Rio's Metro. The bamboo reinforced beam after testing has been exposed to open air in the PUC-Rio university campus. It can be observed that the bamboo segments treated against insects as well as for bonding with IGOL-T show a very satisfactory behavior and appearance after 15 years. However, the steel reinforcing bars after ten years had a serious corrosion problems and are being substituted. The bamboo segments of the beam were taken out of the concrete and tested for their mechanical strength. They had a slight deterioration in their tensile strength as compared with the original untreated bamboo

### 2.5 *Some executed bamboo projects with the participation of the GMTENC*

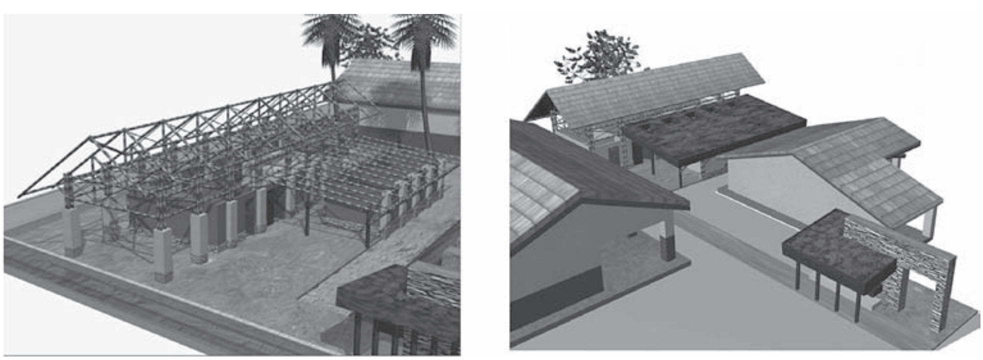
Amongst various executed projects using bamboo, the bamboo show house, entirely fabricated using different species of bamboo. All the internal parts including the wall finishing, tables, chairs, hangers, lamp shades beside the roof tiles, are made of bamboo. This house is located in Itanhangá, in the town of Rio de Janeiro-Brasil and has been used as the bamboo architectural office under the management of MS. Alessandra Debaux. Fig. 12 present frontal and lateral view of the bamboo house. The structural columns, walls, doors, windows, roof tiles and drains are made with treated Dendrocalamus Giganteus and also some part with bamboo Mosso, and Matake.

Bamboo construction in Camburi. On the coast, southeast of Rio de Janeiro, at the border with São Paulo, the community centre of Camburi is a living example of the application of the research results into the use of bamboo, vegetable fibres, soil beside other non-conventional materials and technologies studied by the GMTENC group at PUC-Rio since 1979. In the village Camburi of the municipality of Ubatuba, where the inhabitants live in traditional Taipa houses, which are in a very bad conditions due to the lack of maintenance. The inhabitants have forgotten or are not willing to use this traditional sustainable way of construction and are waiting for the local authority to offer them cement, sands and aggregate for the construction of new houses.

As in other communities when the bamboo construction was suggested to the leaders of the village they categorically rejected. As the objective of the members of the Bamboostic NGO from Belgium and the author of this paper as the coordinator was to introduce bamboo and other non-conventional materials and technologies in less developed regions special strategy had to be chosen.

First in order to gain the confidence of the local community which did not know bamboo nor believed that it could be used in any engineering project, the recently graduated young Belgians,

Figure 13. Construction of kiosk using bamboo and earth.



(a) Virtual Model

(b) Virtual Model

Figure 14. Digital project of sustainable community center of Camburi.

the architect Sven Mouton, the communication specialist Hilde Duerink and the civil engineer Pieter Loose projected and constructed a bamboo pedestrian bridge inside the Mata Atlántica in Ubatuba, SP. After the completion of the bridge the inhabitant of the village could be convinced that bamboo was a good construction material and started to show interest to learn about the techniques in the use of bamboo. At the second stage in collaboration with the local inhabitants Camburi cooperative was organized. It was planned to create a source of income, through tourism and sell the handicraft produced locally. For this a modern kiosk was projected to be constructed with bamboo in the main square of the village. The cable stayed bamboo Kiosk shown in Fig. 13 was used also as a training project for the interested future bamboo builders.

To extend the training of the bamboo builder, a small information center was also at the entrance of the Camburi which is about three km away from the center of the village. In the construction of the building the principal of Taipa construction using bamboo and local clay has been used. Fig. 13 shows the construction of a kiosk using bamboo and earth in an improved Taipa ou pau-a pique method beside the use of local stones. The structure is covered with a locally available straw. With these two last constructions the new builders were trained satisfactorily, so that a community center of 200 m$^2$ as shown in Fig. 14 was projected. In this project it was planned to use the principles of sustainability, as far as possible, by using bamboo, stones, soil, quick lime, green roof and other non-conventional materials and techniques.

The construction projects were carried out in cooperation with Bamboostic which gave a financial support also and the ABMTENC (Brazilian association into non-conventional Materials and technologies). After the construction of the first three relatively small projects and with the scientific/technical experience gained by the young Belgians professionals and their dedication the construction could be realized with success. The total dedication, perseverance and the involvement in the organization of the Camburi cooperative by the architect Sven, Hilde and Pieter were the most important for the the active and effective participation of the community members of Camburi in the execution of this project. Now the local bamboo builders acting enthusiastically and giving suggestions, in order to improve the practical application of the obtained results in the research laboratory (Figs. 15 and 16).

As can be seen in Fig. 15a, beside bamboo stabilized compacted local soil, commonly called "taipa pilão" was used in the construction of the walls. During the construction the architects Márcia Marcul and Sérgio Prado knowing about the Camburi project started to show interest in the project, and participated by the suggestion of the use of PET bottles of 2 liters soft drinks in the construction of some walls. Fig. 15b shows the load testing of the bamboo structure by members of the community after the partial placing of the ceramic roof tiles before the tying of the joints. Fig. 16 shows the 3 construction stages of the community centre.

(a) Compacted earth walls and bamboo structure

(b) Load testing of bamboo structure

Figure 15. Community centre of Camburi in the municipality of Ubatuba, SP.

(a) Lateral view

(b) Details of the joints of the bamboo structure

(c) Start of the second part of construction

Figure 16. Community centre of Camburi in the municipality of Ubatuba, SP.

Figure 17. Nano and ecological architecture, for country towns.

With ecology and sustainability in mind, various architectural projects have been developed at PUC-Rio and also in collaboration with other universities in Brazil and abroad. At the present time the doctoral project of the architect Marko Brajovic is being developed in collaboration with the Technical

University of Cataluña in Barcelona, Spain. The principle of the development of this project is based on nano architecture. The term nano architecture is referred here to the study of nano structure of bamboo which would allow the researcher to treat bamboo with some compatible nano particle or a compatible natural or synthetic polymer with the objective to make bamboo equal or superior to many conventional construction materials made of steel, PVC, aluminum etc. The initial architectural project shown in Fig. 17 digital computer presented in Fig. 17 show how the future construction made of NOCMAT could contribute in the modern constructions using local materials for rural and small town constructions. In this way it is hoped to slow down the emigration of rural workers from small country towns to big cities creating still the existing problems worse.

## 3 CONCLUDING REMARKS

The understanding of sustainability in building construction has undergone changes over the years. First attention was given to the issue of limited resources, especially energy, and how to reduce the impact on the natural environment. Now emphasis is placed on more technical issues such as sustainable materials, building components, construction technologies and energy related design concepts as well on non-technical issue such as economic and social sustainability. Since 1979 research has been carried out in Brazil on non-conventional materials and technologies. New building components were developed using vegetable fiber as reinforcement of cement mortar and bamboo as permanent shutter forms in concrete slabs and columns. Our concern was as well the dissemination of our work which occurred through publications and special courses. The Brazilian Association of the sciences of non-conventional material technologies (abmtenc), was founded to further the dissemination and the cooperation between engineers, architects, designers and civil servants related to housing.

Based on the research results of bamboo obtained in Brazilian universities and other institutes around the world with the leadership of INBAR the first norms for bamboo were created determining the physical and mechanical properties of bamboo. These norms have been evaluated by ICBO and at present is being official ISO standards. Norms are important not only for dissemination but also for the safe usage of a material. The use of bamboo reinforced concrete elements provide an exciting challenge to the housing construction industry, particularly in developing countries, since they are a cheap and readily available form of reinforcement, require only a low degree of industrialization for their processing and, in comparison with an equivalent weight of the most common steel reinforcement, the energy required for their production is small and hence the cost of fabricating these structural elements is also low. In addition, the use of bamboo requires low degree of transportation and only a small number of trained personnel in the construction industry. Development and application of bamboo structural elements thus pose the challenge and the solution for combining non-conventional building materials with conventional construction methods.

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## REFERENCES

Amada, Shigeyasu (1996), *The mechanical structures of bamboos in viewpoint of functionally gradient and composites materials*, Journal of composites materials, Vol. 30, nº 7.

Ashby, M.F. (1992), *Materials Selection in Mechanical Design*; Pergamon Press, Oxford.

Culzoni, R.A.M. (1986), *Características dos bambus e sua utilização como Material Alternativo no Concreto*, MSc Thesis, Dept. of Civil Engineering, PUC-Rio, pp. 134.

Dunkelberg, K. et al, (1985), *Bamboo as a Building Material,* Bamboo-IL 31, Institute for Lightweight Structures, University of Stuttgart, pp.1–431.

Ghavami, K. (1988), *Application of Bamboo as a Low-cost Construction Material,* Proceedings of International Bamboo Workshop, Cochin, India, pp. 270–279.

Ghavami, K. (1995a), *Ultimate Load Behaviour of Bamboo Reinforced Lightweight Concrete Beams*; International Journal of cement and Concrete Composites, 17(4), Elsevier Science Ltd., England, pp. 281–288.

Ghavami, K. and Culzoni, R.A.M. (1987), *Utilização do Bambu como Material em Habitação de Baixo Custo*, 1º Simposio Internacional de Habitação, PT, São Paulo, pp. 181–188.

Ghavami, K. and Hombeeck, R.V. (1981), *Application of Bamboo as a Construction Material: Part I—Mechanical Properties and Water-repellent treatment of Bamboo, Part II—Bamboo Reinforced Concrete*

*Beams*; Proceedings of Latin American Symposium on Rational Organization of Building Applied to low Cost Housing, IPT/CIB, São Paulo, Brazil, pp. 49–66.

Ghavami, K. and Rodrigues, C.S. (2000), *Engineering Materials and Components with Plants*, CIB Symposium, Construction & Environment, Theory into Practice, São Paulo, Brazil, CD-ROM, Global Seven Editor, pp. 1–16.

Ghavami, K. and Villela, M. (2000), *Coluna reforcada com Bambu*, End of the Course Report, DEC-PUC-Rio.

Ghavami, K. and Zielinski, Z.A. (1988), *Permanent Shutter Bamboo Reinforced Concrete Slab*; BRCS1, Dept. of Civil Engineering, Concordia University, Montreal, Canada.

ICBO, (2000); AC 162: *Acceptance Criteria for Structural Bamboo*, ICBO Evaluation Service Ltd.; California, USA.

Janssen, J.A. (1981), *Bamboo in Building Structures*; Ph.D. Thesis, Eindhoven University of Technology, Holland.

Liese, W. (1992), *The Structure of Bamboo in Relation to its Properties an Utilization*, Proceedings of the International Symposium on Industrial Use of Bamboo, Beijing, China, pp. 95–100.

Lopez, O.H. (1974), *Bambu su Cultivo y Aplicationes en: Fabricación de Papel, Ingenieria, Artesania*; Estudios técnicos Colombianos Ltda., Cali, Colombia.

Moreira, L.E. (1997*) Considerações Singulares sobre Comportamento de Estruturas Espaciais do Bambu*, Ph.D.Thesis, PUC-Rio.

Swamy, R.N., (2000),"Sustainable Concrete for Infrastructure Regeneration and Reconstruction", Int. Conf. on Sustainable Construction into the next Millennium Environmentally friendly and innovative Cement Based Materials, Joao Pessoa, Brazil, pp. 15– 44.

Wegst, U.G.K., Shercliff, H.R. and Ashby, M.F. (1993), *The Structure and Properties of Bamboo as an Engineering Material*, University of Cambridge, UK.

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# Bamboo in construction

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ABSTRACT: Bamboo is one of the oldest and most versatile building materials with many applications in the field of construction, particularly in developing countries. It is strong and lightweight and can often be used without processing or finishing. Bamboo constructions are easy to build, resilient to wind and even earthquake forces, and readily repairable in the event of damage. Associated products such as bamboo based panels and bamboo reinforced concrete also find applications in the construction process. In spite of these clear advantages, the use of bamboo has been largely restricted to temporary structures and lower grade buildings due to limited natural durability, difficulties in jointing, a lack of structural design data and exclusion from building codes. The diminishing wood resource and restrictions imposed on felling in natural forests, particularly in the tropics, have focused world attention on the need to identify a substitute material which should be renewable, environmentally friendly and widely available. In view of its rapid growth, a ready adaptability to most climatic and edaphic conditions and properties superior to most juvenile fast growing wood, bamboo emerges as a very suitable alternative. However, in order to exploit fully the potential of bamboo as a construction material, development effort should be directed at the key areas of preservation, jointing, structural design and codification.

KEYWORDS: Bamboo, construction, durability, jointing

## 1 INTRODUCTION

Bamboo has a long and well established tradition as a building material throughout the world's tropical and sub-tropical regions. It is widely used for many forms of construction, in particular for housing in rural areas. Bamboo is a renewable and versatile resource, characterized by high strength and low weight, and is easily worked using simple tools. As such, bamboo constructions are easy to build, resilient to wind and even earthquake forces (given the correct detailing) and readily repairable in the event of damage. Associated products (bamboo based panels and bamboo reinforced concrete, for example) also find applications in the construction process.

There are however a number of important considerations which currently limit the use of bamboo as a universally applicable construction material:

- *Durability*: bamboo is subject to attack by fungi and insects. For this reason, untreated bamboo structures are viewed as temporary with an expected life of no more than five years.
- *Jointing*: although many traditional joint types exist, their structural efficiency is low (Herbert et al. 1979). Considerable research has been directed at the development of more effective jointing methods.
- *Flammability*: bamboo structures do not behave well in fires, and the cost of treatment, where available, is relatively high.
- *Lack of design guidance and standardization*: the engineering design of bamboo structures has not yet been fully addressed.

The majority of bamboo construction relates to rural community needs in developing countries. As such, domestic housing predominates and, in accordance with their rural origins, these buildings are often simple in design and construction relying on a living tradition of local skills and methods. Other common types of construction include farm and school buildings and bridges.

Further applications of bamboo relevant to construction include its use as scaffolding, water piping, and as shuttering and reinforcement for concrete. In addition, the potential number of construction applications has been increased by the recent development of a variety of bamboo based panels.

## 2 BAMBOO BUILDINGS

Bamboo can be used to make all the components of small buildings, both structural and non-structural, with the exception of fireplaces and chimneys. It is, however, often used in conjunction with other materials.

Bamboo building construction is characterized by a structural frame approach similar to that applied in timber frame construction. In this case, the floor, wall and roof elements are interconnected and often one dependent on the other for overall stability. There is a need to control lateral deformations in some traditional forms of building in particular.

The adequacy and suitability of the building for occupancy will also depend to a large extent on good detailing, for example to help prevent water and moisture ingress, fungal attack and vermin infestation.

All of the above features are dealt with in the following sections.

### 2.1 *Foundations*

The types of bamboo foundation in common use are:

- Bamboo in direct ground contact
- Bamboo on rock or preformed concrete footings
- Bamboo incorporated into concrete footings (Fig. 1)
- Bamboo on steel shoes (Fig. 1)
- Bamboo reinforced concrete

In general, it is best to keep bamboo clear of the ground, since untreated material can decay very quickly in ground contact.

### 2.2 *Floors*

The floor of a bamboo building may be at ground level, and therefore consist only of compacted earth, with or without a covering of bamboo matting. However, the preferred solution is to raise the floor above the ground creating a stilt type of construction. This improves comfort and hygiene and can provide a covered storage area below the floor. When the floor is elevated, it becomes an integral part of the structural framework of the building. The floor comprises:

- Structural bamboo elements
- Bamboo decking

#### 2.2.1 *Floor structure*

Bamboo floors normally consist of bamboo beams fixed to strip footings or to foundation posts. The beams therefore run around the perimeter of the building. Where the beams are fixed to posts, careful attention to jointing is required. Beams and columns are generally around 100 mm in diameter.

Bamboo joists then span in the shortest direction across the perimeter beams. The joists are often laid on the beams without fixing, but some form of mechanical connection is recommended. Depending on the form of floor decking, secondary joists, often taking the form of split culms may

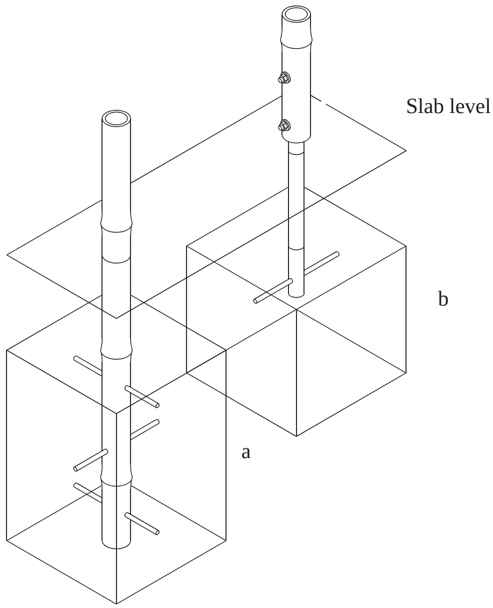



Figure 1. Examples of columns set (a) in concrete footing and (b) on steel shoe.

be required. Joist diameters are in the order of 70 mm. Joist centres are typically 300 to 400 mm, or up to 500 mm if secondary joists are used.

### 2.2.2 *Floor decking*

Bamboo floor decking can take one of the following forms:

- Small bamboo culms
- Split bamboo
- Flattened bamboo (bamboo boards)
- Bamboo mats
- Bamboo panels, laminates or parquettes

## 2.3 *Walls*

The most extensive use of bamboo in construction is for walls and partitions. The major elements of a bamboo wall generally constitute part of the structural framework. As such they are required to carry the building self-weight and loadings imposed by the occupants, the weather and earthquakes.

An infill between framing members is required to complete the wall. The purpose of the infill is to protect against rain, wind and animals, to offer privacy and to provide in-plane bracing to ensure the overall stability of the structure when subjected to horizontal forces. The infill should also be designed to allow for light and ventilation. Not least is its architectural and aesthetic function. This infill can take many forms:

- Whole or halved vertical or horizontal bamboo culms, with or without bamboo mats
- Split or flattened bamboo, with mats and/or plaster
- Bajareque
- Wattle (wattle and daub, lath and plaster, quincha)
- Woven bamboo, or bamboo grids, with or without plaster (see Fig. 2)
- Bamboo panels

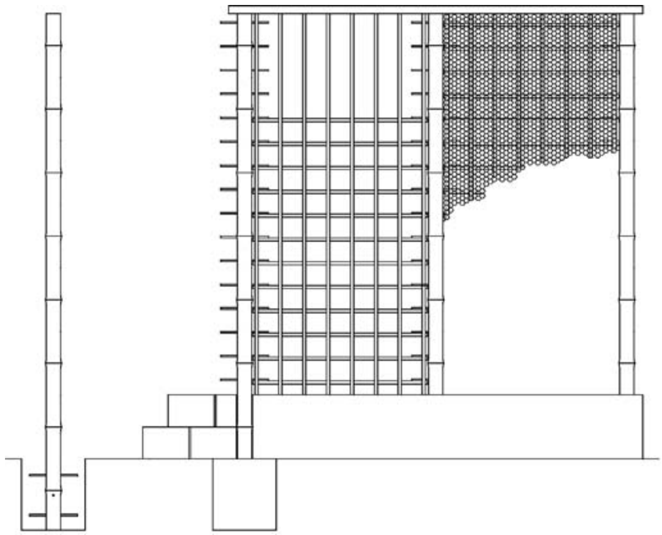


Figure 2.  Wall construction using plastered bamboo grid.

### 2.4 *Roofs*

The roof of a building is required to offer protection against extremes of weather including rain, sun and wind, and to provide clear, usable space beneath its canopy. Above all, it must be strong enough to resist the considerable forces generated by wind and roof coverings. In this respect bamboo is ideal as a roofing material—it is strong, resilient and light-weight.

The bamboo structure of a roof can comprise "cut" components—purlins, rafters and laths or battens, or triangulated (trussed) assemblies. Bamboo, in a variety of forms, is also used as a roof covering and for ceilings.

#### 2.4.1 *Roof covering*

Bamboo roof coverings can form an integral part of the structure, as in the case of overlapping halved culms. More often, they are non-structural in function. Examples include:

- Bamboo tiles
- Bamboo shingles
- Bamboo mats
- Bamboo mat board
- Plastered bamboo

Corrugated sheet made from bamboo mats, currently under development at IPIRTI in India, shows great potential as a roof covering. It is light, strong and resilient, waterproof and impermeable with low thermal conductivity and good fire resistance.

### 2.5 *Doors and windows*

In traditional types of bamboo building, doors and windows are usually very simple in form and operation. Bamboo doors can be side hinged or sliding, comprising a bamboo frame with an infill of woven bamboo or small diameter culms.

Bamboo windows are generally left unglazed and can have bamboo bars, or a sash with woven bamboo infill. The sash can be side hinged or sliding, or, more commonly, top hinged to keep out direct sunlight and rain. At night, windows are closed to protect against insects and animals. Hinges are formed from simple bindings, or connecting bamboo elements.

## 3 PROTECTION OF BAMBOO COMPONENTS

Bamboo is non-durable in its natural state. It provides a ready food source for insects and fungi, and can decay in less than a year in direct ground contact. Protection is therefore essential to ensure the longest possible life for the material, and the building in which it is used.

Protection does not necessarily mean chemical treatment. The first line of defence (post-harvesting) is good design.

### 3.1 *Protection by design*

Protection by design involves 4 basic principles:

- Keeping the bamboo dry
- Keeping the bamboo out of ground contact
- Ensuring good air circulation
- Ensuring good visibility

Large roof overhangs prevent direct wetting of walls in heavy and driving rain, and drainage channels and/or gutters can be used to discharge water a safe distance from the building. The risk of more general flooding can be reduced by building on a graded or slightly sloping site, and using raised masonry or concrete footings.

The effects of water inside the building should not be overlooked. Simple provision can be made to drain away washing and cooking water, avoiding the hazards of prolonged wetting (see Fig. 3).

Raising bamboo columns or wall panels clear of the ground also reduces the risk of termite infestation, and improves visibility, making inspection easier. Termite shields can be used between the footings and walls, if the risk is considered high. Where possible, the roof space should be left exposed to improve both visibility and airflow, and aid routine maintenance.

Bamboo constructions can also provide ideal nesting areas for rodents and other pests. In general, open culm ends should be plugged and cavity construction should be avoided.

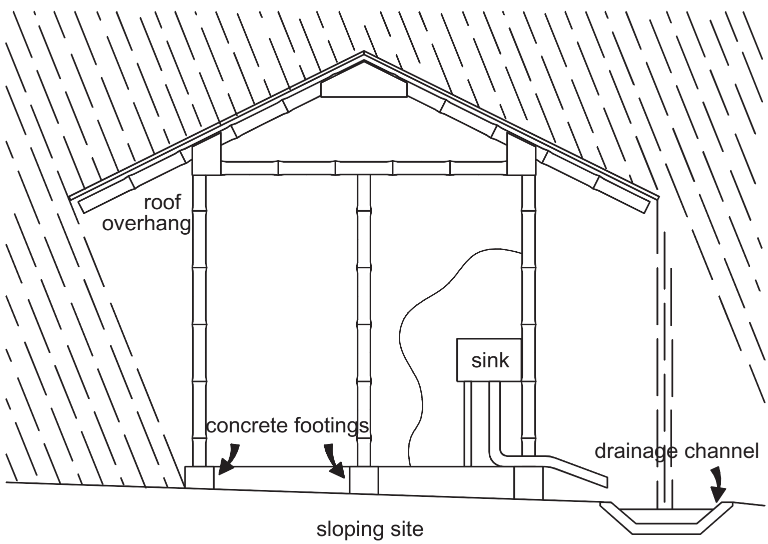
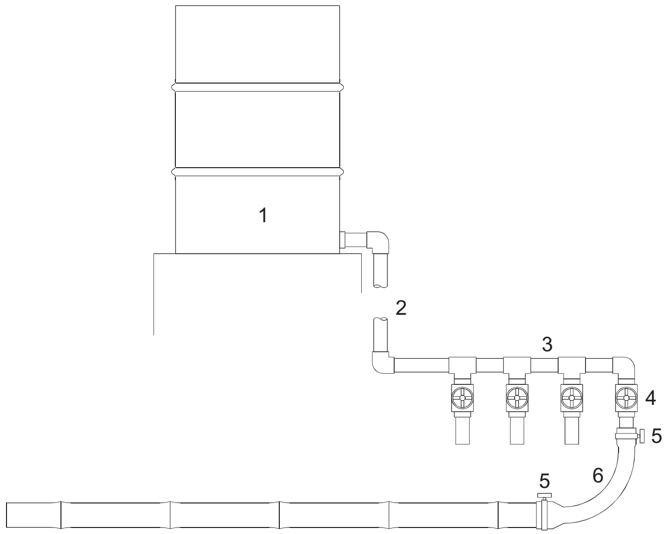



Figure 3. Protection by design.




1. Tank containing preservative, located at high level
2. Connection pipework
3. Distribution manifold
4. Valve
5. Tube clamp
6. Flexible rubber tubing

Figure 4. Arrangement for Boucherie treatment process.

## 3.2 *Protection by preservation*

In general, the natural durability of bamboo can be enhanced by the application of preservative compounds which help to prevent insect and fungal attack. A wide range of preservatives is available, including oil based, oil soluble, water soluble and water soluble “fixed” types. However, chemicals over which there are environmental and health and safety concerns should be discounted. Tar oil and boron based chemicals are relatively safe options, and are often available locally. Four treatment methods are ideally suited to site or workshop application:

- internodal injection of creosote oil
- dip diffusion with boric acid and borax
- hot and cold creosote method
- the Boucherie method (see Fig. 4) using boric acid and borax

Preservative treatment is covered in detail in the book by Jayanetti and Follett (1998).

# 4 OTHER TYPES OF CONSTRUCTION AND CONSTRUCTION APPLICATIONS

## 4.1 *Bridges*

A bridge can be defined as an elevated structure supported at intervals for carrying traffic across obstacles (valleys and rivers, for example). In general terms, therefore, the range of types, spans and capacities is almost infinite. Bamboo bridges, however, are generally of trestle construction and of limited span for carrying only light (usually pedestrian) traffic. Simple trussed constructions have also been built and have been shown capable of supporting substantial loads.

### 4.2 *Scaffolding*

Bamboo scaffolding is widely used throughout South and South East Asia and also South America as a temporary structure for supporting working platforms in building construction and maintenance. The main advantages of bamboo scaffolding when compared with steel are its lightness and low cost. It is also readily tailored to suit the shape of a building. However, problems such as lack of durability, and non-standardised jointing currently limit its wider application.

### 4.3 *Bamboo reinforced concrete*

The use of bamboo as concrete reinforcement is one of the more broadly covered topics relating to bamboo in construction. There are several good reasons why bamboo might be considered as reinforcement for concrete:

- It is of low cost compared with steel
- It is readily available
- Its strength to weight ratio compares favourably with steel

However, bamboo exhibits certain characteristics which limit its effectiveness as concrete reinforcement, and considerable research effort continues to be directed at this subject.

### 4.4 *Bamboo based panels*

The earliest bamboo panel was made in China during the First World War. To date, many different panel types have been developed, mostly in Asia, but investigations into construction applications have only recently been carried out (Ganapathy et al. 1995). Bamboo based panels have proved suitable for structural as well as non-structural applications, in both low and high grade building work. Specific end uses include floors, walls, partitions, doors, ceilings and roofs, and by virtue of their inherent rigidity and enhanced durability (through preservative treatment), such panels can offer significant advantages over the use of bamboo in its natural state. The various types of panel product can be broadly classified as follows:

- Processed strips, laths or slivers
- Processed, peeled veneers
- Strands, particles or fibres reconstituted into panels
- Combinations of one or more of the above
- Combinations of one or more of the above with wood, other lignocellulosic materials and inorganic substances

The two most common panel types, for which product standards have been formulated in countries where they are commercially produced, are:

- Bamboo mat board (bamboo mat plywood)
- Bamboo strip board (bamboo strip plywood)

## 5 JOINTING TECHNIQUES

Effective jointing is fundamental to the structural integrity of a framed construction. Furthermore, the suitability of a material for use in framing is largely dependent upon the ease with which joints can be formed.

Because of its round, tubular form, jointing of two or more bamboo members requires a different approach to that adopted for, say, solid timber. Despite its relatively high strength, bamboo is susceptible to crushing, particularly of open ends. It is also characterised by a tendency to split; the use of nails, pegs, notches or mortises can therefore result in considerable reductions in strength. Connections must also cope with variations in diameter, wall thickness and straightness.

Clearly, these limitations have not presented an obstacle to the use of bamboo in traditional forms of construction. However, the building of structurally efficient, more durable and possibly larger and more economical bamboo structures will depend to a large extent on improvements and developments in jointing technology.

### 5.1 *Traditional joints*

Traditional jointing methods rely principally on lashing or tying, with or without pegs or dowels. The basic joint types are:

- Spliced joints
- Orthogonal joints
- Angled joints
- Through joints

### 5.2 *Improved traditional joints*

The mechanical performance of traditional bamboo joints can be improved by the adoption of the following procedures:

- *Form joints at or near nodes*: nodes are more resistant to splitting than internodes. It is therefore good practice to make joints as close to nodes as possible. For example, in the simple saddle joint, the saddle should be formed directly above a node.
- *Minimise on holes*: it is generally accepted that holes, cuts and notches will reduce the ultimate strength of a bamboo culm. If a hole is made in a culm (for a peg, dowel, mortise, inset support or insert) this should be as close as possible to the node, paying particular attention to the direction of the applied force. Furthermore, whenever possible holes should be round or radiused rather than square cut as these are less likely to propagate splits.
- *Use seasoned culms*: seasoned rather than green bamboo should be used for two reasons. Firstly, bamboo shrinks on drying and this will generally cause joints to loosen. Secondly, drying splits can form which could further weaken the assembly (Narayanamurty et al. 1972).
- *Reinforce against splitting and crushing*: tight binding, especially with wire, can in itself offer good resistance to splitting. In trusses, the use of quarter-round bamboo bearing plates reduces the risk of crushing of the chords by the compression webs (Janssen, 1995).
- *Improve durability*: preservative treatment of the bamboo and protection from wetting by good detailing will increase the life of the joint. The use of wire is in many cases preferable to bamboo lashings or rope as it is not subject to insect attack.

### 5.3 *Recent developments*

By building on traditional methods and exploiting the strengths and advantages of bamboo, a number of jointing techniques have been developed which offer more structurally efficient solutions to jointing problems. However, their adoption and suitability will depend to a large extent on the cost and availability of materials, equipment and skilled labour. Recent examples include:

- Gusset plates
- ITCR joint
- Arce joint
- Filled joint
- Das clamp
- Herbert shear pin connector
- Gutierrez joint
- Steel or plastic insert connectors

## 6 DESIGN CONSIDERATIONS

The use of bamboo as an engineering material is limited from the point of view of design by two major considerations:

- The formulation of structural design guidance is governed to a large extent by practical, engineering experience. In the case of bamboo, information from this source is somewhat limited.
- Basic mechanical properties have been dealt with by many authors, but, unlike timber, bamboo properties do not relate well to species because of the dependency on other factors, such as geographical location and age (Arce, 1993).

Considerable effort continues to be directed at the derivation of mechanical properties, but perhaps with insufficient regard to applications in the field. Janssen (1995), however, has shown that a relationship exists between density and permissible stress which forms the basis of Table 1 below:

Table 1. Allowable long-term stress (N/mm$^2$) per unit volume (kg/m$^3$).

| | Axial compression (no buckling) | Bending | Shear |
|---|---|---|---|
| Air dry | 0.013 | 0.020 | 0.003 |
| Green | 0.011 | 0.015 | – |

For example, if green bamboo has a density of 600 kg/m$^3$, the allowable stress in bending would be $0.015 \times 600 = 9$ N/mm$^2$. As these are long-term stresses, Janssen suggests they may be increased by 25% for live, or medium-term loading, and by 50% for short-term loading.

Other studies relate to specific species, or groups of species. Rajput et al. (1994) considered sixteen species and derived minimum long-term safe working stresses for the green condition as summarised in Table 2 below:

Table 2. Safe long-term green working stress (N/mm$^2$).

| | Bending | Stiffness | Compression |
|---|---|---|---|
| Group A | 17.2 | 1,960 | 9.8 |
| Group B | 12.3 | 1,370 | 8.3 |
| Group C | 7.4 | 680 | 6.9 |

| | |
|---|---|
| Group A | *Bambusa glaucescenes* (syn. *B. nana), Dendrocalamus strictus, Oxytenanthera abyssinica* |
| Group B | *Bambusa balcooa, B. pallida, B. nutans, B. tulds, B. auriculata, B. burmanica, Cephalostachyum pergracile, Melocanna baccifera, Thyrosostachys oliveri* |
| Group C | *Bambusa ventricosa, B. vulgaris, B. bambos* (syn. *B. arundinaceae), Dendrocalamus longispathus* |

## REFERENCES

More information on all the topics covered by this paper can be found in the publications by Janssen, Jayanetti and Follett listed below.

Arce, O.A. 1993. Fundamentals of the design of bamboo structures. Doctoral thesis, Eindhoven University of Technology, Netherlands.

Ganapathy, P.M., Turcke, D., Espiloy, Z.B., Zhu Huan-Ming & Zoolagud, S.S. 1995. *Bamboo based panels—a review* (unpublished). International Development Research Centre, New Delhi, India.

Hidalgo, A.O. 1992. Technologies developed in Columbia in the bamboo housing and construction field. *International symposium on industrial use of bamboo*, Beijing, International Tropical Timber Organisation, Chinese Academy of Forestry, Beijing, China.

Janssen, J.J.A. 1995. *Building with bamboo, a handbook*. Second edition. Intermediate Technology Publications, 103–105 Southampton Row, London, UK.

Jayanetti, D.L. & Follett, P.R. 1998. *Bamboo in construction, an introduction*. TRADA Technology, High Wycombe, UK and INBAR, Beijing, PRC.

Narayanamurty, D. & Dinesh Mohan. 1972. *The use of bamboo and reeds in building construction*. United Nations Secretariat.

Rajput, S.S., Inder Dev and Jain, V.K. 1994. Classification, grading and processing of bamboos for structural and other applications. *Wood news*: 4(1), Ganesh Publications Pvt Ltd 57, P.O. Bangalore 560 086, India.

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# Engineered bamboo as a building material

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ABSTRACT: There has been a serious concern to look for alternative housing materials that are cheap, widely available and environmentally friendly. Bamboo is one of the best materials that have been used for centuries as a building material due to its versatile characteristics. Bamboo housing is not a new concept. It is estimated that more than a billion people live in bamboo houses mostly in developing worlds. The ecological and economical dynamics of bamboo have made it a sustainable building material.

Various testing, researches and practical experiences have revealed that bamboo has high tensile strength, high strength to weight ration and high specific load bearing capacity. Due to its long, strong and elastic nature of fibbers; bamboo is known as high resistance to the earth quake. It has also natural insulation properties that would save thermal energy and it is a very durable material if treated properly. This paper mainly deals with the prospects, constraints and opportunities to use bamboo as building material in the 21st century.

## 1 GENERAL INSTRUCTIONS

### 1.1 *Bamboo as a dynamic plant*

Bamboo is a giant grass. There are about 75 genera and 1250 species worldwide (Sharma, 1980), with total bamboo areas about 22 million hectares and with a yield of 2000 million tons (Zehui, 2007). It grows from tropical to sub-temperate regions, though the great diversity is found in sub-tropical region. It is known to be one of the fastest growing plants in the world. Its growth rate ranges from 30 cm to 100 cm per day. Bamboo grows densely sometime more than 10,000 culms per hectare and can be easily regenerated naturally. Bamboo attains its maximum size in 60–90 days of shoot sprouting and can be harvested in 3 to 6 years depending upon species. Bamboo multiplying is very easy as it expands naturally with rhizome. Its natural expansion capacity and short rotation have made it well known as an environmentally green plant.

Bamboo has a very long history for its use in various purposes such as food, shelter, furniture etc. Bamboo has been serving humanity from cradle to grave in many countries since ages in many different and ingenious ways. It has strength, flexibility and versatility and therefore is suitable material for the various types of construction.

### 1.2 *Bamboo as a building material*

Bamboo is one of the oldest materials used for the construction of houses and other structures. Its strength, flexibility and versatility make it a suitable material for addressing every housing component when treated and used properly. Bamboo is relatively cheap, easy to work with and readily available in most warm climate countries. It is estimated that more than one billion people in the world live in bamboo house and in Bangladesh alone more than 70% houses are made up of bamboo (Vries, 2002).

Bamboo can be a potential building material in the most of the developing countries where it grows. Fortunately, it grows in the most of the African and Asian countries where the affordable

Table 1. Comparison of important strength properties of bamboos and wood of India.

| Species | SG | MC(%) | MOR ($Kg/cm^2$) | MOE ($Kg/cm^2$) | MCS ($Kg/cm^2$) |
|---|---|---|---|---|---|
| *Bambusa bambos* | 0.65 | 15.5 | 674 | 65000 | 483 |
| *B. nutans* | 0.72 | 16.0 | 545 | 85000 | 508 |
| *B. tulda* | 0.71 | 14.9 | 506 | 82650 | 615 |
| *D. strictus* | 0.72 | 10.7 | 1184 | 159490 | 645 |
| *Tectona grandis* | 0.60 | 12.0 | 959 | 119600 | 532 |
| *Shorea robusta* | 0.71 | 12.0 | 1318 | 162045 | 641 |

*Source:* Sattar (1995)

*Note:* $Kg/cm^2$ = Kilogram per square centimeter; SG = Specific Gravity; MC = Moisture Content; MOR = Modulus of Rupture; MOE = Modulus of Elasticity; MCS = Maximum Crushing Strength.

and sustainable building materials are in high demands. There are 65 species of bamboo which are used in construction purpose (Jayanetti and Follet, 1998). *Gauda augustifolia* is the mst popular species in Latin America countries. Similarly, Bambusa nutans, *Dendrocalamus strictus, Dendrocalamus hamiltonii Bambusa balcooa*, *Bambusa vulagris*, *Phyllostachys bambusoides* are widely used in Asian countries. *Bambusa arundinaceae and Bambusa vulgaries* are found to be very suitable species for construction in Africa (Oteng, 2002).

### 1.3 *Mechanical and physical properties of bamboo*

Various physical and mechanical testing carried out for various species of bamboo revealed that it is strong enough to be used as a building material. In certain mechanical properties, bamboo even surpasses timber and concrete. However, it is difficult to generalize the properties of bamboo as it differs with the species, age, climatic factors, moisture content and different heights of the culm.

Generally, the density of bamboo varies from 500 to 800 kg/m3. Bamboo possesses excellent strength properties especially tensile strength. Study shows that bamboo is as strong as wood and some species even exceed the strength of Shorea robusta and Tectona grandis (Sattar, 1995, table 1). An increase in strength is reported to occur at 3–4 years and thereafter it decreases. Therefore maturity period of bamboo is considered 3–4 years with respect to density and strength.

The comparison clearly reveals that bamboo is better in properties than that of Spruce and equal or more than steel in tensile strength. More importantly the failure in bending of bamboo is not actually totally failure. Due to its strong fibers, it first cracks unlike timber which breaks if bending fails (Janssen, 2000). This quality of bamboo gives an opportunity to repair or replace failure parts of house. The elasticity of bamboo is better than wood for seismic resistant housing and as has been proved in the case of several small houses. One more advantage of bamboo over timber is that it does not have rays. Rays are mechanically weak therefore bamboo material is better in shear than timber material.

## 2 BAMBOO BUILDING SYSTEMS

Bamboo can be used various ways for the construction. They can be used as it is without any major processing or can be processed into panels. Based on the ways bamboo used for the construction, bamboo building technologies can be divided broadly into two types (1) bamboo building using round (unprocessed) bamboo culms and (2) bamboo building using engineered (processed) bamboo.

### 2.1 *Bamboo building using round (unprocessed) bamboo*

It is a traditional kind of construction system. This technology emerged from the beginning when people started to use bamboo as a building material and has been improved significantly in accordance with modern housing technology. The technology can be further classified into various construction systems as follows;

Bahareque System: Bahreque is a traditional bamboo building (wall) system in Latin American countries mainly in Ecuador and Columbia. There are two types; hollow and solid. In solid type, horizontal bamboo laths are fixed on both sides of culms or timber frame and the space is filled with mud. In hollow type, *estrilla* (flattened bamboo) is fixed both sides of culm and is plastered with mud or cement mortar (Paudel and Lobovikov, 2003).

Quincha system: Quincha is also a Latin American System. There are two types of quincha. The first one is Quincha with wooden frame which is a slight modification of traditional Bahareque. The main structure of the wall is a wooden frame. Each side of the frame is covered with horizontally placed bamboo esterilla with the green side facing inwards. In some cases bamboo laths are used the fix the flattened bamboo to the wall panel. The wall is then plastered with cement mortar. The second system is Quincha with bamboo frame in which wall is fabricated with bamboo poles and flattened bamboo with the green side facing inwards. The exterior of the wall was plastered with mud and cow dung. The interior of the wall was left for the bamboo view.

Grid system: The system was developed by TRADA International in collaboration with Indian Plywood Industries Research and Training Institute (IPIRTI), Banglore India. The IPITRI bamboo-housing system is based on the principle of modular systems in which bamboo columns spaced at 1.2 m center to center that act as main load bearing elements for transmission of roof dead loads. The columns are tied at the top with wooden plates and bottom is embedded in foundation concrete. The wall is made up of grid of bamboo lath and chickens mesh and plastered with cement mortar and bamboo lath and steel dowels hold spaces between columns. Roof consists of bamboo trusses, bamboo purlins and bamboo corrugated mats.

Pre-fabricated system: Hogar de Cristo, a Christian based NGO in Ecuador has developed a pre-fabricated bamboo and wood composite house. A typical Hogar de Cristo wall includes a wooden frame with flattened bamboo on one side of the frame. However, the system has been modified and improved with double bamboo wall in wooden frame plastered with mortar both sides of the wall. This modified system has been used in Nepal to build low cost residential houses and community buildings. This system gives more stability and durability to the house.

Modern pre-fabricated system: This system is developed by Bamboo Technologies, a Hawaii based company that pre-fabricates bamboo houses in Vietnam and shipped them to the final destinations. In this system, bamboos are used for poles, trusses, beams and wall panels. The wall is made of flattened bamboos that sandwich plywood. Bamboo view can be seen in both sides of the wall.

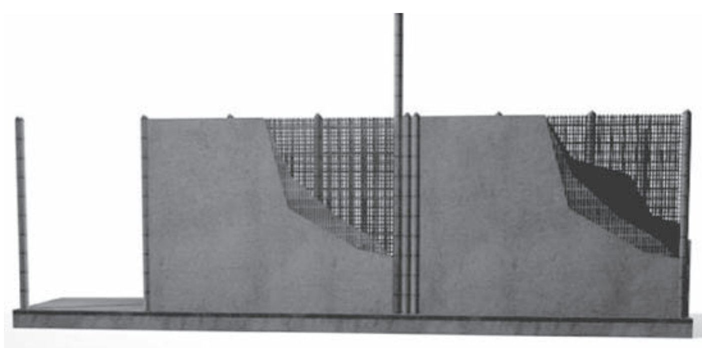

Figure 1. Hollow and Solid Bahareque walls (Courtesy: Arch. Daniel Romero).

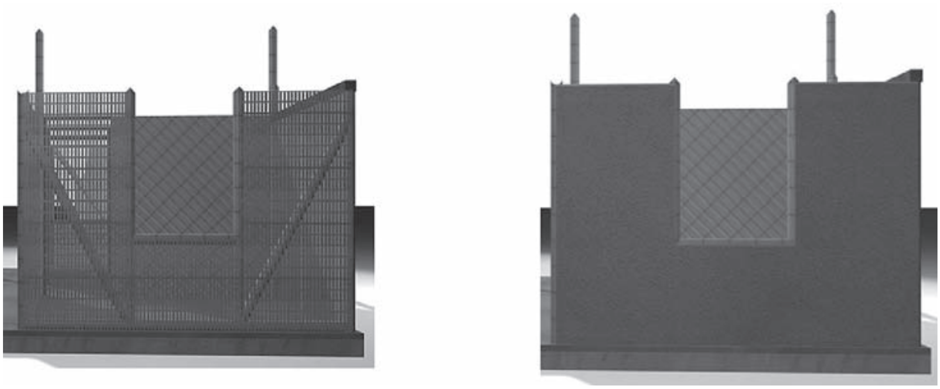

Figure 2. Quincha walls with bamboo poles (Courtesy: Arch. Daniel Romero).

Figure 3. Grid wall system (Courtesy: Arch Daniel Romero).

Figure 4. Pre-fabricated bamboo house in Nepal (Courtesy: Himalayan Bamboo).

### 2.2 *Bamboo building using engineered bamboo*

It is a recent technology developed in India and China. INBAR has recently researched and built various kinds of pre-fabricated modular bamboo houses and established them in its demonstration site in Beijing. The houses were developed with the financial support of Blue Moon Fund and in close collaboration with Chinese Academy of Forestry, FUSTAR Bamboo, Beijing Chengdong, and International Center for Bamboo and Rattan. The houses were designed by Beijing Architectural Design and Research Institute.

Figure 5. A modern bamboo house by Bamboo Technologies.

Figure 6. Pre-fabricated bamboo buildings with engineered bamboo (developed and constructed by INBAR) in Beijing.

## 2.3 *Advantages and disadvantages of using processed and unprocessed bamboos for housing*

The both technologies have their own strengths and weakness. In certain conditions, using unprocessed bamboo could be beneficial and useful. In other situation, using processed bamboo may give better comparative advantages. The advantages and disadvantages of the technologies have been summarized in the table.

Table 2. The advantages, disadvantages and limitations of using processed and unprocessed bamboo for housing.

| | Using unprocessed bamboo | Using processed bamboo |
|---|---|---|
| Advantages | • Doesn't require big investment<br>• Offers flexible design<br>• Low technical requirements and can be done any locations where bamboo available | • Can make use of all kinds of bamboos<br>• Less wastage (can use much of bamboo culms)<br>• Can be standardized for its quality<br>• Large quantity production and supply is possible<br>• Can be modular and pre-fabricated<br>• Durable and flexible |
| Disadvantages and limitations | • Limited species of bamboo can be used<br>• Quality control problem (bamboo species, size, age etc)<br>• Durability depends upon the quality of bamboo and preservation<br>• Production and supply of houses in large quantity in a short period of time may be a problem | • Require considerable investment<br>• Constant supply of raw materials can be a problem. A pure bamboo forest of at least 200 hectares is required for the sustained supply bamboo raw material to a medium size industry |

## 3 STRENGTHS, WEAKNESSES, OPPORTUNITIES AND THREATS (SWOT) OF PROMOTING BAMBOO FOR HOUSING

Bamboo is a very dynamic building material. It has a lot of economical and ecological strengths. However, it has also several limitations and weaknesses that have been summarized in the table below.

Table 3. SWOTs of bamboo housing.

| Strengths | Weaknesses |
|---|---|
| (i) Eco-friendly<br>• Reduce deforestation. Bamboo can replace wood for housing that would save thousands of hectares of forests.<br>• Less environmental impacts. A bamboo house contributes 40% less environmental impacts than a masonry house (Murphy et al 2004). | (i) Non-dimensional material<br>• Bamboo doesn't come in uniform shape and size. Based on species, age and locality it has different length of internodes, culms thickness, tapering ratio and size of hollowness. It makes difficulties to standardize the material unless it is processed into panels. |

(*continued*)

Table 3. (*continued*)

| Strengths | Weaknesses |
|---|---|
| • Total energy saving. Processing of bamboo requires only 1/8 of the energy that concrete needs to create a building material of the same capacity. In comparison to steel bamboo needs only 1/50 the amount of energy for its processing (Roach, 1996).<br>(ii) Economical<br>• Low cost. Various experiences indicate bamboo houses can be up to 60% cheaper than masonry houses.<br>• Community employment. Bamboo housing and related industries can provide direct employment opportunities to the local communities through cultivation, management, pre-preprocessing and processing stages. In India only, bamboo generates jobs for a total of 60–72 million workdays before primary processing and 120 million workdays for weaving works (Janssen, 2000).<br>(iii) Durability and safety<br>• If treated and used probably, bamboo house can long last as any modern wooden house.<br>• Test results show bamboo house are high resistance to earthquake and can resist up to 7.6 Richter scale (Jayanetti, 2005). | (ii) Difficulties in quality control<br>• There are more than 1200 species of bamboo. They differ greatly in their physical and mechanical properties. It makes difficult to control the quality of the bamboo as a building material.<br>(iii) Proper treatment Vs durability<br>• Bamboo requires proper treatment for its durability. Knowledge of treatment has still not reached to the needy communities. |
| **Opportunities** | **Limitations and Threats** |
| (i) Improved technology<br>• To mitigate the problems associated with non-dimensional material, technology has been developed to process raw bamboos into panel, board and beam. Panel and beam can be standardized for their dimensions and properties and can be pre-fabricated and commercialized at industrial scale.<br>(ii) Wider target group<br>• Bamboo offers a range of building options from very low cost to expensive one. It has a market potentiality both for low and high income classes.<br>(iii) Resource availability<br>• Bamboo grows in the wider climatic regions and even in degraded soil condition. It can be grown easily and harvested in very short rotation to supply required quantity of bamboo culms.<br>(iv) Housing in seismic areas<br>• Bamboo housing has a great potential in seismic and disaster prone areas. Due to lightweight and favorable elastic property, its quality to resist earthquake pressure is very good. | (i) Lack of bamboo building codes<br>• One of the major limitations to promote bamboo for housing is lack of national building codes in most of the countries.<br>(ii) Social stigma<br>• Bamboo still has a low social status in many developing countries. It has an image of poverty associated with it. People in many countries believe that bamboo is not a durable material and living in a bamboo house is just a temporary solution.<br>(iii) Improper use of bamboo for building<br>• There is a serious threat that improper and non-scientific uses of bamboo for housing, and therefore quick deterioration of houses, may negatively influence the overall image of bamboo for building in the future. |

## 4 CONCLUSIONS

Bamboo is an excellent building material that offers a range of building options from very low cost to high end and therefore can meet the requirements of wider economic groups. However, there are still a few constraints and limitations that inhibit the promotion of bamboo as a building material at large. The main limitation is the misperception of people regarding bamboo as a poor men's timber. However, such perception could be altered with proper extension education such as training, workshop, demonstration of high end buildings.

The other problem of using bamboo lies within its own physical characteristics. Bamboo is a non dimensional material and is very difficult to use compared to other building material. However, technologies are being emerged to process bamboo into panels and beams that could be standardized for its dimensions as well as mechanical strengths. INBAR has recently developed a pre-fabricated modular bamboo housing system using engineered bamboo panels and beams. The engineered bamboo has a great potential to be used as a building material in the future to solve the problems associated with unsustainable building materials.

## REFERENCES

Jayanetti, L. 2005. Seismic testing of a bamboo based building system. Presented at an INBAR international workshop in Beijing, China in Nov 24–25, 2005.

Murphy, R.J., Trujillo D., Londono X. 2004. "Life Cycle Assessment of a Guadua House". Paper presented to Simposio Internacional Guadua, Pereira, Colombia Sept. 27–Oct. 2, 2004.

Oten Amaoko, A.A. 2003. "Sustainable Development of Bamboo Resource of Ghana: an indispensable option". Paper presented at Bamboo Housing Workshop in Kumasi Ghana, April 1–5, 2003.

Paudel, S.K. and Lobovikov, M. 2003. Bamboo housing: market potential for low income group. Journal of Bamboo and Rattan, No. 2 Vol. 4, 2003.

Roach, M. 1996. Bamboo solution. Discover, June 1996, pp. 93–96.

Sattar, M.A. 1995. Traditional Housing in Asia: "Present status and future prospects" Bamboo, People, The environment (1995) Vol. 3. INBAR Technical report No. 8. Editors: Ramanuja Rao I.V. and Sastry C.B. (Ed.)

Sharma, Y.M.L. 1980. Bamboo in Asia Pacific Region, In Bamboo Research in Asia G. Lessard and A. Chouiard (Eds.) World Publications, Singapore, pp. 99–120.

Vries, S. de. 2002. Bamboo construction Technology for housing in Bangladesh: "Opportunities and constraints of applying Latin American bamboo construction technologies for housing in selected rural villages of the Chittagong Hill Tracts Bangladesh". Thesis submitted to Technical University of Eindhoven, the Netherlands.

Zehui, J. 2007 (Eds.) Bamboo and Rattan in the World. China Forestry Publishing House.

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# Development of a new type Glulam—GluBam

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ABSTRACT: Laminated timbers or the glulam girders have been well developed and widely used in timber buildings and bridges in North America and elsewhere. The authors conceived and tested a new type of glulam girder using laminated bamboo veneers. In good correlation with conventional glulam, the new structural member is named as glubam or GluBam®, which has been registered as a trademark. This paper discusses some testing results of various types of the newly developed glubam members.

## 1 INTRODUCTION

Glue laminated timber or Glulam is an engineered lumber product using structurally graded timber laminations. The glulam can be in redwood, larch, Douglas fir or other wood basis. Each lamella is end jointed to allow production of beams or girders to the preferred design lengths. Glulam has been widely used in North America, Europe and other industrialized countries. Due to the shortage of forest resources, the production and construction application of timbers are quite limited in China.

Comparing with the limited domestic supplies of timber, bamboo is relatively more available in southern part of China. Despite the fact that bamboo has been used for thousands of years, the modernization of bamboo production industry has not fully penetrated into the construction of modern buildings and bridges. Existing bamboo products are limited to furniture, floor panel or veneer sheet for concrete formwork, etc.

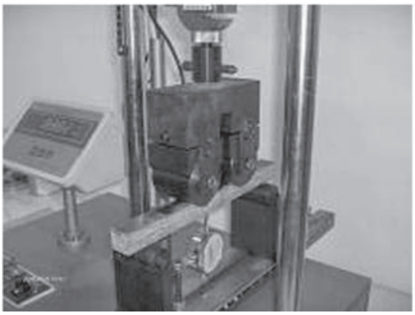
After an extensive review of the existing industrial base in the Hunan Province, one of the major bamboo grow areas in China, the first author conceived several new types of bamboo products for the applications of bamboo in modern structures. This paper reports the research development of GluBam®, which is a bamboo based glulam.

## 2 STUDIES ON BAMBOO VENEER SHEETS

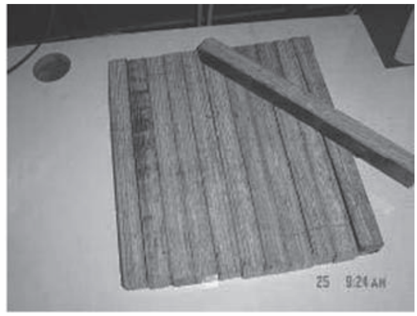
Bamboo veneer sheets are widely produced in Hunan, primarily for the concrete formwork application and for floor panels of cargo containers. The planner dimension of a bamboo veneer sheet is generally 2,440 long by 1220 wide (or 8 ft. by 4 ft.). The thickness ranges from 6 mm to 30 mm. Basic material properties shown in Table 1 were obtained by significant amount of material tests following conventional mechanical testing methods for timber materials, as shown in Figure 1.

Table 1. Basic material properties of laminated bamboo.

| In-plane longitudinal compressive strength (MPa) | Perpendicular to plane compressive strength (MPa) | In-plane longitudinal tensile strength (MPa) | Bending strength (MPa) | Elastic modulus (MPa) | Density (kg/m$^3$) |
|---|---|---|---|---|---|
| 25 | 68 | 20 | 75 | 888 | 6000 |



(a)




(b)

Figure 1. Material property study of laminated bamboo veneer sheets: (a) testing setup; (b) samples.

Based on the extensive material property studies of laminated bamboo veneer sheets, modifications to the existing manufacturing procedure and standards are made. Then, the new type of glulam—glubam was produced, using a processing method invented by the authors. The process involves finger-jointing the sheets and cold pressing, etc. Figure 2 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.

## 3 FULL-SCALE TESTING OF GLUBAM GIRDERS

### 3.1 *Experimental design*

In order to study the load carrying capacity and deformability of laminated bamboo girder, the authors tested two full-scale specimens. Both model girder specimens B1 and B2 had a cross section of 600 mm deep and 110 mm wide with a length of 9600 mm. The materials and processing methods for the two laminated bamboo girders were the same, except that specimen B2 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. The specimens were tested as simply supported beam with a concentric load applied at the mid-span, as shown in Figure 2. In order to prevent out-of plane instability during the testing, lateral supports were provided using steel frames and ball-bearing contacts.

The testing was controlled by monotonically increasing the applied load at the mid-span of the girder specimen until failure. The increment of the load was 2.5 kN to 5 kN. Instrumentation included measuring the applied force, deflections at mid-span and at points of quarter-span, and strains of the mid-span section.

Figure 2. Laminated bamboo girder.

Figure 3. Setup for full-scale glubam girder testing.

(a) (b)

Figure 4. Final failure patens: (a) Fracture of mid-span section of Specimen B1; (b) Rupture of CFRP of Specimen B2.

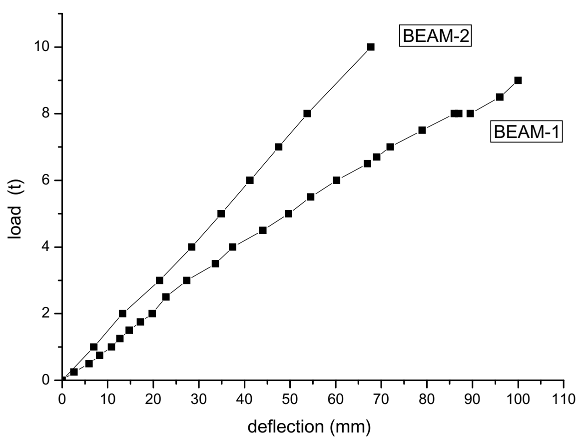



Figure 5. Load and mid-span deflection relationships for full-scale bamboo girder specimens.

### 3.2 *Experimental observations*

For bamboo girder specimen B1, the initial increase of deflection was essentially linear corresponding to the increase of the applied mid-span load. The deflection increment corresponding to the same load increment became apparently larger when the load exceeded 60 kN. When the load exceeded 80 kN, sounds indicating the cracking development in the beam were audible. The girder failed due to the fracture of the overall section at the mid-span when the load approached to 95 kN. For CFRP strengthened bamboo girder B2, 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 at mid-span following the rupture of the CFRP. Figure 4 shows the final failure patterns of the two girder specimens.

### 3.3 *Load and deflection relationships*

Figure 5 exhibits the applied load and the mid-span deflection relationships of the two bamboo girder specimens. A linear elastic response can be seen from the load and deflection relationship of specimen B1 when the load is below 2.5 kN. After this stage, the stiffness of specimen B1 gradually reduced slightly until reaching its ultimate load carrying capacity of about 95 kN. As shown in Figure 4, the stiffness of specimen B2 are apparently higher than that of B1, indicating the further enhancing effects using CFRP. Specimen B2 behaved essentially in a linear elastic fashion and failed at an ultimate load carrying capacity of 100 kN, marginally higher than that of B1.

Based on elastic analysis without considering the FRP strengthening, the initial flexibility of the girders was estimated at 1.52 mm/kN (15.2 mm/ton), larger than the values that can be obtained from the test results shown in Figure 4, indicating that both beams had adequate stiffness.

The authors are currently continuing the testing of more specimens with different experimental parameters along with testing of the fatigue life of bamboo girders.

## 4 APPLICATIONS OF GLUBAM IN BRIDGES

### 4.1 *Pedestrian bridge*

In November 2006, the authors designed and built the first modern bamboo bridge as an initial trial of the laminated bamboo girder technology [1]. Based on experimental testing of prototype girder specimens, the authors 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 with 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. Figure 6 shows the completed modern bamboo pedestrian bridge. The bridge is functioning well for more than one year after it was opened to usage.

### 4.2 *World's first truck-safe modern bamboo bridge*

With the experience of building the first modern bamboo footbridge in 2006, the authors are given the opportunity of designing and constructing a 10 m long roadway bridge to carry truckload. The bridge, shown in Figure 7, was built in the Daozi village in Leiyang, Hunan Province, and was officially opened to traffic on December 12, 2007. With the majority of the structural elements prefabricated, the actual bridge was erected within a week, essentially by a daily labor team of four to eight workers, without need of heavy construction equipment. The bridge was designed to carry a truckload of 8 ton, however, the actual loading capacity is much higher. Based on field testing, where the bridge was subjected to a two-axle truck overloaded to a total weight of 8.6 ton, the

Figure 6. A 5-m long modern bamboo bridge using glubam.

(a) (b)

Figure 7. Ten meter long modern bamboo bridge: (a) under construction; (b) under field truckload testing.

authors verified that the bridge behaved satisfactorily with the critical deflection well below the design code requirement.

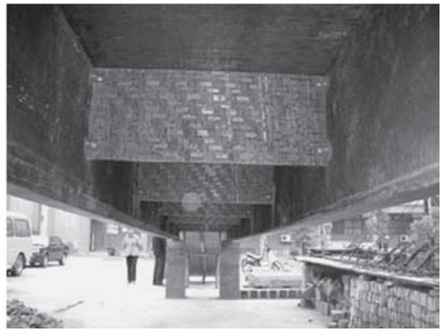
### 4.3 *Long-term loading test bridge*

The modern bamboo bridge in Leiyang is currently monitored regularly to obtain its long-term performance and to assure the safety of the operation. Meanwhile, as shown in Figure 8, 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 test.

## 5 BUILDING APPLICATIONS

The authors also made efforts to build bamboo buildings using the newly developed laminated bamboo structural elements. Figure 9 shows a single story bamboo mobile house (She et al. 2007). The design of this building adopted a module design concept so the design can satisfy various different plan need with relatively low cost. The authors also designed a two-story residential modern bamboo house with 260 $m^2$ floor area using the newly invented technologies. The house uses similar design details as lightweight wood frame structures. Figure 10 shows the modern bamboo residential house near completion. The work demonstrated that the laminated bamboo technology developed by the authors is viable in constructing buildings.

(a)



(b)

Figure 8. Long-term loading test bridge at IBTCS laboratory: (a) overall bridge; (b) underneath view of two laminated bamboo girders.

Figure 9. Low cost or mobile bamboo building developed by the authors.

Figure 10. Two-story modern bamboo residential house near completion.

## 6 CONCLUSIONS

A bamboo based new type of glulam, named as GluBam has been developed by the authors. Experimental testing on full-scale glubam girders demonstrated that the new type of glulam has sufficient stiffness and load carrying capacity. The use of fiber reinforced polymer (FRP) can further enhance the stiffness and increase the strength of the laminated bamboo girder. The newly developed modern bamboo structural elements have several design and construction merits such as being lightweight with sufficient load carrying capacity and stiffness, suitable to be utilized for carrying load. Installation procedures similar to those practiced in wood frame construction can be adopted for the construction of modern structures using laminated bamboo elements. A 5 m long pedestrian bridge, a 10 m long truckload roadway bridge and a 10 m long testing bridge have been completed to date.

## ACKNOWLEDGEMENT

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# Development of bamboo structure in India

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ABSTRACT: Bamboo building techniques as it exists is mostly traditional in nature gained over years. Referring to India, a lot of studies have been carried on preservation of bamboo with a view to enhance service life followed by determination of physical/mechanical properties of several species in a systematic manner with a view to assist engineers to select and make design decisions. However, there has been growing interest among engineers and architects in recent times in Bamboo as building and structural material. Factors like high strength to weight ratio of bamboo, its low energy construction, short rotation required to raise bamboo on a sustainable basis, tendency to pollute less, have contributed to its recognition as a building material.

In this paper, an attempt has been made to give overview of work carried out in India in development of bamboo structures from the past to present. It also covers bamboo structures based on non engineered principles, structures for mass housing and quake resistant bamboo shelters.

## 1 INTRODUCTION

Bamboo building techniques as it exists is mostly traditional in nature gained over years. As bamboo by nature is a highly perishable material, its use in construction has always been considered temporary and not surprisingly bamboo is replaced almost every year in most of the rural constructions. It is only recently the engineering and material properties have been studied exhaustively. When forest cover is fast depleting and availability of wood is increasingly becoming scarce, the research and development undertaken in past few decades have established and amply demonstrated that bamboo could be a viable substitute of wood and several other traditional materials for housing and building construction sector.

Main characteristic features, which make bamboo as a potential building material, are

- its High tensile/bending strength and comparable to that of mild steel and wood
- High strength to weight ratio and high specific load bearing capacity
- Requires less energy for production compared to material like steel, plastics, aluminium etc.
- Physical-mechanical properties of bamboo which grows to maturity in 4 to 5 years compares favorably with that of hardwood which requires 40 to 50 years to attain maturity.

Above all bamboo is renewable raw material resource from agro-forestry and if properly treated and industrially processed, components made by bamboo can have a reasonable life of 30 to 40 years. Though natural durability of bamboo varies according to species and the types of treatments, varied uses and applications in building construction have established bamboo as an environment-friendly, energy-efficient and cost-effective construction material. More than 100 species of bamboo are native to India and a few of them are solid but most of them are hollow in structure. Out of 67.5 M Ha of forest area, bamboo covers about 13% of it. In India, The commonly used species in construction are Bambusa balcooa, Bambusa bambos, Bambusa tulda, Dendrocalamus giganteous, Dendrocalamus hamiltonii, Dendrocalamus asper, etc.

## 2 TRADITIONAL BAMBOO CONSTRUCTION

Bamboo houses are not wholly unknown to India. Villagers living in the vicinity of bamboo forests often construct them and live in them. It is hence known as poor mans material. Figures 1 and 2 show some examples.

### 2.1.1 *Bamboo houses in North-Eastern parts of India*

The general characteristics of the house in north-eastern parts of India are houses on the plains and those on the hills. The houses of the plains are simpler, mostly with mud plaster on walls and with mud floor. The houses on the hills are mostly on the ground with a plinth.

### 2.1.2 *Bamboo house with thatch roof: The most economical of its kind*

Easy availability of bamboos and thatch makes it cheaper. Planning is confined to rectangular shape because of limitation of the construction system. Walls both inner and outer are of woven bamboos. Doors and windows are of wooden or even bamboo frames. The thatch is of straw.

### 2.1.3 *Riang bamboo house*

Riang tribals of Tripura build their houses with bamboo used as the primary material for construction. In some cases, even the thatched roof is made of bamboo leaves. These houses are typical hill dwellings, constructed on bamboo slits to create a large horizontal platform, the floor of the house. Bamboo posts are arranged on a square grid and inclined whole bamboo members strengthen these. A required number of posts extend above the surface of the floor platform to support the roof structure.

The plan of the Riang house is normally a long rectangle, with a covered verandah in front and an open verandah at the back. A large enclosed room is located between these verandahs. A single roof covers the front verandah and the room. The roof slopes downwards on either side.

Boards made of flattened bamboo culms are used to cover the floor of the room and to make the walls and doors. The floor of both verandahs are made from either whole bamboo or longitudinal halves placed side by side and bound to the beam structure below the floor. A single log, which is notched, forms the short ladder at the front of the house.

### 2.1.4 *Bamboo reinforced mud wall*

Mud wall gives protection against heat and cold. Now a days mud walls are constructed by reinforcing these with quartered split bamboo culms properly treated with hot bitumen. Properly kneaded mud mixed with rice husk, cinder and a little lime and water are applied layer by layer keeping the bamboo grid in the center which is later plastered and smoothened and finally white washed.

### 2.1.5 *An experimental house constructed in 1973*

Shown in Figure 3, interesting observations made by Bipul Kumar Das on an experimental house constructed during 1973, at Guwahati, a part of Assam in India reveals that the condition of the

Figure 1. A unique Bamboo tree house.

Figure 2. Bamboo house with thatch roof.

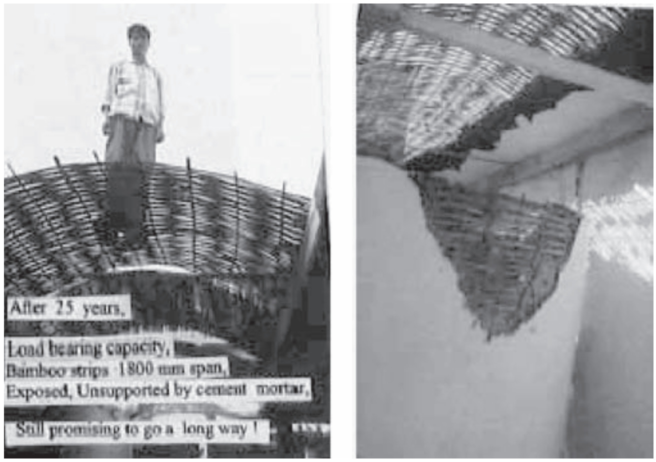


Figure 3. An experimental house with bamboo strips constructed during 1973.

bamboo strips that were used for 25 years inside the structure was good without any proper treatment. The bamboo strips were used for both the roof and wall construction. Bamboo used were not chemically treated but taken from the lots that were river transported. This proves that the bamboo promises a very long lasting period provided that the conditions are conducive.

#### 2.1.6 *Experimental houses at FRI*

CCA—preservative treated bamboo experimental house using half split treated bamboo and bamboo reinforced mud wall have performed very well and still in existence even after 35 years. Treated bamboo thatch served as roof in their experimental houses.

### 2.2 *Bamboo houses in southern parts of India*

Generally, the houses in these parts can be grouped into thatched and tiled houses. In both the types, bamboos are invariably used for making roof structure. In certain houses, especially thatched houses, in addition to roof, bamboos are used for wall, window, door and even partitioning.

#### 2.2.1 *Thatched bamboo house*

The thatched bamboo houses are small in size. In Kerala state, the average plinth area of thatched house and the average plinth area per person are 39 $m^2$ and 8 $m^2$ respectively (P K Murlaeedhara et al. 1999). The corresponding figures for Karnataka are 31 $m^2$ and 7 $m^2$. The average plinth area of thatched houses was found to be higher in highland areas than in mid and lowland areas of both states, as bamboos are available at a low price in the highland areas. The basement of bamboo houses in Kerala and Karnataka is predominantly made of low quality materials like mud and sand and only in a few houses are brick and rubble used. This is attributed partly to the poor economic conditions and partly to its small size.

Many houses in the highland areas in Karnataka have bamboo reinforced mud walls. This structure is very cheap and lasts for more than ten years. Wood is the preferred material for windows and doors in majority of the bamboo houses. Roof of all the selected houses is constructed with bamboos.

Grass, straw and coconut leaves are used as thatching materials, of which the latter is used in majority of the thatched houses in both the states. This may be due to the abundance of coconut trees and easy availability of thatching leaves from them.

2.2.2 *Tiled houses*

In Kerala, the average plinth area of the tiled house is 58 $m^2$ and plinth area per person is 14 $m^2$. Of the study conducted on total sample in the State tiled bamboo houses constitute only 8 per cent. Around 35 per cent of the total samples in Karnataka are tiled houses with an average plinth area of 72 $m^2$. The average plinth area of the tiled houses in Karnataka varies between 82 $m^2$ in highland areas and 51 $m^2$ in lowland areas.

In Karnataka and Kerala, 80 to 85 per cent of tiled houses have their basement made of brick. Wood is widely used for windows and doors in both the states. Bamboo is used as roof frame in all the sample houses that are taken for study. In highland areas, where very thick bamboos are available, they are used even as the main and lateral supporting beams. But in other areas, some houses have used wood or Casuarina poles as main or supporting poles.

## 3 BAMBOO HOUSING—EARTHQUAKE PRONE AREAS

As India has large areas falling in the zones of high seismicity, bamboo can play a vital role in appropriate housing and construction aiming to its suitability and availability. For this purpose it is necessary to develop technological packages, which can be easily adopted for mass housing in such areas. Typical Assam House, shown in Figure 4 has wooden frame with infill plastered bamboo lath and has been found to be effective in resisting earthquakes. A demonstration house was constructed at Mizoram using Latin American earthquake resistant bamboo housing technology, as shown in Figure 5.

## 4 IPIRTI-TRADA BAMBOO BASED HOUSING SYSTEM

In India, although bamboo is widely used in some regions, it must be emphasized that its use has been secondary as a semi load bearing element or as infill material in timber framed houses. It is in this context that the bamboo housing technology developed at IPIRTI is of greater significance.

Bamboo based housing system has very high potential for mass housing, housing in disaster prone areas and for earthquake resistant structures/houses and other applications. The low mass of the bamboo based building is an advantage under earthquake condition as compared to masonry structures. The buildings constructed in bamboo using this method are able to withstand the highest levels of earthquake loading likely to be experienced in India. The test building of 2.7 $m^2$ resisted seven repetitions of a typical Zone 5 earthquake, the highest in India and equivalent to 7 on the Richter scale, as well as a replication of the notorious Japanese Kobe earthquake (Richter 7.8), without any damage whatsoever, as shown in Figure 6.

Figure 4. Typical Assam House (Wattle & daub, bamboo lathe infill walls).

Figure 5. Demonstration house at Mizoram, Latin American (Colombia, Ecuador) earthquake resistant housing technology.

Figure 6. Bamboo House under shake table testing at CPRI, Bangalore.

### 4.1 *Characteristics of the bamboo based housing system*

The system has following unique characteristics:

1. *Affordability*: Foundations are minimized, wall panels are non-load bearing and can be reduced in thickness, basic components like bamboo, binding wire, bolts, chicken mesh etc are inexpensive and available locally.
2. *Sustainability and environmental impact:* Bamboo is available in commercial quantities using the established supply system. It is a renewable resource with short rotation period and can be grown on degraded lands. The bamboo is treated using environment friendly preservatives. The usage of high energy embodied materials like cement steel is minimized.
3. *Cultural Acceptability*: The system offers traditional materials in modern engineering context. The result is homely with feel of permanence.
4. *Durability and Safety:* All bamboo components are effectively treated with safe preservatives to give extended life, the structure is engineered to resist wind and earthquake forces and other imposed loads.
5. *Improved jointing techniques:* nailing of bamboo is eliminated therefore splitting is prevented. Wiring, bolting and strapping provides the positive connections.
6. *Modular construction:* suited to either prefabrication or fabrication in situ i.e., all components like infill grids, roof trusses are designed to be prefabricated or prepared on site.
7. *Ease of Assembly:* only basic carpentry and masonry tools and skills are required to undertake the construction.

### 4.2 *Construction techniques*

Treatment of components with preservatives: Bamboo columns can be treated either by internodal injection with creosote or by the Boucherie process using Boron. This process can be used for fresh green bamboos only. Portions of bamboo columns which is in direct contact with soil and below the soil can be treated by hot and cold creosote treatment. Inter nodal injection of preservative is used for all structural frame work (Trusses, beams etc.,) & columns above plinth. Split bamboo slivers used for infill wall panels plastered with cement mortar can be treated by diffusion process using boron chemicals. This technique has found to be very effective.

Trusses, rafters and purlins whether made from whole culm or split culms are protected from direct wetting and can therefore be treated using the boron dip diffusion method.

Foundation: The bamboo building system developed by IPIRTI-TRADA is very light compare to usual trial/masonry structures. As such extensive foundation work is not required and is limited to individual footings $400 \times 400 \times 600$ mm deep for each bamboo column.

Columns: Treated bamboo using internodal injection of preservatives of 80–100 mm dia. and a wall thickness of 10–12 mm, spaced at a interval of 1.2 M and set in concrete footings provide the basic load bearing framework for the building. A wooden wall plate 100 × 40 mm sawn plantation timber is fixed to the top of the columns by skewering into wooden inserts ties the columns at top and distribute dead loads due to weight of trusses, purlins and sheet roofing. The columns are pierced by steel dowels at 150 mm centres provide connection to the bamboo grid infill.

Plinth and Flooring: The Plinth consists of few courses of concrete block/size stone/brick raised to a height of 40–45 cm and filled with compacted earth and topped with brick bats and skidded with 20 mm of cement mortar.

Wall infill panels: The wall infill shown in Figure 7 is non-load bearing and comprises a grid of splits bamboo (19 mm × 9 mm) tied together with MS binding wire to form 150 mm × 150 mm grid. The grid is tied to steel dowels passing through the columns. Chicken wire mesh is fixed on the outside face of the grid. A 1:3 mix cement mortar is applied on both side of the grid to a finished thickness of about 50 mm. The same principle can be extended to the construction of gables. Alternatively gables may be formed with bamboo mat board.

Although the walls are basically non-load bearing and only 5 cm thick, they are capable of withstanding racking loads due to wind normally prevailing in India and is taken to be 100 kg/m$^2$. A wall of 2.4 M height showed no sign of failure with racking deflection of only 0.35 mm when racking load of 500 kg was applied at the top. The walls are also capable of withstanding soft and light body impact and hard body impact tests as per British Standards. It is also capable of resist shocks due to 30 kg filled spherical leather bag as per Indian Standards without damage.

Roof structure: Bamboo trusses shown in Figure 8 offer a good substitute for supporting roof loads and transmitting them to the foundation through columns. Bamboo trusses are fabricated using culms having an outer diameter of 75–100 mm. When the top and bottom chords and strut members are properly jointed by suitable fastening devices, a truss can resist compressive and tensile forces conglomerately and as such act as a stronger supporting component even in earthquakes compared to rafter-purlin system

The roof comprises of 30° pitch trussed rafter (collared trusses] spaced at 1.2 M fixed to the wall plate (over columns) using purpose made steel strips. The truss members are 80–100 mm dia. bamboo and joints are gusseted using 6 mm BMB and 8 mm dia. bolts. The trusses are designed for a maximum dead load of 10 kg/m$^2$ due to purlins and roof covering and a live load of 40 kg/m$^2$. The bamboo mat gusset provide excellent connection between chord and collared members and

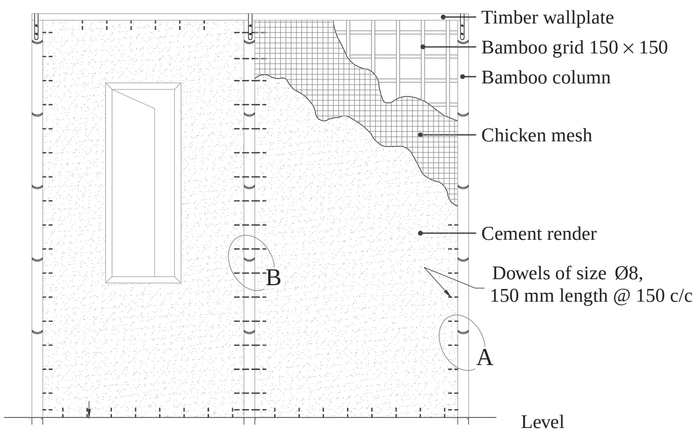


Figure 7. Infill Wall Panel.

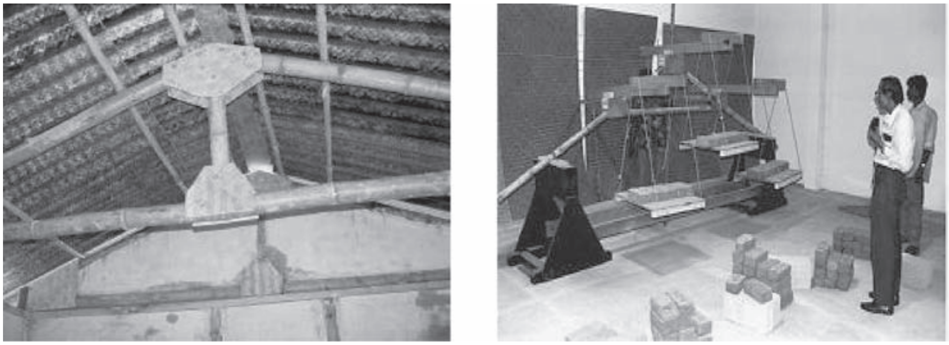

Figure 8. Roof structure.

detailed tests have shown that joints have failed due to bearing of BMB and not due to shearing or splitting of bamboo with enough factor of safety.

Roof Covering: Bamboo Mat Corrugated Sheets currently developed and produced at Institute offers a convenient alternative to existing roof cladding materials like asbestos cement, CGS. 3 mm BMCS with a pitch of 7.5 cm and depth of 3 cms has a load bearing capacity of 5 N/mm for a span of 1 M. These sheets have been used for the houses and fixed to 25 mm dia. purlins spaced at 1 M using standard J-bolts. Purlins are tied to the trussed rafters using MS bolts and binding wire.

Door and Windows: Frames are made of $75 \times 60$ mm sawn plantation timber like silver oak and shutters consists of single skinned BMB infill panels stiffened with silver oak rails and styles. Door and window frames are tied to the grids through nails driven into the outer perimeter of door and window frames as fixing points.

Finishing: Infill walls can be finished outside either with cement paint or usual lime wash inside finished with distemper. Exposed bamboo and wood work have been successfully and economically finished with semi transparent CNSL based varnish. Interior ceiling also can be finished with colourless cardinal based varnish. Alternatively, bamboo and wood work would have been also finished with synthetic enamel paint available in the market.

### 4.3 *Promotion of bamboo houses*

Demonstrate structures are needed to create awareness and it should show the different applications. Based on the IPIRTI-TRADA technology a few demonstration houses have been built at different parts of Southern India are as shown in Figure 9 and 16.

Figure 9. Prototype House at IPIRTI, Bangalore, February 1999.

Figure 10. Demonstration House at Chikkabettahalli, Bangalore, October 1999.

Figure 11. Demonstration House at IPIRTI—Bangalore, March, 2001

Figure 12. Demonstration two bed room house at IPIRTI—Bangalore, January 2002.

Figure 13. Pantry Building at Raj Bhavan, Bangalore, January 2001.

Figure 14. Security House at IPIRTI, Banalore, 2004.

Figure 15. Solar Bamboo Hut at Bangalore—Karnataka, 2005.

Figure 16. Bamboo House at FRI, Chennai—Tamil Nadu.

## 5 RECENT STUDIES IN IPIRTI-TRADA BAMBOO BASED WALLING SYSTEM

### 5.1 *Fly ash as part replacement of cement*

Recently, a study has been conducted to utilize the fly ash as part replacement of cement in Bamboo walling system. The results shows that utilization of fly ash as part replacement of cement (up to 1/3rd ) in bamboo based walling system provides better bonding with chicken mesh & bamboo strips, improved surface finish and high water retentivity (as observed visually) when compared with the control panel as tested for the purpose. The forces imposed on the test panels, shown in Figure 17, were intended to replicate the most severe conditions likely to be experienced during the life of the structure. The test panel with fly ash resisted the forces with minimal deflection and

Figure 17. Testing of panels under progress.

total absence of damage (including superficial cracking) on par with the panel without fly ash and is more than adequate for its intended applications. The study emerges that inclusion of fly ash in mortar does not alter the structural performance of bamboo based walling system.

### 5.2 *Soil cement mortar*

Preliminary studies conducted on a prototype wall where the soil cement mortar has been used in place of cement mortar in bamboo based walling system. With the mix proportion (1:3:3) (cement: soil: sand) negligible hair line cracks were observed during impact tests conducted on prototype wall. To improve the overall performance of the walling system the first coat can be with the same proportions and finished coat may be with the cement mortar of 1:3 which is economical with the regular walling system.

## 6 PREFABRICATED HOUSE

Bamboo construction technique is also amenable to prefabrication either in the form of pre-cut or prefabricated components like trusses, frames, columns, wall panels and beams (BMB and wood glued components) or as fully prefabricated units which could be transported. Roofing using bamboo mat corrugated sheets (BMCS). Figure 18 shows an example.

Recently a prefabricated composite house was made, as shown in Figure 19. A composite connection was made between wall system and the foundation. The walling system is of prefabricated frames made using Aluminum/Steel angles & channels and pre fabricated Bamboo Mat Board (BMB) panels of various sizes were fitted into the frames. BMB is used as roofing. Prefabricated

Figure 18. Prefabricated BMB wood shelter IPIRTI, Bangalore.

Figure 19. Prefabricated BMB composite house IPIRTI, Bangalore.

housing systems developed by various organizations are being used in various places such as army shelters, guest houses, quick toilets and it was also proposed to use in Tsunami reconstruction programmes in India.

## 7 DEVELOPMENT OF BAMBOO COMPOSITES

Bamboo boards and panels developed earlier at FRI and now perfected, demonstrated, standardized as well as taken to industrial level by IPIRTI has enormous potential in building industry.

During last two decades IPIRTI has developed cost effective technologies for manufacture of bamboo composites which have been commercialized. These technologies are not only environment friendly but also people friendly as they have immense employment generation potential particularly for women in the bamboo growing area. Use of bamboo composites will lead to reduction of pressure on non renewable building materials, reduce pollution and lead to substantial energy conservation. The Institute has brought out specification for all the three bamboo composites developed i.e. IS: 13958 Bamboo Mat Board for General Purpose, IS: 14588 Bamboo Mat Veneer Composite for General Purpose and IS: 15476 Bamboo Mat Corrugated Sheet as roofing material. These products are well accepted in the market and there is a great demand.

Recently the National Mission for Bamboo Application (NMBA) in consultation with Planning Commission has recommended the use of Bamboo mat board [BMB] in Tsunami affected areas.

### 7.1 *Bamboo Mat Board [BMB]*

BMB is essentially a layered composite comprising several layers of woven mats of herringbone pattern, having excellent internal bond strength, and are resistant to decay, insects and termite attack. They have physical and mechanical properties on par with waterproof plywood and are fire resistant. Their mechanical properties depend upon the species of bamboo used for mat making, the weaving pattern and the adhesive used for bonding. BMB has high in-plane rigidity and hence high racking strength and is more flexible than equivalent plywood. This property of BMB can be advantageously used in many engineering applications.

### 7.2 *Bamboo Mat Veneer Composite [BMVC]*

In BMVC, wood veneers are placed in between the layers of bamboo mats. The properties of BMVC depend on the type of construction in addition to the species of veneer and type of adhesive used. The strength of a panel made by plantation timber is substantially enhanced when made in combination with bamboo mats. BMVC can be used for structural applications similar to plywood.

### 7.3 *Bamboo Mat Corrugated Sheet [BMCS]: [BMTPC-IPIRTI Technology]*

As shown in Figure 20, BMCS is made of four or more bamboo mats bonded with an adhesive and pressed in a specially designed sinusoidal platen dies. They have very high potential as eco-friendly roofing material. The load deflection curves of various corrugated roofing materials indicate the comparative advantage of BMCS over other corrugated materials. The load bearing capacity of BMCS is comparable to that of ACCS and CGI sheets and much superior to ACS. BMCS being light in weight possess high resilience.

BMCS is water proof and resistant to decay, termites/insects and fire. The thermal conductivity of BMCS (0.1928 Kcal/m°c) is lower compared ACCS.(0.3422 kCals/m°c) and provides better thermal comforts compared to houses having ACCS or CGIS as roofs.

### 7.4 *Bamboo Mat Ridge Cap (BMRC)*

The size of the Bamboo mat ridge cap is 1.05 m $\times$ 0.43 m with a thickness between 3.5 to 3.7 mm, having a weight of 2.0 kg. Bamboo mat ridge cap is dimensionally stable and compatible with BMCS and suitable for wide range of roofs, shown in Figure 21.

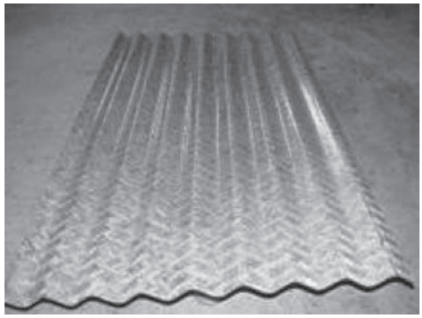

Figure 20. Corrugated sheet.

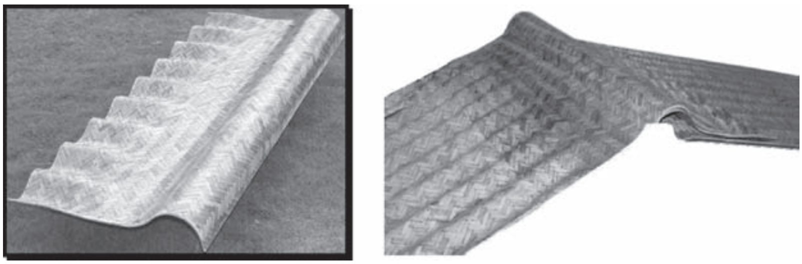

Figure 21. BMCS roof components.

## 8 GOVERNMENT INITIATIVES

In the modern context when forest cover is fast depleting and availability of wood is increasingly becoming scarce, the research and development undertaken in past few decades have established and amply demonstrated that bamboo could be a viable substitute of wood and several other traditional materials for housing and building construction sector and several infrastructure works. Its use through industrial processing have shown a high potential for production of composite materials and components which are cost-effective and can be successfully utilized for structural and non-structural applications in construction of housing and buildings.

### 8.1 *National Mission on Bamboo Applications (NMBA)*

Advances in structural engineering and the development of bamboo based composites have made possible light weight, durable and aesthetic construction for variety of applications, enabling informed choices for housing, community and functional structures. NMBA, an autonomous organization under Department of science and technology (DST), supports application oriented research and development activity, utilizing bamboo for constructional applications. It also seems to demonstrate the virtues of combining bamboo with a range of material locally available and appropriate, newly developed and non conventional. The mission supports innovation with different construction techniques and sets bench marks of quality of construction, functionality, strength and safety and aesthetics.

### 8.2 *Building Materials & Technology Promotion Council (BMTPC)*

BMTPC (under Ministry of Urban Employment & Poverty Alleviation, Government of India) is actively involved in developing bamboo based technologies and to promote these technologies in the

North-Eastern Region and other bamboo growing areas, by setting up of Bamboo Mat Production Centres for processing of bamboo, encouraging commercial production of bamboo based products, construction of demonstration houses etc.

As demonstrated in Figure 22, BMTPC has involved in construction of 10 demonstration structures, each, using bamboo based technologies in Mizoram and Tripura (North Eastern Parts of India). These include houses, community buildings, Library buildings, Picnic huts, Schools, etc in order to propagate use of locally available bamboo. The cost of construction is considerably reduced by 25% to 30% using bamboo based technologies for different types of structures as compared to conventional construction. During constructing various types of structures local contractors, masons, artisans were provided training on use of bamboo in building construction.

### 8.3 *Cane and Bamboo Technology Centre, Assam, India*

This was initiated under UNIDO/ UNDP PROJECT and currently supported by The North East Council and also a technical support group for the National Bamboo Mission(NBM) (North Eastern Region, Orissa, West Bengal, Jharkhand) working in bamboo plantation, bamboo craft and design sector and housing sector. Typical houses constructed by CBTC, Gawahati are as shown in Figure 23.

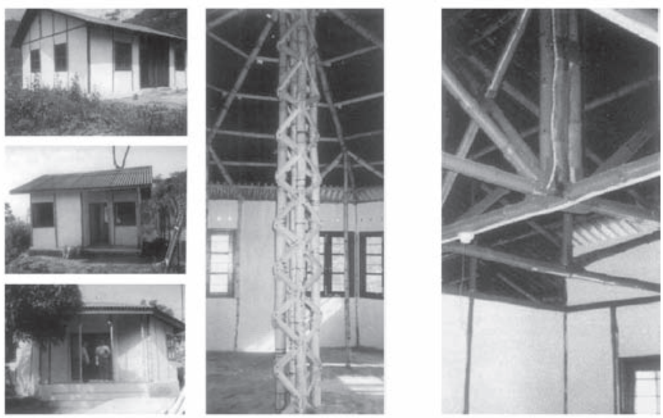

Figure 22. Houses at Mizoram, 2005.

Figure 23. CBTC house examples.

## 9 STANDARDISATION

Research results have not yet found acceptance in changing construction techniques and there is hardly any standards evolved on bamboo construction and design. Although bamboo was traditionally used for different construction works, especially housing in many areas throughout the world, scientific investigations to establish bamboo as a structural material are relatively not so old. India was one among the countries to recognize the need for generating data base on physical and mechanical properties of different species of bamboo. Indian standard methods on testing bamboo for evolution of physical and mechanical properties were developed in 1973 & 1976. (IS 6874: 1973 method of tests for round bamboos and IS: 8242-1976—method of test for split bamboo).

Bamboo has the potential of being used in sophisticated urban house construction and also for reinforcement in concrete. But due to absence of any standard building code for bamboo so far apart from method of test, it has not been officially recognised as a building material in house construction activity. Absence of recognised standard does not allow bamboo based building material to be accepted freely by construction industry.

An interesting point is that the information about the various bamboo species available in India and their physical and mechanical properties, grading for structural purposes, its durability and treatability and also design considerations has been included recently in Section 3B, Part—6 of National Building Code of India (NBC) 2005.

## 10 CONCLUSION

In conclusion, development of bamboo structures depends upon availability of graded & standardised raw material; Access to design information like standards & codes, design procedures to engineers/Architects; Availability of eco friendly preservatives and preservative facilities; trained man power in bamboo carpentry & joining methods; Participation of NGO's and Government in encouraging wider use of bamboo building; development of standard designs and Do-it-yourself kits.

## REFERENCES

Arun K. Bansal, Dr. H.N. Jagadeesh & H. Guruvareddy 2001. Bamboo based housing system. *New Building materials & Construction world* 7(6): 33–36.

Bipul kumar das. 2001. Bamboo in the field of construction in North east India. *Technical Report No. 1*, CBTC.

IPIRTI. 2001. Status of bamboo housing technology developed at IPIRTI. *IPIRTI Miscellaneous Report*: 13.

Jagadish Vengala, K. Shyamasundar & C.N. Pandey. 2006. An Experimental Study on Bamboo based walling system. *Journal of The Indian Academy of wood science* 3(1): 92–100.

K. Shyamasundar and Jagadish Vengala. 2006. Promotion of bamboo housing system & recent developments. *World Bamboo and Rattan* 4(2): 5–10.

National Building Code of India. 2005.

Websites: *www.bmtpc.org, www.bambootech.org, www.ipirti.gov.in, http://ignca.nic.in/craft207.htm*

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# Conceptual development of bamboo concrete composite structure in a typical Tribal Belt, India

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ABSTRACT: This paper presents a scientific documentation of the extensive work carried out by Dr. Sudhakar and his students on 'Bamcrete', (bamboo concrete combination) housing applications with special emphasis to the Bamboo bows as load bearing elements of buildings, in a tribal belt in Khammam district, Andhra Pradesh, India at Haritha Ecological Institute. The work spaned over 18 years in their search of building material that can be grown in 4 to 6 years. The concept of the bamboo bow with one horizontal tie and two cross ties evolved out of a 10th class students' experiment in 1988 at the institute. It was found that Dendrocalamus strictus, a widely available species with thick wall could be easily bent into bows which are strong enough to take the roof loads with spans of over 6 m in the first experimental structure in 1989. After four years of observation of the structure, the group developed 7.3 m span bamboo bows with one horizontal and two cross ties and produced over 600 of them to build nearly 2000 $m^2$ area in 1994. Most structures have barrel roofs of corrugated GI sheets that hug the bamboo bows while a few have conventional sloped thatch. Since then, the group has been living in and using these buildings. The bamboo bows are still in excellent condition after 12 years with no additional need for maintenance. Subsequently ferro-cement band as a cost effective rigid tie between bamboos has been developed and used in bamboo bows which are separated vertically resulting in stiffened roof load bearing elements. Currently scientific validation of some of these concepts is being carried out at IIT Delhi and efforts are on to disseminate the technology to selected institutions and NGO's for larger use.

## 1 INTRODUCTION

### 1.1 *Problem areas*

The primary concern was to green the vast waste lands in a cost effective self sustainable manner. For Sudhakar, it all began in 1981, when he came across a paper arguing for plantations for fuel wood to generate decentralized thermal power as an economically viable way of harvesting solar energy. It was felt that the wood from plantations would fetch a far better return as timber for structural applications (eg., in housing) and that fiber pulp and fuel wood should be the options in that order for the use of the waste wood that remains after sawing the timber with the tiny wooden chips and saw dust explored for particle board. That way, it was felt that greening of the waste lands would be an economically viable activity. However, if the activity is to be taken up by small and marginal farmers, ways and means must be found to use the small dimension timber from the 4 to 6 year old trees in realizing structural members in housing with decent spans of over 3 to 5 m, which has a huge demand. This is the challenge because the traditional methods of building houses with timber use fairly large cross sections which require trees of over 30 years old.

### 1.2 *The initial experiments and the future vision*

The first experiments involved using a few meter long slender sawn members of wood having a thickness of under 15 mm and width of 50 mm to 100 mm in the form of 'I' and 'T' shapes primarily with nails. A 10th class students' experiment in 1989 explored the 'I', 'T' and bow shapes built out of 6 mm thick and 50 mm wide strips of ply wood with a span of 1 m. The bow shape was recognized as a very efficient structural member to take on the roof loads, if it was held in a vertical plane. Finally it was recognized that bamboo is easy to be bent into a bow of long spans of over 6 m. Bamboo also has the advantage of maturing in its timber in just under 4 years after it shoots up, which when properly treated can last for decades thus effectively acting as a carbon sink.

Thus, Dr. Sudhakar recognized bamboo as an ideal choice to green the waste lands. Its shallow but dense network of root system together with large leaf litter helps in prevention of soil erosion and improving the soil humus. Its prolific growth means it is a huge carbon sink. Thus bamboo is not only eco-friendly but a great 'eco-healer'. The multitude of other utilities for bamboo would definitely help in generating sustainable livelihoods and help the process of greening the waste lands. The increasing demand for carbon trading can be of substantial help in the economics of bamboo plantations.

These efforts at Haritha Ecological Institute were appreciated by IITD, HUDCO collaborative project, namely, National Resource Facility for Bamboo Technology (NRFBT). Through discussions, a holistic perspective based on modern S&T inputs and social engineering for waste land regeneration and bamboo plantations and using it for various applications for development of rural economy and ecology has been envisaged.

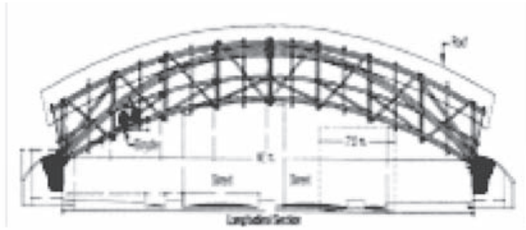
## 2 BAMBOO IN STRUCTURAL APPLICATIONS

### 2.1 *An overview*

Bamboo is an extremely light weight, functionally graded and high strength natural composite. It fits well into the minimal weight and energy structures that the future demands. Bamboo has been used in various pioneering structural and other applications in the past. Ranjan et al. have presented a review of the applications of Bamboo in Northeastern part of India. Hidalgo's book is one of the best reviews that presents a wide range of works on bamboo. It presents the remarkable bridges in Chinese/Tibetan/Himalayan regions. In some of these applications, high strength ropes from bamboo skin have also been reported. It also describes the pioneering work of Latin Americans in bridges and sophisticated buildings, including the multi level ones. Figure 1 shows some of the structures.

In India, as else where, bamboo has been primarily used as a load distributor of a thatched roof. Modern attempts at using the bamboo as a main roof load bearing structural element predominantly use it as a linear element such as in 'A' frames of timber. Various researchers have tried to use bamboo as reinforcement in RCC by replacing steel with limited success in roofs and load bearing members. According to Gutierrez, South America, building with bamboo assumed serious efforts from enthusiastic architects, dedicated as they are to preserving and advancing their native ways of building with bamboo all the way from 1960. They work on improving the methods of combining cement-based masonry with bamboo constructions and pursued the line where the bamboo is used in a way it is not so visible but functionally critical and complementary to the concrete, primarily aiming the poor communities as a low cost substitute.


(a) Himalayan Suspension Bridge



(b) Modern Bamboo Bridge, Colombia

(c) A Modern Structure, Columbia

Figure 1. Some great applications (Oscar 2003).

Work initiated by Prof. Jules Janssen in Eindhoven Institue of Technology, Netherlands, in 70's, received the attention of International Network for Bamboo and Ratan (INBAR) as reported in the three excellent technical reports on structural aspects of building with bamboo.

### 2.2 *Building with bent bamboo*

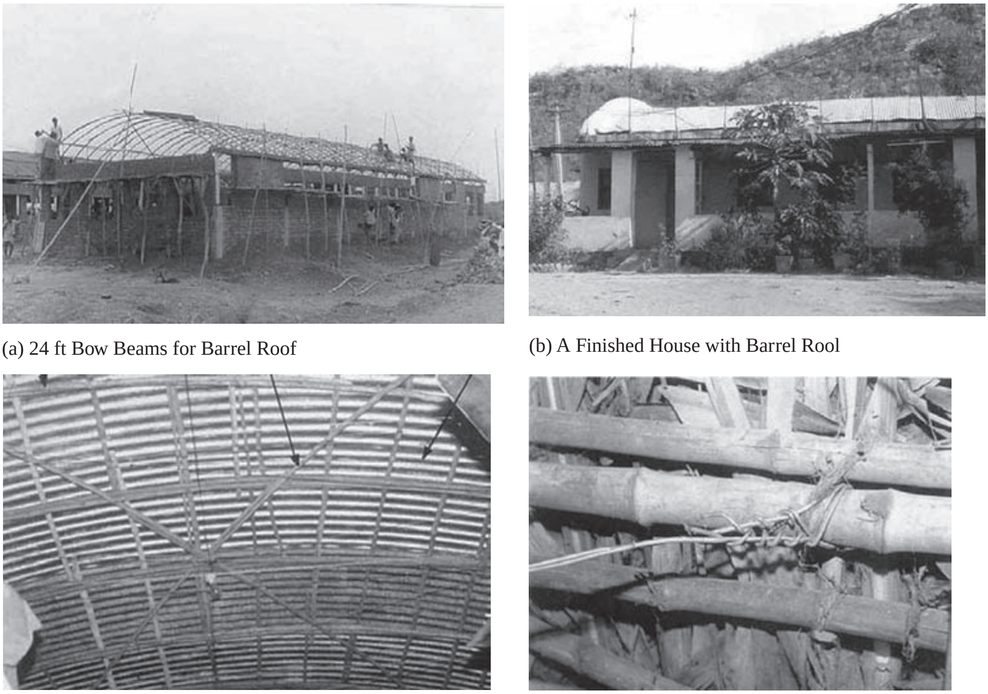
Vinoo Kaley reports that the natives in India used bamboo bent at site to make temporary pens (confinement) for their domestic animals with no roof cover. Hidalgo reports the use of bent round bamboos in India which are the remnants of Vedic period and that the temple architecture in India involving arches and domes with stone is modeled after the bamboo constructions. It is suggested that the elite took to building the arches and domes with stone, relegating the bamboo to the background. Only the poor continued to live with bamboo constructions.

Hidalgo also reports that in 1987, one French designer named, Yona Friedman, had built domes with bamboo slats in Chennai which were displayed in 'The Museum of Simple Technology' in Anna University, Chennai. But these are to be used with temporary roof covers such as with tarpaulin. It is a common sight to see the nomads building small temporary huts with bent bamboo in Andhra Pradesh, using again plastic tarpaulins for the cover. Das reports the use of woven slivers of bamboo with sufficient thickness bent into an arch of short span of under 2 m that rests on RCC beams and then plastering the same with cement mortar, way back in 1971–72, for his own house.

### 2.3 *R&D efforts in a rural school environment*

Blissfully unaware of these developments, both at the national and international level, Sudhakar and his school students M.V.N. Satyanarayana and P. Siva Prasad experimented with 'bow' as a load bearing structural element in 1989 at Haritha Ecological Institute, Paloncha, Andhra Pradesh. This was further developed into a full fledged bamboo bow beam with two cross ties of span 6.1 m and was demonstrated in a shed, capable of taking the roof load from a variety of roof covers: from corrugated GI sheets to thatch. This was used as a classroom.

During 1994–95, a new campus of Haritha Ecological Institute was built with over 2000 $m^2$ of covered area for class rooms and residences, all with 7.3 m span bamboo bows as roof load bearing



(a) 24 ft Bow Beams for Barrel Roof

(b) A Finished House with Barrel Rool

(c) Inside view of the Roof

(d) Details of the Tie

Figure 2. Class room/residences at Haritha, India—7.3 m span, bow beams, 2000 m$^2$.

elements as shown in Figure 2. These bamboo bow buildings use a variety of roof covers—from corrugated GI sheets to thatch and are still in good condition even after 12 years of regular use. The analysis of these structures was done by SARMET from Mumbai and presented as a report to INBAR. Subsequently ferro-cement band as a rigid tie between bamboos has been developed and used in bamboo bows which are separated vertically resulting in stiffened roof load bearing elements. Some demo constructions built with spans from 3 m to 7.3 m were found to be cost effective in housing.

## 3 STRUCTURAL APPLICATIONS AT HARTHA ECOLOGICAL INSTITUTE

### 3.1 *Typical barrel roof building*

Figure 2 shows houses of 7.3 m span with bamboo bows supporting the roofs which are in use since 1994. The bamboos were not painted and are all in excellent condition and required no maintenance. The steel trusses would have needed painting at least two times in the 13 years and the cost of painting alone would have been more than the cost of the bamboo bow beams. (The timber beams are unthinkable for the 7.3 m span buildings.) The details of the construction, beginning from the concept can be found in ref [11].

The erection of bamboo bows is illustrated in Figure 2a; a typical barrel roof of corrugated GI (Galvanized Iron) sheet can be seen in Figure 2b; and the under side view of the barrel roof with diagonal cross ties with bamboo is depicted in Figure 2c. Steel pegs grouted in the ground define the arch and bamboos are bent using the pegs. Two 5.5 m bamboos with their thick ends (4 cm dia.) starting from each end are used so that there is a substantial over lap between them for almost

Figure 3. Skeletal view of the bamboo bow supported sloped roof.

the entire mid half portion of the bow. The two bamboos are tied with several steel binding wires spaced about 15 to 20 cm apart, much like the steel rods in RCC works. One horizontal and two cross ties for each bow are of GI wire of 1.5 to 2 mm and are simple as shown in Figure 2d. These involved practically no nailing or drilling, even though the latter could also be used. Each of the two cross ties starts from the base at one end and reaches the bow at close to the three fourth span point on the other side. The bow more or less retains its shape even after it is taken out of the pegs. The crown height of the bow is approximately a fifth of the span. The cross ties concept was an important contribution, introduced to increase the stiffness of the bow by the then 10th class students, MVN. Satyanarayana and P. Siva Prasad.

### 3.2 *Thatched roof house with bamboo bow elements*

The barrel roof of corrugated GI sheet was elegant but very expensive, costing about 3 to 5 times the cost of the roof supporting super structure of bows and purlins, all of bamboo. Faced by a financial crunch towards the end of the project, the master carpenter, Mr. Rangachari proposed the idea of erecting modified king posts over the crown of the bow and then having a conventional sloped thatched roof. (The bow has too small a slope near the central part to be water proof for a thatch roof.)

Figure 3 shows the skeleton of a typical house (span of 4.5 m and 35 m$^2$ area) with bamboo as horizontal ties. Some short pieces of bamboos in vertical position connect the horizontal bamboo and the arch bamboo. These enable the formation of a deck over the columns that creates a storage space between the deck and the under side of the roof. The typical cost of a good grass thatch is less than half of the roof support super structure. Thus the house is affordable. It provides excellent thermal comfort in summers when the temperatures in the region soar to around 50°C. But it has the problem of annual maintenance for the thatch roof and a complete replacement of the thatch periodically once in 3 to 6 years.

### 3.3 *Development of ferrocement band as a shear connector in bow beams*

Supported by INBAR, SARMET of Mumbai, India conducted a study of these structures in 2000. SARMET felt that, even though the structure was absolutely safe for distributed loads, it was not clearly so for asymmetric loads. Decreasing the spacing between the bows was not a promising solution since the bows were already fairly closely spaced: 0.6 m for 7.3 m span GI roofs and less than 5 m span thatch roofs and 0.3 m for 7.3 m span thatch roofs. And even at this spacing, the horizontal and other ties clutter the under side of the roof so much that it is not very convenient to clean up the cob webs. It was therefore felt that the bows be clubbed into groups and each group further into two subgroups that are separated vertically. The bamboo bows in the two sub groups would be joined by a small number of ferro-cement bands spaced properly along their arch lengths. The bands are also expected to improve the stiffness of the beams against asymmetric loads. Figure 4 and 5 show the developments using bamboo bows with ferro-cement bands. 2000–2001. Each one has 4 bows in it and has several ferro cement bands that tie up the different bamboos of the bows rigidly. One such beam was enough to support the entire roof load of a 7.3 m × 5.5 m thatched house. Eight such houses were built in 2004 in Nagineniprolu, a village in Burgampahad mandal of Khammam district in Andhra Pradesh and have been in regular use. When visited in June 2007, these were in good condition with residents happy.

Fabrication of the ferro-cement band involves making at least two stirrups of 6 mm dia. rods round the four bows separated by about 25 cm, wrapping the bamboos in the region with hexagonal mesh of very thin steel wire (diameter of about 0.8 mm) and cement concreting the region where the gravel aggregate consists of under 6 mm chips and course river sand along with fly ash. The only problem was that the weight of the bow beam increased to almost 500 kg. Apart from increased costs of transportation, this requires the use of a chain block pulley system to erect the beam in position over the columns.

### 3.4 *Twin vertically separated bamboo bows with ferro-cement bands*

A work shop on building with bamboo bows and domes was conducted by the first author in 2004 at VNIT, Nagpur. During the work shop, Prof. Ingle of VNIT suggested fixing the overlapping bamboos in the arch such that they remain one above the other in a vertical plane instead of one next to the other in a curved horizontal plane. He pointed out that it would enhance the stiffness of the bow. Subsequently the ferro-cement bands were made so that the two bamboo arches remain fixed with a desired vertical separation. Figure 4 show buildings supported by bow beams with ferro-cement bands. The spans of the structures in Figure 4a and Figure 4b are 3.3 m and 7.3 m respectively and have ‘A’ frames supported by the bamboo bows. These have corrugated bamboo mat boards for the roof. The Figures 4g and 4h show the structures with 4.5 m span with barrel roof of plastic sheet and grass thatch, the plastic providing the water proofing and the grass protecting the plastic from the sun light and heat. These structures are light and can be prefabricated as was the case here, where these were transported about 200 km for installation. The cement bands were cast at site. After curing, the bow beams were erected manually. Figure 4d shows the ‘A’ frame supported by twin arch bamboo bow beam with ferro-cement bands with 7.3 m span used in the building of Figure 4b. Figure 4f shows the interior of the building showing the detail of the landings for the bow beams—the cement band at the base of the beam gets merged into the supporting brick wall. The shelves in the lower part of the side walls below the windows are of half split bamboo cement concrete composites. The gable wall that can be seen is also of half split bamboo cement concrete composite with the concrete on the outer face and convex bamboo surface on the inside. We suggest the generic term ‘BAMCRETE’ to represent bamboo concrete composite structures of the kind shown in these figures in which a substantial part of bamboo surface is not covered by concrete. It is significantly different from the classical bamboo reinforced concrete.

### 3.5 *Fabrication details of the ferro-cement bands*

Figure 5 shows the details of the fabrication and preliminary testing of the ferro-cement bands between different bamboos. Figure 5a shows the insertion of 6 mm dia. steel “U” clamp through the two separated bamboos that make up the twin arch (The bamboos are bent into an arch shape on a specially developed work bench that has provision to fix the steel pegs/studs to define the required arch shape, usually a parabola.). Once inserted, the ends of the clamp are closed such that the steel rod makes a rectangular stirrup, the two arms of which act as dowels to the two bamboos along their diameters. Figure 5b shows the wrapping of steel mesh around the bamboos in the band region for

(a) Structures with 3.3 m span

(b) Structures with 7.3 m span

(c) 7.3 m Bow Beam

(d) 7.3 m A Frame

(e) Bow Beams with Steel Ties

(f) Inside View—7.3 m Structure

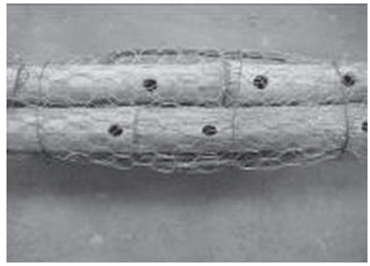
(g) Landing Details in 4.5 m span

(h) Crown Details in 4.5 m span

Figure 4. Bow beams with ferro-cement bands.

the specific case when there is no gap between the bamboos. Figure 5d shows a sample of the finished ferro-cement band tie between two bamboos. The initial tensile tests indicated that the joint exhibits elastic behavior up to 10 kN of tensile load. Figure 5c shows the testing of a pair of the 3.3 m span vertically separated twin arch bow beams with ferro-cement bands under a nearly uniformly distributed dead load of close to 10 kN. Work on detailed testing of these structures is under way at IIT Delhi.

(a) Drilling for the Steel Connector



(b) Steel Mesh Wrap

(c) Testing with Dead load

(d) Sample Joint for Tensile Test

Figure 5. The fabrication details of ferro-cement band and testing.

## 4 CONCLUSIONS

The search for an economically viable route for greening of the waste lands in India led us to explore building houses with what could be grown in four to five years. Experiments at Haritha Ecological Institute in 1989 have led to the development of bamboo bow as the main roof load bearing structural element with large spans and light roofs. The slender but thick walled dendrocalamus strictus variety of bamboo locally available in Andhra Pradesh was found to be suitable to be bent into a bow. Several large span (up to 7.3 m) constructions where roof load of corrugated GI sheets and thatch were supported by simple bamboo bows were built and proved to be satisfactory over the past 13 years. These are also found to be very cost effective. Ferro-cement band as a rigid cost effective tie has been developed and used for building vertically separated twin arch bamboo bow beams to build structures with spans up to 7.3 m with a variety of roofs. These are expected to substantially enhance the performance capabilities of the structures even against asymmetric loads and still retain the cost effectiveness. The use of natural round bamboo for the bow beams in large span structures needs only a minimal processing while fully utilizing the natural structural advantage of round bamboo. The process is also compatible with conventional masonry. Use of bamboo opens up the way for carbon trading. Firstly it can save the steel required in traditional structures with trusses (or of RCC) and hence reduces $CO^2$ emissions. Secondly bamboo is an effective carbon sink as its timber matures in just less than 4 years (as against over 30 to 40 years in conventional timber) and can last for several decades when properly treated and used. Thus it is a rapidly renewable resource that has a unique potential of generating sustainable livelihoods when used for mass housing. It is hoped that the above pioneering efforts of Haritha Ecological Institute along with the expertise and facilities at NRFBT and Civil Engineering Department of IIT Delhi would go a long way in using bamboo as a modern engineering material for sustainable rural development.

ACKNOWLEDGEMENTS

This paper has been made possible by NRFBT, funded by HUDCO. The first author wishes to sincerely thank Dr. Ranga of Ranga Inc, USA, and Usha Rani for funding the initial constructions in 1994; Mr. Venkateswara Rao for technical and moral support initially and sponsoring some of the later constructions using bamboo bows with ferro-cement bands near Vijayawada and NMBA (TIFAC, DST of Government of India) for the financial support towards the engineering evaluation of the bamboo bow based constructions which led to the development of vertically separated twin arch bamboo bow beams with ferro-cement bands. HUDCO award 'Design Ideas Competition for building with Bamboo—2004' for this work was encouraging. The encouragement of Mr. D. Madhusudan Rao of Tenneru and K. Srinivasa Murthy of APTDC, Hyderabad has been a constant inspiration.

REFERENCES

Beukers, A. & Hinte, E.V. 2001. *Lightness—The inevitable renaissance of minimum energy structures*. 010 Publishers, Rotterdam.

Das, B.K. 2001. *Bamboo in the field of Construction in North East India*. Technical Paper No. 1, Cane & Bamboo Technology Centre, Guwahati.

Jayanetti, D.L. & Follett, P.R. 1998. *Bamboo in Construction An Introduction*. TRADA Technology Ltd, INBAR, No. 15. ISBN 1-900510-3-0.

Janssen, J.J.A. 2000. Designing and Building with Bamboo. *INBAR, No. 20.*

Gordon, J.E. 2003. *Structures or why things don't fall down*. Da Capo Press, ISBN 0-306-81283-5.

Jorge, A. Gutierrez. 2000. Structural Adequacy of bamboo Constructions in Latin America. *INBAR, No. 19*: pp. 91, 97.

NMBA. 2004. *Building with Bamboo a Training manual TM 01 02/04*. Published by NMBA (TIFAC, DST, GOI).

Oscar Hidalgo–Lopez. 2003. *Bamboo—The Gift of Gods*: pp. 206–418. ISBN 958-33-4298-X.

Sudhakar, P. 1995. *Haritha Villu*. Haritha Ecological Institute, Paloncha, Khammam district, A.P., India, (in Telugu)

Ranjan, M.P., Iyer, N. & Pnadya, G. 1986 & 2004. *Bamboo and Cane Crafts in Northeast India*. National Institute of Design, Ahmedabad, India.

SARMET. 1999. A review report and recommendations for Design upgradation. *International Network for Bamboo and Rattan (INBAR)*, Beijing, China.

Sudhakar, P. 2006. Engineering evaluation of Bamboo Bow Beams as Load Bearing Structures. *Project Completion Report NMBA*, TIFAC, DST, Govt. of India.

Vinoo Kaley. 2000. V*enu Bharati, A comprehensive volume on Bamboo*: p. 65. Published by Aproop Nirman, Nagpur.

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# Bamboo design workshop expressions with bamboo material

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ABSTRACT: In Japan, bamboo material was, and partly still is these days, very often used in landscape design projects, in world famous beautiful traditional Japanese gardens, in interior and architecture design projects. However, unfortunately these days the use of bamboo material as a building material has abruptly declined. Many reasons can be list up for the decline of the use of bamboo materials.

In 2002 and 2005, with the intention of rethinking the problems of bamboo as building material, two bamboo design workshops were organized by the NPO Kitakyushu Biotope Network Group (NPO, Non Profit Organization) in Kitakyushu (Japan). The main purpose of those workshops was finding new ways and methods for the use of bamboo as building material. The designs and proposals of the first workshop were mainly craft work objects and small art objects.

The second workshop, held from 3 to 6 November 2005, a four day long lasting design workshop, was called "Shelter 3 × 3 × 3". The aim of this design workshop was to plan and create small-scaled temporary architectural structures made of bamboo material. A total of 48 people, mostly students and local citizens, participated at the workshop. Divided in three groups, each group made one small-scaled bamboo structure which was constructed in the gardens at the campus of the University of Kitakyushu. The first day of the workshop, bamboo material had been taken and collected from the nearby bamboo forests. During the second and third day, construction methods for bamboo material had been investigated and finally three different types of construction methods have been applied. The three structures were planned to be temporarily, but one of the structures was built so strong that it still is on site these days.

In this report, both workshops as well as the three demonstration structures of the second design workshop will be explained more in detail.

## 1 THE FIRST BAMBOO DESIGN WORKSHOP

### 1.1 *Program of the first bamboo design workshop*

The four day long lasting first bamboo design workshop was held during summer holidays from 19 until 22 August, 2002. The number of participants was 48, mostly students but also several local elderly citizens. The workshop was organized by the Kitakyushu Biotope Network Group, and took place at the University of Kitakyushu, in the Kitakyushu Science and Research Park, city of Kitakyushu (Japan). The program of the workshop is shown in table 1. This workshop was one of the first activities organized by the Kitakyushu Biotope Network Group related to bamboo forest preservation, with the aim to make people aware of the problems bamboo forests are facing, because it seemed that these problems are not well known among students and local citizens. The second aim was to find new ways for the use of bamboo material. During the first day of the workshop, the problems bamboo forests are facing were explained. Then afterwards, two visits had been brought to bamboo forests. The first bamboo forest was a not maintained bamboo forest near the campus of the university; the second visit was to the Ouma Bamboo Forest Park in

Kitakyushu. The Ouma area is very famous in Japan for its bamboo sprouts. In the Ouma Park, a large collection of different kinds of bamboo is planted and the adjacent bamboo forest is a good example of a well maintained bamboo forest.

### 1.2 *Preparation of the bamboo material*

At the first day of the workshop, bamboo material was collected from a bamboo forest near the campus. The used bamboo was Moso bamboo (Phyllostachys edulis), as is shown in picture 1. For reasons of security, all the bamboo was cut manual by a normal bamboo saw; we did not make use of any kind of electric driven saws.

The bamboo was used in different ways; some bamboo was split and bended. Some examples of the craft works are shown in picture 2. The crafts were made in group or individual.

After the workshop, all the craft works were exhibited for about one month.

Table 1. Program of the first bamboo design workshop.

| | |
|---|---|
| Monday 19 August, 2002 | FIRST DAY OF THE BAMBOO DESIGN WORKSHOP |
| 9:30 – 9:40 | Welcome and opening speech |
| 9:40 – 10:30 | Explanation of the workshop, its aim and schedule |
| 10:30 – 10:45 | Formation of groups (individual or group work) |
| 10:45 – 12:00 | Visit of a not maintained bamboo forest |
| 12:00 – 13:30 | Lunch time |
| 13:30 – 18:00 | Visit of the Ouma Bamboo Forest Park |
| 18:00 – 21:00 | Welcome party |
| Tuesday 20 August, 2002 | SECOND DAY OF THE BAMBOO DESIGN WORKSHOP |
| 9:00 – 12:30 | Cutting and preparing of the bamboo material |
| 12:30 – 13:30 | Lunch time |
| 13:30 – 18:00 | Craft Workshop |
| 18:00 – 20:00 | Lecture |
| Wednesday 21 august, 2002 | THIRD DAY OF THE BAMBOO DESIGN WORKSHOP |
| 9:00 – 12:30 | Morning Craft Workshop |
| 12:30 – 13:30 | Lunch time |
| 13:30 – 18:00 | Afternoon Craft Workshop |
| Thursday 22 August, 2002 | FOURTH AND LAST DAY OF THE BAMBOO DESIGN WORKSHOP |
| 9:30 – 12:00 | Installation of the bamboo craft works |
| 12:00 – 13:30 | Lunch time |
| 13:30 – 17:30 | Presentation of the bamboo craft works |
| 17:30 – 19:30 | Farewell party |

Picture 1. Preparation of bamboo material.

Picture 2. Some of the craft works.

## 2 THE SECOND BAMBOO DESIGN WORKSHOP

### 2.1 *Program of the second bamboo design workshop*

Three years after the first bamboo design workshop, a second bamboo design workshop was organized. This workshop was held from 3 until 6 November, 2005. Unexpectedly, the number of participants was also 48, exactly the same as the first workshop. Also this workshop took place at the campus of the University of Kitakyushu, Kitakyushu Science and Research Park, Kitakyushu (Japan). The program of the workshop is shown in table 2.

Table 2. Program of the second bamboo design workshop.

| | |
|---|---|
| Thursday 3 November, 2005 | FIRST DAY OF THE BAMBOO DESIGN WORKSHOP |
| 10:00 – 10:10 | Welcome and opening speech |
| 10:10 – 10:45 | Explanation of the workshop and schedule |
| 10:45 – 11:30 | Self-introduction of all participants and staff |
| 11:30 – 12:00 | Formation of three groups |
| 12:00 – 13:30 | Lunch time |
| 13:30 – 16:30 | Collecting of bamboo material |
| 16:30 – 17:00 | Free time |
| 17:00 – 20:30 | Bamboo lantern installation, welcome party |
| Friday 4 November, 2005 | SECOND DAY OF THE BAMBOO DESIGN WORKSHOP |
| 9:30 – 12:00 | Design workshop 1 |
| 12:00 – 13:30 | Lunch time |
| 13:30 – 18:00 | Design workshop 2 |
| 18:00 – 19:30 | Dinner time |
| 19:30 – 21:00 | Design workshop 3 |
| Saturday 5 November, 2005 | THIRD DAY OF THE BAMBOO DESIGN WORKSHOP |
| 9:30 – 12:00 | Design workshop 4 |
| 12:00 – 13:30 | Lunch time |
| 13:30 – 17:30 | Design workshop 5 |
| 17:30 – 18:30 | Free time |
| 18:30 – 21:00 | Exchange party |
| Sunday 6 November, 2005 | LAST DAY OF THE BAMBOO DESIGN WORKSHOP |
| 9:45 – 12:00 | Installation of the bamboo shelter |
| 12:00 – 13:00 | Lunch time |
| 13:00 – 15:00 | Lecture, Architect Hirofumi Sugimoto (Professor at the Tokaido University, Japan) |
| 15:00 – 17:00 | Presentation of the bamboo shelters |

2.2 *Shelter 3 × 3 × 3*

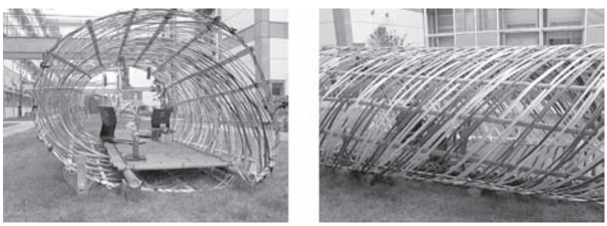
The participants at the workshop were divided into three groups, each group made one bamboo structure, which in this report are named as shelter 1, shelter 2 and shelter 3.

2.2.1 *Shelter 1*

The bamboo used in shelter 1 was split bamboo, which then was bended into a round small-scaled structure as can be seen in picture 3. The finished structure is shown in picture 4. Figure 1 and 2 show the elevations and plan of shelter 1.

As can be seen in picture 4, there was a small bamboo floor made as well. The floor and the structure of the shelter were not connected to each other. The floor was supported by four short pillars made of bamboo; the floor itself was made of bamboo which was split in two. Only rope was used for the floor. The surrounding round structure was knit by split bamboo. Only the end parts were fixed with rope. Because the structure was very light and not fixed to the ground, each time a strong wind passed, the structure rolled away. Later on, small steel bars were placed to connect the structure with the ground.

Picture 3. Construction process of shelter 1.



Picture 4. Shelter 1.

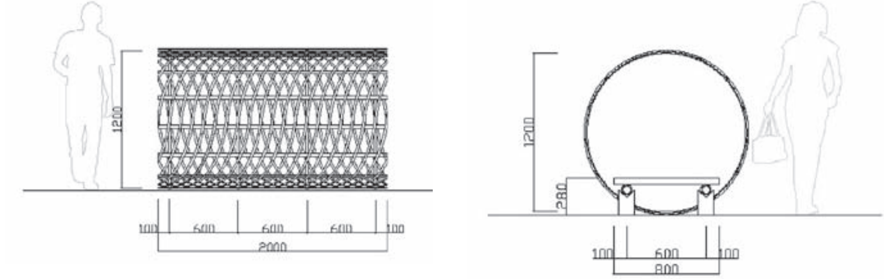



Figure 1. Elevations of shelter 1.

2.2.2 *Shelter 2*

The idea behind the structure of shelter 2 was using the bamboo material as much as possible without splitting or bending the bamboo, and to assemble the vertical placed bamboo wall with only one rope. Partly, the shelter did have a bamboo floor and roof. The curved wall was assembled as one element; all the bamboos of the wall were connected to each other by only one rope. It is difficult to see on the pictures where the rope was used, in all the bamboos were made three holes; one at both ends and one in the middle. One long rope was knit through these holes. To let the bamboo wall stand by itself, the wall had to be curved as is shown in picture 5. The triangle shaped roof on top was not planned in the original concept but was add after the wall was finished. Three columns were used to support the roof. Split bamboo was used for the roof to keep the construction as light as possible. The wall was very strong and stable in contrast with the columns supporting the roof; they were very unstable and short after the workshop finished, due to a strong wind the roof felt down. Picture 6 shows the finished shelter 2. The elevations and floor plan of this shelter are shown in figure 3 and 4.

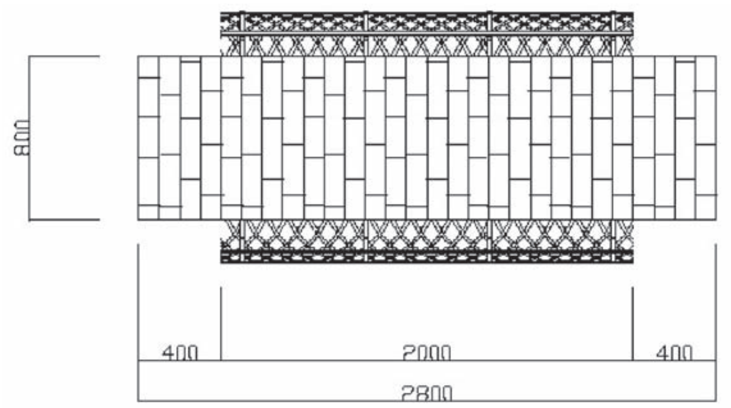
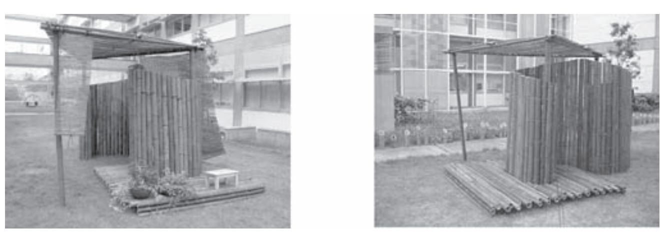



Figure 2. Floor plan of shelter 1.

Picture 5. Construction process of shelter 2.



Picture 6. Shelter 2.

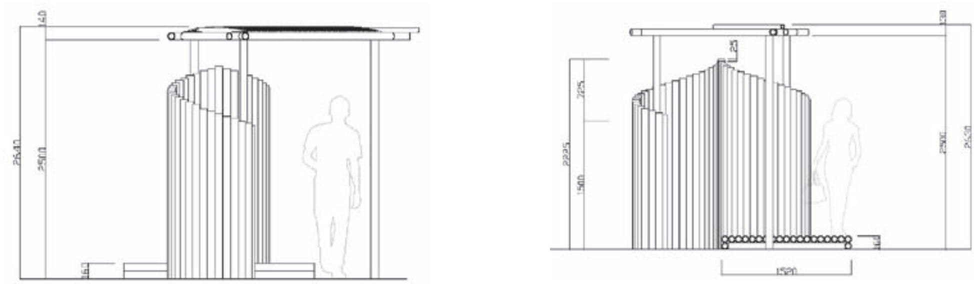


Figure 3. Elevations of shelter 2.

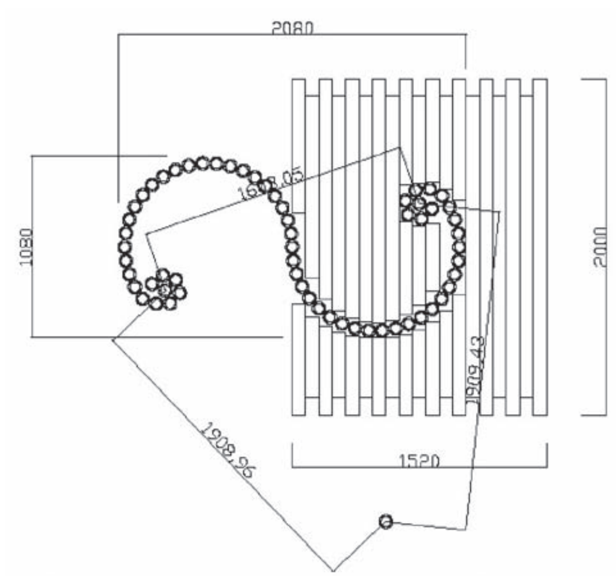



Figure 4. Floor plan of shelter 2.

### 2.2.3 *Shelter 3*

Shelter 3 was the biggest and strongest among the three shelters. 13 bamboo columns were used to construct the different walls. Wooden stakes of about 60 cm were driven into the ground for about 35 cm. The bamboo columns were placed over these wooden stakes. The two front walls of the shelter were flat and the back wall was curved as is shown in figure 5. All the walls were made of split bamboo.

In the case of the flat walls; the split bamboo was fixed with screws to the vertical columns. In the curved wall; the split bamboo was knit between the columns. For the curved wall it was not necessary to use screws because knitting made the structure stable enough.

There was no roof planned for this shelter. Behind the curved wall of the shelter is a floor which was made out of split bamboo and was put directly on the grass as is shown in picture 8 (right picture). Normally, it is not recommend putting the bamboo direct on the grass, but usually there is kept some distance for ventilation. But two years after the shelter is finished the floor is not yet rotten at all. Picture 7 shows the shelter under its construction process. The figures 5 and 6 show the floor plan and elevations.

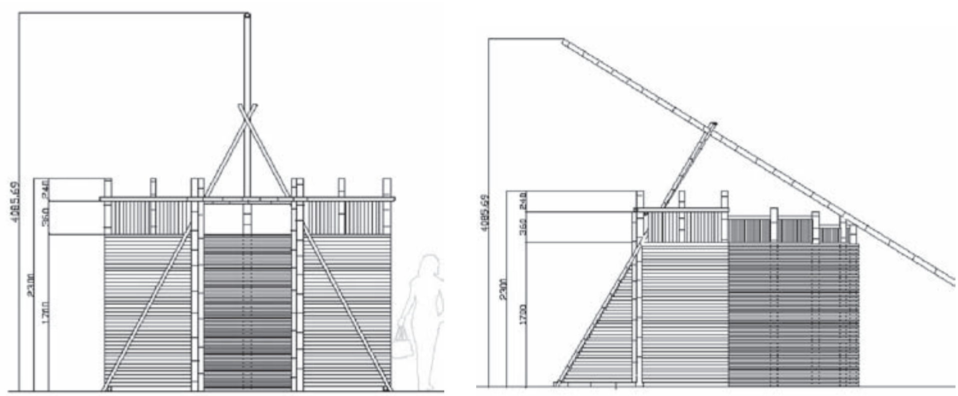


Figure 5.  Elevations of shelter 3.

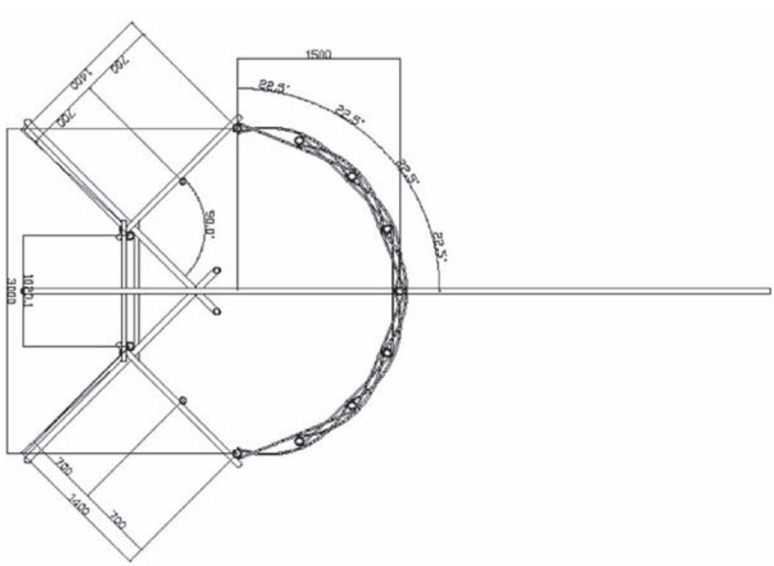



Figure 6.  Floor plan of shelter 3.

Picture 7.  Construction process of shelter 3.

Picture 8. Shelter 3.

## 3 CONCLUSION

In this report, with the aim of finding new ways for the use of bamboo material, two bamboo design workshop are explained.

The design works of the first workshop were craft works; in the second workshop three small-scaled structures were built. It is hard to say that new building methods for building with bamboo material were developed, but without any knowledge of building with bamboo, the participants found simple ways in which the structure could be built in a short time. Even if the three teams worked side by side, they used three different building methods.

These workshops have shown that building small structures with bamboo can be erect in a very short time, even by non-professionals. If some care is taken for the construction of the walls, and the structures are fixed to the ground, it is proven that bamboo structures can last long even without treatment of the bamboo material. In future workshops, we would like to spend more time to develop structures and building methods made of bamboo which are easy to build, easy to dismantle and rebuild, and which do have a long life span. Of course such kind of structures should be easily to build by also non-professionals and they could be used in case of emergency as temporary shelters.

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# Investigating laminated bamboo lumber as an alternate to wood lumber in residential construction in the United States

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## 1 INTRODUCTION

Energy awareness at the beginning of the 21st century has caught the attention of people all around the world. Fossil fuel is simply running out. This will contribute to energy shortage and difficulty in supplying global industries. Government officials in many countries have brought much attention to this issue. Energy substitutes have been studied to prolong humanity. The words Green and Sustainability have become commonly used in world business. In Architecture, sustainability is becoming a design norm. In the United States, projects are finally beginning to incorporate healthier methods to improve building and preserve resources. Sustainability plays a major role in architectural research to improve building technology and energy use to conform to the high standards of environmental friendliness. One subject of architectural research is the search for new materials. The goals are many; to be lighter and stronger, to be efficient, to be cheaper, to be all of these things. How can we use minimal natural resources and receive the highest performance? Bamboo is potentially an answer to that question. In its raw form, Bamboo has proven itself for thousands of years as a viable structural material. Bamboo is light. Its strength allows for less material use in building. We have not taken full advantage of this material. Utilizing today's technology to improve the way we use bamboo as a building material is a way to begin to adopt it into our sustainable way of living.

This paper investigates the viability of engineered bamboo as an alternative structural material. It takes a different approach from conventional raw bamboo structures. This study is particularly focused on Laminated Bamboo Lumber or LBL, which is one type of manufactured bamboo. It is designed by transforming raw bamboo into an industrialized and standardized product. LBL is used for many products, especially flooring, furniture, and other building finishes. Currently, there is no evidence of the use of LBL as structure commercially in the U.S. LBL is comparable to wood lumber, appropriate in smaller scale structures, such as residential construction. The residential construction industry in the U.S. is a billion-dollar business, which makes it a good place to start and set an example. The investigation is delivered via the comparison of structural properties of LBL to typical wood lumber, conforming to building codes as a structural material, cost issues, and other related advantages, like LEED certification. At the end, the outcome is aimed to promote the use of LBL not only to be a structural material globally, but an environmental friendly material as well. Firstly, it is important to understand bamboo's use leading to the creation of LBL.

## 2 BAMBOO DEVELOPMENT

Bamboo's utilization has been well demonstrated from past to present in vernacular and traditional architecture. The world has stepped into the 21st century, the era of rapidly developing new technology. Architecture and Construction has changed greatly due to the new technological progression. In the design and development of bamboo structures, most research tends toward the use of bamboo in the traditional, raw form, including studies of bamboo connections and bamboo truss-frames. Figure 1 shows one good example of the research pertaining to raw bamboo, bundling

Figure 1. Research of utilizing bamboo in raw-form by developing bamboo bundling connections for stronger structural properties.

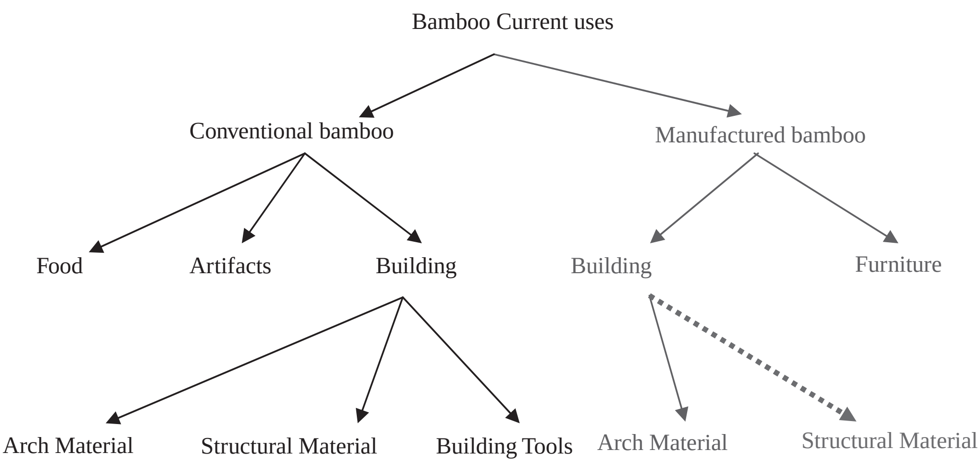


Figure 2. Diagram shows the hierarchy and relationship of current uses in bamboo products.

connections for stronger structural properties. The interest in bamboo's raw form is coming from the demand of usage, especially in many developing countries. Its abundance makes bamboo easily available and affordable. It is used for food, basketry, and mostly in construction. The demand is also high in the need for shelters, and still keeps rising. This may explain why many research and projects are in the direction of raw form. Truly, this conventional method of using bamboo is still valuable. However, there should be many more creative ways to utilize this versatile material using today's advanced technology.

If we look globally at bamboo usage, there are two major directions, see Figure 2. The most used one is the conventional way, which is in raw form. Raw bamboo is very utilitarian and made into many things from food to building materials. The down side is that raw bamboo is hard to standardize due to its irregular dimensions. Raw bamboo is also susceptible to splitting due to dryness. Splitting changes the bamboo's geometry, which results in lowering the structural capacity. The other type is manufactured bamboo. This method splits the bamboo before it splits itself,

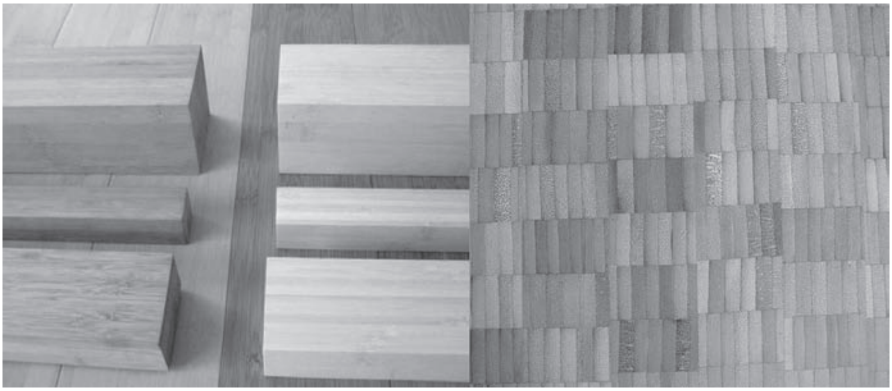

Figure 3. (left) Laminated Bamboo Lumber from one of the manufacturers in China and shipped to the US for many building finishing products (image courtesy of 4windsbamboo.com); (right) close up look of the bamboo lumber section that is a makeup of many strips laminated together.

and puts it back together. It may also involve the breaking down bamboo into fiber elements. It is transformed and engineered into new geometry as required by the specific application, having a completely different appearance from raw bamboo. Products include bamboo lumber, bamboo ply wood, bamboo board, bamboo plank, bamboo mat, and bamboo linens. Manufactured bamboos are increasing in use and popularity in the U.S. The most popular is for flooring. The trend seems to be not only for its wood-like looks and workability, but also to follow the eco-friendly trend.

However, underutilized is the great structural capacity of bamboo. Research addressing manufactured bamboo has dealt with improving its structural properties, manufacturing process, and use of different species. Many of them are still ongoing and under development. Referring to Figure 2, this study is trying to expand the development of manufactured bamboo as a structural material in building.

## 3 LAMINATED BAMBOO LUMBER (LBL)

Of all the types of manufactured bamboo, laminated Bamboo lumber has the most potential, due to its solidity and flexible geometry. LBL is made of a series of bamboo strips laminated together in layers, see Figure 3. It is laminated with LFM Resin with high bonding strength. The density is a bit heavier than normal wood, which is about 720–780 kg/m$^3$, which is almost the same as oak. Oak is known as a hard wood that is commonly used in the U.S. Because it is made of many tiny strips, it can be designed into many sectional geometries as required by structural applications. Figure 4 demonstrates how raw bamboo is transformed into LBL.

LBL is comparable to other wood products, like glue-laminated beams and trusses. Still, LBL has problems just like other wood products. It has to be treated for fire and insects. Two major keys to produce high quality LBL are culm diameter and thickness. They are controlling sizes of bamboo strips. LBL is also comparable to engineered wood products like Glue-laminated lumber and Laminated Veneer Lumber (LVL). Glue-laminated lumber and LVL are other types of engineered woods with similar manufacturing processes to LBL. LVL is more similar in appearance to LBL than Glue-laminated lumber because LVL uses a thin layering process. Glue-laminated lumber is made of small wood sections that in comparison to LBL are much larger than the bamboo strips. Due to its large section, Glue-laminated lumber can be produced to any large custom designed structural section, which can provide greater span. While LBL may be more appropriate for smaller scale, shorter span situations. Since they both are engineered products, the goal is to

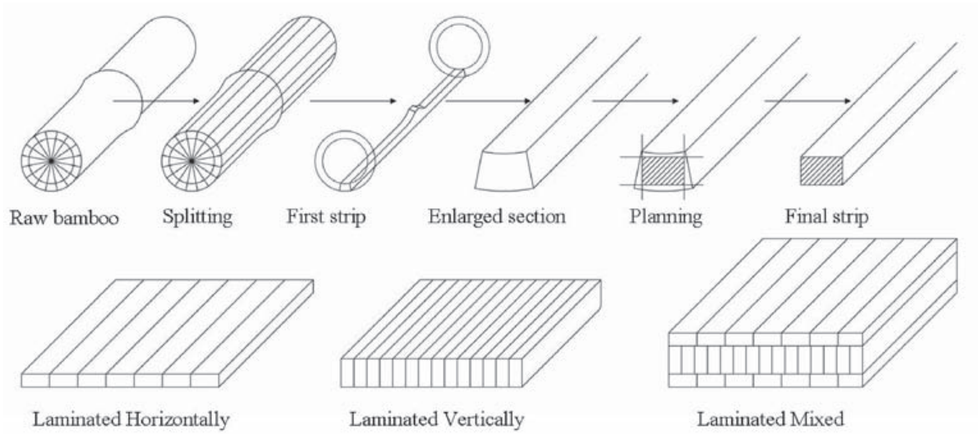


Figure 4. Simple diagram shows manufacturing process of Laminated Bamboo Lumber from harvesting bamboo to finish product.

improve the structural ability, and they do. However, in aspects of eco-friendliness, LBL presents its advantage over the others by being made of a rapidly renewable material.

LBL currently is produced where bamboo forest is abundant, mostly in Asian countries such as China, India, and Vietnam. It is still under the development for advancement in terms of better properties and other applications. Moreover, the production is still limited in size and section. LBL sections are determined by obtained bamboo species. Different species have different culm diameters and wall thicknesses. These make LBL dimensions varied and custom made for specific uses.

LBL in the U.S. is used in flooring and countertops, molding, stair treads, and railings. These products have demonstrated applications that are close to human contact, so clearly they are safe enough to be used in human environment. However, these products do not demonstrate the true structural capacity. To adapt this material for structures used in the U.S., it is important to compare the structural applications of wood timber and LBL.

## 4 STRUCTURAL FEASIBILITY

Bamboo undoubtedly has superior structural qualities as used in the past for many vernacular residential projects, as well as contemporary designs by famous bamboo architects, like Simon Velez or Jorg Stamm. Many of their structures are made of raw bamboo. As shown in Table 1, the structural properties of raw bamboo (bamboo pole) demonstrate its lightness compared to timber with one and a half times the strength. The ratio of strength over density of bamboo pole, indicating material efficiency, is 2.5 times higher than wood and 3 times of steel. This shows how bamboo is extremely efficient because it has lightness with high strength. LBL's modulus of Elasticity or the stiffness is almost one tenth that of structural steel and 1.5 times that of timber.

In residential construction, wood framing is commonly used due to its workability. Because there are many wood species used in the U.S., it is important to understand their properties and compare them with LBL as well. There are two major types of wood species used for commercial construction in North America, Conifers and Angiosperms. Conifers are a type of wood that produces cones. They are a softwood material used for lower grade framing, trim, or molding. Some of their common names are Pine, Fir, Spruce, Cedar, Redwood, and Cypress. Angiosperms are a type of harder wood that are used for structural framing and cabinetry. Commonly used are Oak, Maple, Walnut, Ash, and Birch. This last type is one that has property that LBL can match.

Table 1. Comparison table of structural properties among other structural materials.

| Building Materials | Density p/cf | Modulus of elasticity | | Yield strength | | Ultimate strength | | Strength over density 1/ft. |
|---|---|---|---|---|---|---|---|---|
| | | ksi | Mpa | psi | Mpa | psi | Mpa | |
| Carbon fiber | 110 | 21,800 | 150,305 | n/a | n/a | 819,463 | 5,650 | 1,072,752 |
| Structural steel | 490 | 29,000 | 200,000 | 36,260 | 250 | 58,000 | 400 | 17,045 |
| Aluminum alloy | 170 | 10,000 | 68,947 | 26,106 | 180 | 29,000 | 200 | 24,565 |
| Cast iron | 435 | 27,500 | 190,000 | n/a | n/a | 29,000 | 200 | 9,600 |
| *Bamboo pole* | *25* | *2,694* | *18,575** | *n/a* | *n/a* | *8,700* | *60** | *50,112* |
| Timber | 40 | 1,600 | 11,000 | n/a | n/a | 5,800 | 40 | 20,880 |
| Concrete | 150 | 3,000 | 20,684 | n/a | n/a | 435 | 3 | 418 |

* Janssen, 1991

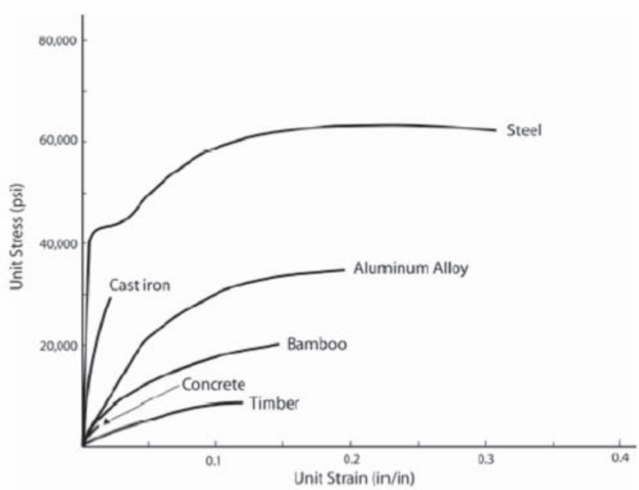


Figure 5. Comparison stress/strain diagram of different structural materials (left); Relationship of ultimate and allowable tensile stress of bamboo in stress/strain diagram (right).

LBL is the reassembly of bamboo back together to produce solid lumber. This obviously makes the density higher, even more than timber, as seen in Table 2. The compressive strength parallel to grain is 50–60% higher than regular commercial hardwood species. Looking back to the density of LBL that is twice of raw bamboo, the strength increases almost 1.5 times.

The improvement of structural property has affected directly to the designing of structures. Member sizing depends on loads which produce moment. Bending moment (*M*) is also proportional to bending stress (*fc*) of the material, see Figure 6. If bending stress of material increases, the ability to receive bending moment also increases. This will increase ability for the same structural section to receive more loads, which will lead to increase in tributary area (*A*) received. LBL has approximately 50% higher compressive stress than in typical wood lumber, so it makes the area greater. If having the same span (*L*) and structural section, and the area increases by 1.5 times, the interval dimension will increase by 1.5 times as well. For a typical floor framing of $d1 = 24$ inches (0.60 m) on center, using LBL can increase to $d2 = 36$ inches (0.9 m) on center, which eventually yields less material, lighter structure and potential cost savings. LBL is determined to be a great

Table 2. Comparison table of structural properties of LBL among other commercial lumber species.

| | Density | Modulus of elasticity | | Compressive strength* | |
|---|---|---|---|---|---|
| Commercial lumber | pcf | ksi | Mpa | psi | Mpa |
| Ash | 41 | 1,740 | 12,000 | 7,411 | 51.1 |
| Birch | 41 | 2,016 | 13,900 | 8,166 | 56.3 |
| Douglas fir | 32 | 1,827 | 12,600 | 7,426 | 51.2 |
| Elm | 37 | 1,537 | 10,600 | 7,049 | 48.6 |
| Maple | 46 | 1,827 | 12,600 | 7,832 | 54.0 |
| Oak | 36–57 | 2,045 | 14,100 | 8,601 | 59.3 |
| *LBL (Horizontal)* | *49* | *2,509* | *17,300* | *12,750* | *87.9*** |
| *LBL (Vertical)* | *47* | *2,403* | *16,570* | *12,280* | *84.7*** |

* parallel to grain

** Bansal and Prasad, 2004

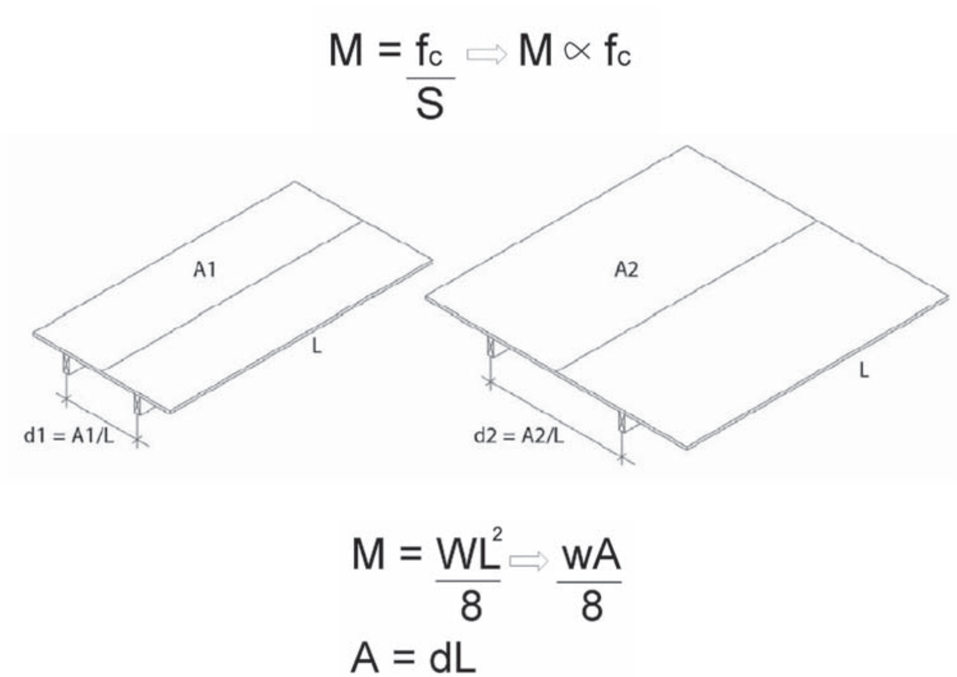


Figure 6. Comparison table of structural properties of LBL among other commercial wood species.

structural performer. Then, where it will be applied is the next step to look at. It is important to understand the current use in residential framing before a recommendation is made.

## 5 TYPICAL FRAMING IN THE U.S.

There are two common types of residential framing in the US: Balloon Framing and Platform Framing. Balloon framing was very popular in the 19th century, and later was replaced by Platform framing. Balloon framing in North American was believed to have originated in Chicago and spread throughout the country. In early 19th century when timber was abundant, cities were growing, and housing was in need. Residential construction was extremely uprising by using cut timber. After Augustine Taylor introduced Balloon framing, a lighter frame construction using 2x timber, it became a common method of building houses in the U.S., typically two-story buildings with brick veneer. An easy way to distinguish Balloon framing is the continuous vertical studs, which extend from the bottom of the sill plate on the foundation to the top of the roof rafter (see Figure 7). One of the major disadvantages of this type of construction is that fire can spread so quickly from lower floors to the roof. This is also one of the reasons why the Chicago fire of 1871 spread so quickly and covered a large amount of the city. Other disadvantages of using long continuous members are significant wood shrinkage, and high working platform requirements.

Platform framing construction was created to replace balloon framing, which is simply the division of framing for each floor of a building. It only requires member length per floor and has the potential to keep fire from spreading due to interruption in members from floor to floor. This is still a common method used today. The floor, wall, and roof framing consists of dimensional lumber (2x — read "two by"). They are 2 × 4, 2 × 6, 2 × 8, 2 × 10, and 2 × 12, depending on the span or height of wall. They are typical 12", 16", or 24" on center. A 2 × 4 's real dimensions are 1.5" × 3.5". Timber is cut to actual size of 2 × 4 as a rough sawn timber. After they are planed and re-surfaced, the dimensions are decreased by 0.5" in both directions. People still call it 2 × 4 for ease, and all design professionals and builders are aware of these typical nominal dimensions in wood framing. Later, as technology developed, floor joists were made of engineered beams or trussed frames for longer spans or accommodating mechanical systems.

Typical sizes of wood lumber and applications used in residential construction are:

Exterior wall framing — load bearing — 2 × 6, 2 × 8, 2 × 10
Exterior wall framing — non load bearing — 2 × 4, 2 × 6
Interior wall & partition — 2 × 4
Floor Joist — 2 × 6, 2 × 8, 2 × 10
Structural beam — 2 × 6, 2 × 8, 2 × 10, 2 × 12
Column — 3 × 3, 4 × 4, 5 × 5, 6 × 6
Roof framing — 2 × 10, 2 × 12, trussed frame (2 × 8)

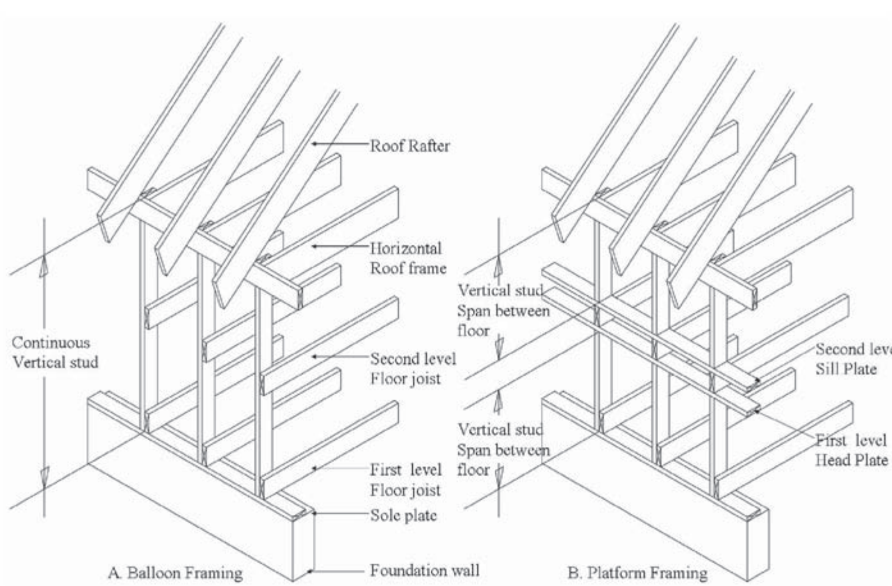


Figure 7. Comparison diagram of two different residential framing systems, Balloon and Platform Framing.

Typical sizes of LBL and their applications are:

LBL is currently produced in dimensions as required per application.
LBL Stair treads are $2 \times 12$, with a length of 4' or 6'.
LBL moldings are ½" or 5/8" thick × 3", 4" or 6", and can be as long as 92".
LBL planks to produce countertops are made 12" wide × 2" thick, and 4' to 6' long.
Bamboo flooring has a thickness of 5/8", a width of 5 to 6", and a length of 6'.
Small posts are 3" × 3", 42" or 48" long.
Railings are 1.5" × 2.6", with length ranging from 42" to 90".

Figure 8 is the summary of typical lumber sections that are commonly used in relations of width depth, and length. The height of bars indicates the maximum produced length. Wood lumbers are used in increment of 2 inches (5 cm). Rectangular sections that are used for floor and wall framing are $2 \times 4$ to $2 \times 12$. Lumbers are produced longer, if depths increase. Square shapes are used for column. Wood lumber dimensions are predictable as shaded in gray area. On the other hand, there are no dimension criteria to produce them. Dimensions were created based on what they are used for. Thin LBL are used for molding, while bigger geometry is related to structural uses. The sectional dimensions of LBL are still scattered in the chart, as shaded in black. Moreover, it is easily observed that LBL are not produced as long as wood lumber.

Since LBL is made of tiny bamboo strip sections, it is possible to produce any size and perhaps match typical dimensions used in the U.S. LBL can be produced in any length by using the same technology as Glue laminated beams, however splicing of smaller pieces will occur. Manufacturers typically cut strips at a length of 8 feet (2.4 m) or less, due to the fact that dimensions of raw bamboo change throughout the culm. It is suggested to have uniform strips throughout the length of the resulting structural member. Therefore, structural members that are 8 feet (2.4 m) or less will have lumber with continuous, unspliced strips, providing greater structural capacity.

Connecting frames together is another issue to discuss. Wood lumber is connected in one of three ways depending on loading capacity. The first is nailing and screwing, the second, nuts and bolts, and the third, nail plates. The members can receive more loads from nailing, bolting, and

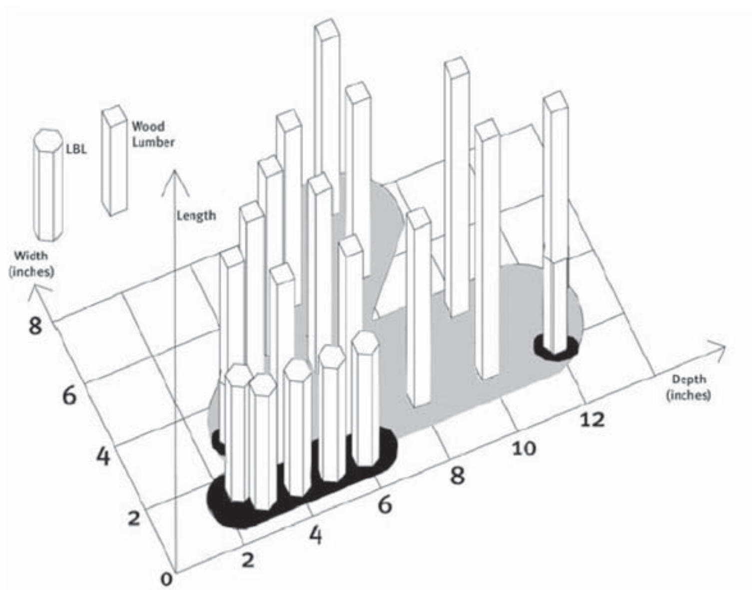


Figure 8. Diagram summaries the produced section of wood lumber and LBL.

nail plate, respectively. LBL can be put together the same way; however it is more vulnerable to splitting. Nailing with a hammer will promote separation, while a pressure gun may not. Bolting requiring pre-drilling should not do any harm to the member. Nail plates provide large contact area, and if the LBL separates or splits, it is still held together since the steel plate adds more shear resistance. Comparing screw withdrawal strength, LBL is a little higher than timber (Bansal and Prasad, 2004). This is explains by the fact that LBL has a bit more density that timber. LBL is produced with control over its moisture content, just like wood. At the end of the process, they are dried to 8–10% moisture content (MC), while wood should not exceed 16%. Having a low MC and higher density should provide the material with a low shrinkage rate, making material dimensions very stable, allowing little or no movement to the connectors.

The above reasons suggest that LBL can be an alternative to typical wood lumber. Other issues to discuss are code compliance and cost. They are practical matters that should be seriously taken into consideration.

## 6 CODES

This study takes serious look at how LBL can be integrated into the market. It is realistic to look into codes and regulations. Hopefully, this paper can contribute significantly as source of information for Building code officials and future codes to accommodate bamboo. Building codes are laws in the U.S dealing with the safety of the human environment. LBL usage is the same as wood lumber, so it should deal with similar codes. They mostly involve fire, insects, and earthquake. LBL is considered to be a combustible material, like wood. Restrictions will apply as they do to wood. They will be classified in construction types that are made of combustible materials, based on the International Building Codes (IBC). Type III and IV, treated wood framing is allowed if exterior wall assemblies have 2-hour rating. Materials simply have to be treated before use. The purposes of treatment are mostly to protect from insects or termites and to be fire retardant. Based on manufacturing bamboo in Vietnam, before processing raw bamboo to any products, poles are vacuum pressured with Borates or Boric acid to protect from termites and fungus, which is also used in timber. Boric acid may be considered to be friendly to humans. It is even found in some everyday products, like eye wash solution. Pressure treatment is a way to help the chemical solution penetrate deep inside the material.

In terms of fire, besides complying with fire protected environment for wood and bamboo as required by code, there are many products offered in the market for fire retardance. They are solutions that require surface application, and have passed ASTM E-84, standard test method for surface burning characteristic for building materials. It is proven that they can improve the flame spread rating.

When dealing with earthquakes, Bamboo seems to have a small advantage over timber. Witnessing its nature of being tall and skinny bamboo shows its ability to withstand wind and other lateral movement. There is more supporting evidence, as seen in bamboo houses that remain unharmed during an earthquake in Central America in the early 1990s. Those houses are made from raw bamboo. However, it is not appropriate to compare raw bamboo with LBL, since LBL has been transformed into something different. Comparing LBL with other wood framing seems more appropriate. Table 2 shows that LBL has 1.5 times more stiffness than wood lumber by comparing their Modulus of Elasticity. If LBL is used in same way as wood, LBL will provide extra protection of earthquake movement.

## 7 COST

Wood lumber in the U.S. is sold by either volume or length for large volume purchases and by piece for retail purchases. Prices vary with different species, treatment, and length. Lengths commonly range from 8 feet (2.43 m) to 16 feet (3.6 m). Longer pieces cost more as well as deeper sections.

For small scale projects, wood lumber is considered an affordable material. A treated $2 \times 4$, 10-foot piece is equivalent in cost to a large café latte, while Glue laminated of the same section cost 2.5 times more. Obtaining pricing directly from one of the manufacturers in China, the cost of LBL was estimated based on one fixed unit price per volume. After extensive data gathering and calculation, LBL seems to be 4 times more expensive than wood lumber, and 1.6 times more expensive than Glue Laminated Lumber. The shipping cost is additional and varies. Obviously, products form oversea cost more to ship. Most LBL products are produced in China, India, and Vietnam. Some manufacturers offer more product variation but they do not have representatives in the U.S., so consumers will have to pay extra for shipping from overseas. With the high cost comes a high quality selection of bamboo. Bamboo flooring, which uses another form of lamination, costs much less than LBL and is comparable to its wood counterpart. One of reasons is because bamboo flooring is manufactured for beauty as a primary goal, while LBL is manufactured for strength. Strips cut for use in structural LBL have to be more carefully selected, while for bamboo flooring, the strip length is not as critical. That makes bamboo flooring more affordable than structural LBL.

In cost conclusion, even though LBL cost 4 times more than wood, the quantity of structural framing needed can be 1.5 times less based on its structural property. This quantity savings acts to counter balance higher price. Moreover, the purpose of this study is also to promote the popularity of the material, allowing it to be locally grown and manufactured, which is another factor to bring the cost down. An advantage to Bamboo is that it can be grown in most parts of the world.

## 8 BAMBOO AND LEED

Another goal in promoting LBL usage is about its sustainability. LEED is a standard system used in the U.S. to measure of the sustainable side of a project. LEED is Leadership in Energy and Environmental Design. Its Green Building Rating System is a voluntary, consensus-based national standard for developing high-performance, sustainable buildings, founded by the U.S. Green Building Council (USGBC). LEED has become very popular among design professionals in the U.S. It provides a set of standards for assessing building performance and meeting sustainability goals. LEED promotes the achievement and expertise in green building by offering certification for architectural projects and design professionals. For certification, LEED addresses six major strategies:

1. Sustainable Sites (SS)
2. Water Efficiency (WS)
3. Energy & Atmosphere (EA)
4. Materials & Resources (ME)
5. Indoor Environmental Quality (EQ)
6. Innovation in Design (ID)

The compliance of project due to each guideline will be provided with credits or points. LEED certified building is not mandatory like building code, but LEED certification can help promote the projects in respect of friendly environmental concern to our world. The ratings of credit are awarded as follow:

| | |
|---|---|
| Certified | 26–32 points |
| Silver | 33–38 points |
| Gold | 39–51 points |
| Platinum | 52–69 points |

Based on LEED-NC (new construction) Version 2.2, October 2005, the use of LBL is evaluated for credits in two potential categories: Material & Resources (MR) and Indoor Environmental Quality (EQ). A project can gain total of 5 points towards LEED certification, with 26 points

Table 3. Summary of LEED credit earned if using LBL in projects.

| LEED category | | Points |
|---|---|---|
| Material & Resources (MR) | | |
| MR 5.1 | Regional materials, 10% | 1 |
| MR 5.2 | Regional materials, 20% | 1 |
| MR 6 | Rapidly renewable materials | 1 |
| MR 7 | Certified wood | 1 |
| Indoor Environmental Quality (EQ) | | |
| EQ 4.4 | Low-emitting materials | 1 |
| Total | | 5 |

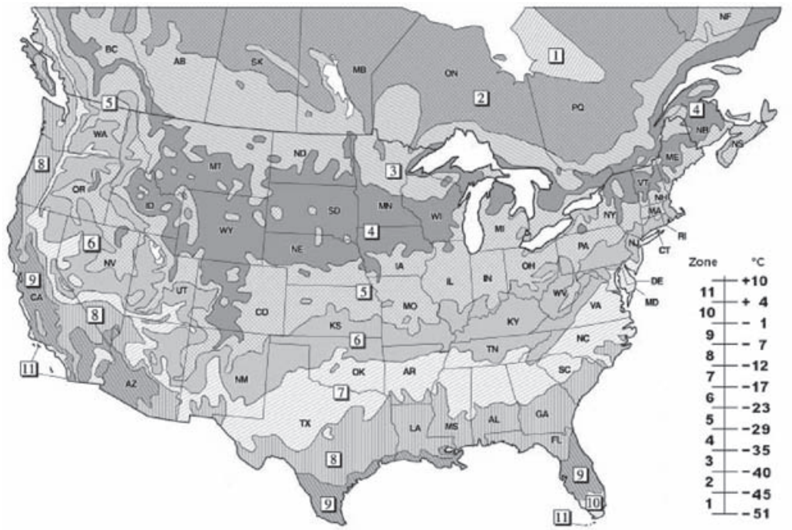


Figure 9. USDA zoning map indicates average minimum temperature zones from cold in zone 1 to warmer with higher zone number.

being the minimum needed for certification. LBL already contributes almost one fifth of total required points (see Table 3).

MR 5.1 and 2 are applicable if bamboo is planted and harvested within the U.S., it will become a local material that reduces the environmental impacts from shipping and transporting materials. Bamboo has been known as an invasive plant growing the U.S. The fast growing, running-culm bamboo is hard to maintain its boundary. For bamboo garden in people's home, they are mostly removed due to its fast-growing and property invasion. This may not be an issue for plantation concern. However, in commercial levels, there have been extensive efforts trying to raise bamboo plantation in the U.S., especially in Pacific Northwest, and Southeast states. The results show many species can survive and live comfortably in these climates. Many bamboo species are susceptible to cold climate. U.S. Department of Agriculture (USDA) has divided North America into 11 zones for growing plants, based on average minimum temperature, see Figure 9. Bamboo should be able to grow as low as zone 7, but more suitable for 8 and up. Based on USDA zone map, there are 21 states in U.S. continent that are in zone 7 and higher.

MR 6 is applicable because bamboo is considered a renewable material. The requirement asks for products that are produced from plants with a ten-year cycle. Bamboo has a short harvesting period, as early as 3 years and up to 6 years. It's use is promoted by its ability to turn around so quickly.

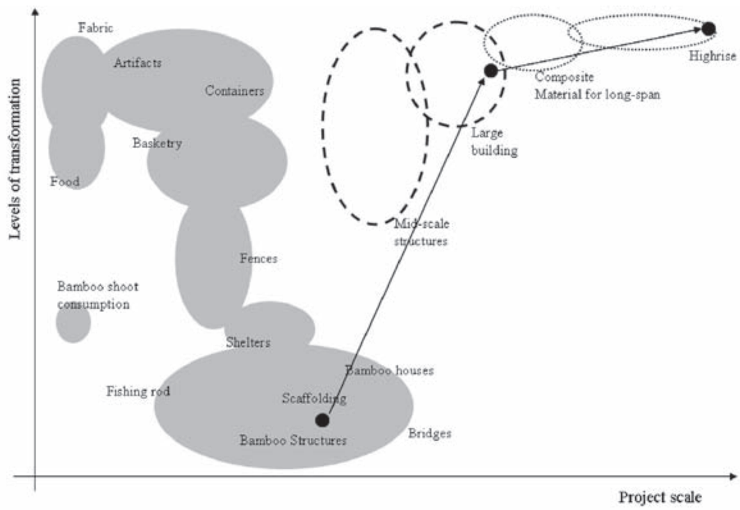


Figure 10. Chart demonstrates the relationship of bamboo projects between project scale and levels of transformation.

MR 7 requires 50 percent of wood-based products used in a project to comply with Forest Stewardship Council (FSC) standards. FSC is a non-profit organization created to manage the world's forests responsibly. Manufacturers that sell timber or forest products will seek FSC certification to verify that they have practiced forestry consistent with good standards. In order for bamboo to be grown in the U.S. industry, they are critical to follow the local standards, which will regulate bamboo products to be certified.

EQ 4.4 pertains to indoor environments using materials that have low gas emissions. Americans spend almost 90 percent of their time inside buildings. It is critical to choose building materials that are friendly to users' indoor air quality. The materials that contain Volatile Organic Compounds or VOCs will emit gas to the indoor air. Formaldehyde that is used as an adhesive chemical to glue laminated bamboo lumber together plays parts of gas emission. If the emissions in the air reach above 0.1 parts per million (ppm), it can cause headaches, dizziness, mental impairment, and other related symptoms. U.S. OSHA (Occupational Safety Health and Welfare Administration) allow level up to 0.75 ppm, while LEED requires no added urea-formaldehyde at all. LBL is mostly manufactured outside the U.S., and the formaldehyde control is not strictly enforced. The levels also vary from brand to brand. There are many brands that offer bamboo products that have formaldehyde as low as 0.03 ppm. While the eco-friendly trend grows, it shall promote the regulation to manufacture LBL with low formaldehyde level.

## 9 FUTURE RESEARCH

In the past, raw Bamboo has been used in domestic products which required no treatment or transformation. Referring to Figure 10, the diagram demonstrates the relationship of different levels of transformation with the scale of its applications. Current bamboo development occurs mostly on right side of chart in both higher and lower corners. That means that bamboo utilization is still within small to medium scale; if small scale refers to household objects and medium scale refers to residential construction. They were transformed from raw bamboo in many level in producing small products, and quite minimal in building scale. The activities took place on the left side of the chart. There is more empty space on the chart for bamboo to be explored. With today's technology, the study is aimed to encourage the relationship of high transformation and bigger scale projects, which is towards the right, upper side of the diagram. This study starts to introduce LBL in residential framing scale, hopefully encouraging more studies in this direction, such as bamboo in mid to large commercial scale, long-span, and perhaps high-rise applications.

## 10 CONCLUSION

Bamboo has been always known as a material for the poor because it is abundant in rural areas and can be used as-is. However, its irregularity in shape and size do not provide practicality in modern world. That is why this study purposely is intended to illustrate that bamboo can be modernized, industrialized and standardized. It is a material for anybody and any project. LBL, the focus of this study, can be transformed into any required structural section because it is made of tiny bamboo strips. It is possible to produce sections to match what is in current use. LBL's structural properties and superior quality compared to wood lumber in terms of higher strength, higher density, lower shrinkage, and dimension stability, have been proven through many studies. LBL is 2 times stronger than timber. For the same loading condition, LBL offers less material than timber, which eventually makes lighter dead loads and potential cost saving. LBL can comply with building codes as well as typical 2x wood lumber and will have the same limitations. However, in terms of seismic properties, using LBL is a bit more advantageous because LBL is 1.5 times stiffer than timber. When it comes to cost, LBL is still expensive because it is still under development. Due to most of LBL being manufactured overseas, costs of LBL in the U.S. have to include the shipping expenses. Promoting knowledge of LBL will lead to more usage. Bamboo as an eco-friendly, strong, and yet attractive material will advertise itself. Having bamboo plantations in the U.S. is possible. Finally, after investigating in many matters, the study recommends the use of LBL as the alternative material for wood lumber in typical residential construction in the U.S. It is possible, feasible, available, and sustainable.

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## REFERENCES

Villalobos A.; Antonio O. 1993. *Fundamentals of the Design of Bamboo Structure*, Doctoral Thesis the Eindhoven University of Technology, Eindhoven, Netherlands.

*Bamboo Research in Asia*. 1980. Proceedings of a workshop held in Singapore, International Development Research Centre, Ottawa, Canada.

Bansal, A.K., and Prasad, T.R.N. 2004. Manufacturing Laminates from Sympodial Bamboos—an Indian Experience. *Journal of Bamboo & Rattan (VSP International Science Publishers)* 3.1: pp. 13–22.

Breyer, D.E. 1980. *Design of Wood Structures*, 3rd Edition, McGraw-Hill, Inc., USA.

Janssen, J.J.A. 1981. *Bamboo in Building Structure*, Doctoral Thesis the Eindhoven University of Technology, Eindhoven, the Netherlands.

Janssen, J.J.A. 1991. *Mechanical Properties of Bamboo*, Kluwer Academic Publishers, The Netherlands.

Janssen, J.J.A. 1995. *Building with Bamboo: A Handbook*, ITDG Publishing, Warwickshire, UK.

*Recent Research on Bamboos*. 1985. Proceedings of the International Bamboo Workshop, the Chinese Academy of Forestry, China.

Rittironk, S. 2006. Bamboo bundling as structural member, Illinois Institute of Technology, Chicago.
Simon, V. 2000. *Grow Your Own House*, Vitra Design Museum.
Marcello, V. 2003. *New Bamboo: Architecture and Design*, Villegas Editores, Colombia.
U.S. Department of Agriculture. 1999. *Wood Handbook: Wood as Engineering Material*, USDA Forest Service, Madison, Wisconsin.
U.S. Green Building Council. 2005. *LEED-NC, Reference guide*, version 2.2, 1st edition, USGBC, USA.
Wang, Z. and Ren, Y.P. 2003. A study on the physical properties of a bamboo molding compared with wood and MDF moldings, International Network for Bamboo and Rattan (INBAR).

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# Preservation of bamboo forest by local citizens in Kitakyushu City, Japan

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ABSTRACT: In Japan, nearly all the bamboo forests are not maintained any longer, and because bamboo trees are very fast growing, this result in a rapid expanding spread of large bamboo forests. There are now devastating problems occurring for the bamboo forests, which are invading the adjacent forests and surrounding areas. Bamboo forest thinning had always been the solution to prevent damage of such spread of bamboo forests to other tree varieties and the surrounding fields. Especially since there is no any longer a large demand for bamboo material, as well as the high loan costs in Japan, bamboo forest thinning is quiet difficult to undertake, in terms of economically efficiency. In Kitakyushu (Japan), the NPO Kitakyushu Biotope Network Group undertakes thinning of bamboo forests through participation of citizens, all of them volunteers. Since November 2001, several environmental preservation activities were organized with the goal of preserving the bamboo forests in danger. Some of the main purposes of these activities were to make the citizens and the local government aware of the aggravating and severe problems and try to find also ways for the use of bamboo material. Already more than 1000 local citizens have participated in these activities, and several hectares of bamboo forest are being maintained these days. Unfortunately however, because there is nearly no local demand for the bamboo material, all the bamboo material was chipped and the chipped bamboo material had been used for making of soil products.

## 1 INTRODUCTION—PROBLEMS WHICH ARE FACING THE BAMBOO FORESTS

In former times, bamboo has played a crucial role in the daily life of many Japanese people. Bamboo was used as building material, in fishery and agriculture, and as a basic material for making daily life tools and utensils. Moreover, bamboo sprouts were and still are a much loved food in Japan. Probably, bamboo charcoal was used as energy resource as well. The change from an agricultural society into an industrial society, which means changes in life style, resulted in the fact that there was less need for bamboo material. Above that, the very high loan costs in Japan are another main reason for the import of cheaper bamboo sprouts and with bamboo prefabricated tools, mainly from China and other Asian countries, resulting in less demand for local bamboo. Since there is no any longer a market for the local bamboo material, the bamboo forests could not been kept maintained any longer.

## 2 SITUATION OF THE BAMBOO FOREST IN KITAKYUSHU

The city of Kitakyushu is located in the western part of Japan on the island of Kyushu. Kitakyushu has one of the largest bamboo forest areas of Japan due to its large city area (city area: about 480 $km^2$); the total bamboo forest area is not exactly known but is estimated to have expand about

Picture 1. A not maintained bamboo forest (left), and a maintained bamboo forest (right).

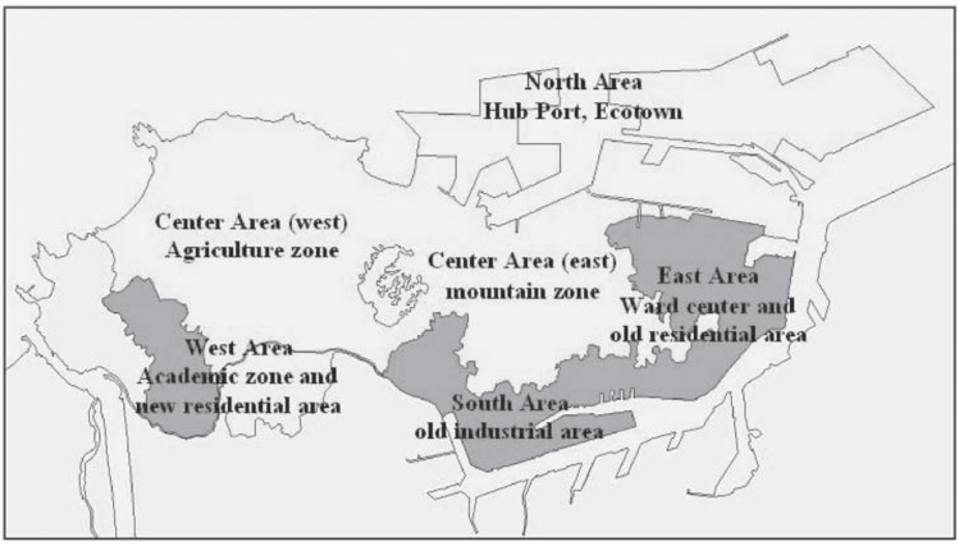


Figure 1. Map of the Wakamatsu ward.

1400 to 1500 ha. Ouma, which is located in the southern parts of the Kitakyushu city is an area well-known in Japan for its bamboo sprouts. The Ouma bamboo sprouts are distributed all over Japan. Because there is still a large demand for the Ouma bamboo sprouts, the bamboo forest in this area are rather well maintained compared to bamboo forests in other parts of Kitakyushu which are not maintained at all.

One other part of the city, located in the north of Kitakyushu is the Wakamatsu ward. The Wakamatsu ward is a very rural not densely inhabited area, and a place with large not maintained bamboo forests. In former times, the Wakamatsu ward was an island. Still these days Wakamatsu ward is surrounded by water; in the north by the Hibiki Nada Sea, in the south and east by the Dokai bay, in the west by the Onga River, and in the southwest by the Egawa River. The Wakamatsu ward can be divided into 5 zones, as is shown on the map in figure 1.

The 5 zones are:

Zone 1: The old ward center, which is located in the eastern zone. In this part of the ward are left many old buildings, of which some of high historical value.

Zone 2: In the south, an old industrial area along the northern shore of the Dokai bay.
Zone 3: In the west, a new residential area and academic zone, with in the center of it the Kitakyushu Science and Research Park.
Zone 4: In the north, the Wakamatsu seashore area, with a new hub port and the so-called Eco-town, an industrial area where industries related to recycle techniques are located.
Zone 5: The most central part of the Wakamatsu ward has a rich abundant nature. This area can be split up in a western and eastern part. The western part is mainly occupied by agricultural land. The eastern part has plenty of beautiful mountains with the Ishimine Mountain and Takato Mountain as the one with the highest peaks. The bamboo forests are mainly situated in the zones 3 and 5.

## 3 BAMBOO PRESERVATION THROUGH PARTICIPATION OF LOCAL CITIZENS IN KITAKYUSHU

In recent years, the role and participation by local citizens in Sustainable Community Planning has become more and more important because the improvement of our environment cannot any longer be realized only on a scientific level, but through participation of local government, local industries, research institutes and local grassroots environment citizens' organizations. Also the problem of thinning out and maintaining the bamboo forests must be undertaken through a good collaboration between bamboo forest owners, local government, local industry and citizens.

### 3.1 *NPO kitakyushu biotope network group*

The Kitakyushu Biotope Network Group has been created in July 2001. Members of the group consist of academics, company people, local government people, local citizens, students, etc. There are about 20 to 25 core members. Since June 2003, the Kitakyushu Biotope Network Group has become a Non Profit Organization (NPO). The main goal of the Kitakyushu Biotope Network Group is to work on issues of environmental protection, mainly dealing with preservation of nature in the urban and suburban area as well as dealing with topics of environmental education.

The Sustainable Community Planning Activities undertaken by the NPO Kitakyushu Biotope Network Group can be divided into environmental preservation activities related to; forest and bamboo forest preservation river and seashore preservation agriculture activities for children Since 2001, the Kitakyushu Biotope Network Group has organized over 100 Sustainable Community Planning Activities. In this report only the activities related to bamboo forest preservations will be mentioned as is shown in table 1.

Besides the environmental preservation activities (EPA) and other activities mentioned in table 1, bamboo forest maintenance activities are undertaken every second Saturday of each month. Since January 2004, except for the month of August, on every second Saturday of the month, a small group of citizens has started to preserve the bamboo forests in the area in and around the Kitakyushu Science and Research Park. The cut bamboos are chipped and these chips are used for soil making products. The cut bamboo material was also used in all the activities mentioned in table 1. A part of the bamboo material was also used for bamboo objects, small artistic objects made by the students of the University of Kitakyushu. These bamboo objects are explained in another report.

In the area in and around the Kitakyushu Science and Research Park are five forests which are maintained as is shown in figure 2.

1. the Yatsurugi Shrine, a small shrine surrounded by a small forest, in this forest nearly all the bamboo has been cut away because in a shrine forest was originally no bamboo,
2. the Hibikino South Park, a 4ha large park, in the middle is a pond and around the pond are forests and bamboo forests,

Table 1. List of Bamboo related activities.

| Date | Name of the bamboo related event |
|---|---|
| 10 Nov. 2001 | 2nd EPA: Bamboo Forest Preservation Project |
| 29 April 2002 | 3rd EPA: Clean Up the Egawa River by use of a bamboo raft |
| 19–22 Aug. 2002 | 5th EPA: First Bamboo Design Workshop |
| 14 Sept. 2002 | Junior Meister Course: Making of Bamboo Charcoal Part 1 |
| 12 Oct. 2002 | Junior Meister Course: Making of Bamboo Charcoal Part 2 |
| 23 Nov. 2002 | 6th EPA: Bamboo Forest Preservation—International Collaboration |
| 9 March 2003 | 9th EPA: Satoyama Preservation |
| 29 Nov. 2003 | Dream Cupid: Making of Bamboo Charcoal |
| 12–14 Nov. 2004 | 17th EPA: Green Town Planning Workshop in the Kitakyushu Science and Research Park |
| 20 Aug. 2005 | Bamboo Craft Course for children Part 1 |
| 11 Sept. 2005 | 21st EPA: Fishing with bamboo pole in the Egawa river |
| 3–6 Nov. 2005 | 23rd EPA: Second Bamboo Design Workshop [Shelter $3 \times 3 \times 3$] |
| 18 Feb. 2006 | 26th EPA: Egawa River and Dokai Bay Project Part 9: Water Purification of the Dokai Bay by using of bamboo |
| 9 July 2006 | 28th EPA: 5 year Commemoration Project Part 1: Cooking Papa |
| 17 July 2006 | 28th EPA: 5 year Commemoration Project Part 2: Cross the Dokai Bay with a bamboo raft |
| 5, 6 Aug. 2006 | 28th EPA: 5 year Commemoration Project Part 3: Nagasaki Historical Road Bamboo Lantern Event |
| 27 Aug. 2006 | Bamboo Craft Course for children Part 2 |
| 14 Oct. 2006 | Bamboo Craft Course for children Part 3 |
| 23 Nov. 2006 | Bamboo Craft Course for children Part 4 |
| 10 Feb. 2007 | 31st EPA: Bamboo Preservation Commemoration Event |
| 2, 3 June 2007 | Bamboo Craft Course for children Part 5 |
| 18 Aug. 2007 | Bamboo Craft Course for children Part 6 |

*Note:* EPA = Environmental Preservation Activities.

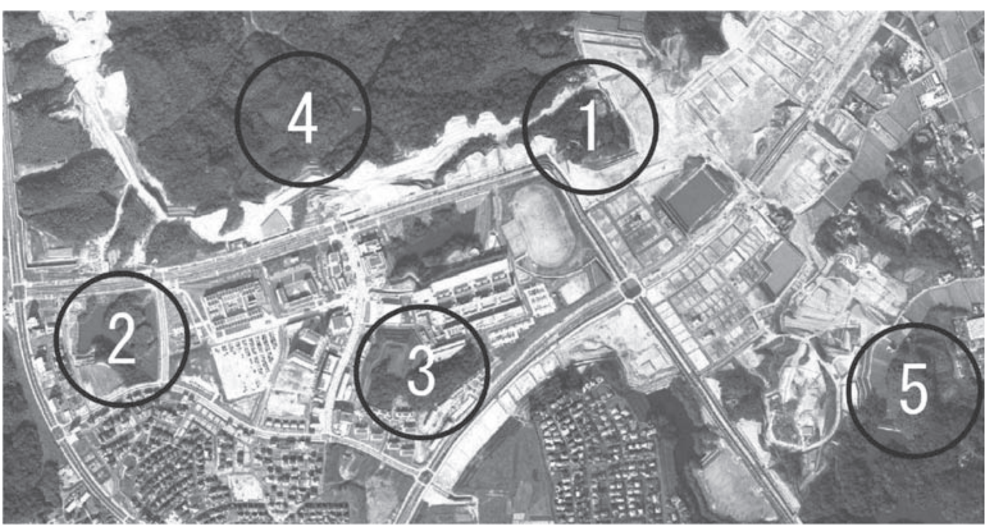


Figure 2. Area map of the Kitakyushu Science and Research Park (Aerial photograph reference: Google Map).

3. a small forest which is located behind the foreign students' house,
4. the Funao Mountain (70 m),
5. the Honji Green Conservation Area.

There are three cases for the preservations of bamboo forests and adjacent forests:

Case 1: Case 1 is the case that bamboos have invaded the adjacent forests. In that case all the bamboos are cut down. The main reason for that is because most of the trees died because no sunlight infiltrates any longer the forest once bamboos have reached their full grown height.
Case 2: The zones with only bamboo are preserved the following way. First of all, the older bamboos are cut away. Afterwards thinning of the bamboo forest occurs, until a well balanced density has been reached. Depended on the place, 2 or 3, up to 10 and more bamboos are left on 3.3 $m^2$ (1 tsubo is corresponding to 3.3 $m^2$, a Japanese area unit).
Case 3: The third way of preservation is keeping bamboos and normal trees together. The density of trees and bamboos vary from place to place. The infiltration of sunlight is one of the most important elements to decide the density of thinning the forest.

Due to the fact that all participants are non-professionals, these preservation and thinning methods cannot always be seen as the most appropriate ones.

### 3.2 *Number of participants*

The bamboo forest activities have started in 2001, but since January 2004, 35 regularly organized maintenance activities were undertaken with a total of 1245 participants as is shown in figure 3. A total of about 200 volunteers are helping with these activities. Every month, among the 200 volunteers, about 30 to 35 volunteers are attending. The first months of 2004, when the activities started, more than 50 participants attended the events, many people were interested but due to the hard labor work of cutting and carrying the bamboos, many participants attended only once or twice. The peak moments are events with more than 70 participants, events which are organized together with events organized by the city or by other organizations. Due to long lasting bad weather in 2006, the number of participants decreased. At the end of 2006, the employees of two local companies joined the group of volunteers. In Japan, Corporate Social Responsibility (CSR) has become very important and local companies are starting to join the bamboo forest preservation activities. Another company is preparing its employees to join these activities.

The average is 35 participants a month. The age of the participants is not investigated, but we can see that there is a shift from mostly elderly participants in the beginning, to a more mixed age structure of participants. This can be explained by the fact that people working in the companies have joined. Moreover, nearly all participants are males, and since companies have joined the number of female participants has increased.

Picture 2. Cutting and carrying of the bamboos.

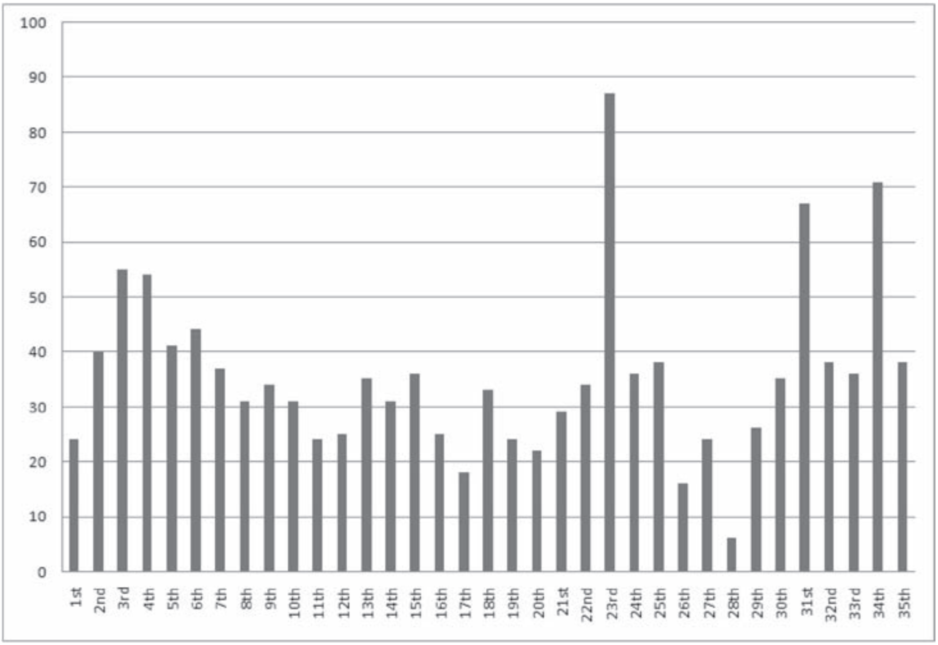


Figure 3. Number of participants.

### 3.3 *Conclusion*

In this report the role of the NPO Kitakyushu Biotope Network Group (KBNG) in the preservation of bamboo forests has been explained.

1. It can be said that the preservation of bamboo forest in Japan only can be solved through intense participation of local government, industries (and companies CSR program), research institutes, local grassroots environment organizations, NPO's etc.
2. With over 100 activities, the NPO KBNG has elaborated a lasting bamboo preservation project, these activities show to be a solution to let local citizens take part in solving bamboo forest problems. All activities attracted many participants, which show also that the citizens of Kitakyushu are concerned about the bamboo forests.
3. In the near future, it will be important on the one hand to establish several bamboo preservation key areas (= bamboo forest station), and make a network of these stations, so that the local citizens not only participate in one-day events but become member of these organized preservations stations and take more initiative in their own local area.

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# An experiment with a locally constructed bouccherie treatment plant in Nepal

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ABSTRACT: This paper deals with an experiment by ABARI, a specialized bamboo and adobe research and design firm of Nepal's experiment with various treatment methods: which included vertical soak diffusion method, traditional soaking method and bouccherie treatment method using boron compound and neem solution.

## 1 INTRODUCTION

### 1.1 *Background*

Bamboo has played an important part in the traditional life of Nepal. (Poudyal 2006, Bista 2004, Karki et al 1998) From the "untouchable" Dalits castes to the "high caste" Brahmins: bamboo has played a vital roll in income generation. (Bista 2004) Eighty one species (5.2% of the world species) belonging to 23 genera (24% of the world genera) are found in Nepal. (Poudyal 2006) Nepal has both tropical bamboos found in the South-East Asia and temperate bamboos found in Tibet and Bhutan. (Karki, et al 1998) Traditionally, bamboo is used either for food, fodder, construction material, medicinal and domestic utilitarian uses. (Bista 2004, Karki et al 1998) Bamboo products such as mats and household items are manufactured by local farmers and artisans, which are sold in local markets. (Bista 2004, Karki et al 1998) Despite prominence in the production and lifestyle, owing to the poor infrastructure, disappearing knowledge and poor craftsmanship bamboo based economy only contributes 1–2% to the national GDP. (Karki et al 1998)

The quality of bamboo craftsmanship, is generally poor due to several reasons: bamboo used for construction is not mature enough, bamboo is not treated, improper handling, lack of connection materials and skills, inadequate tools, lack of finishing materials and lack of exposure to the different bamboo designs. Furthermore, though people are aware of the beauty and the strength of bamboo, they are reluctant to make permanent structures with it because they are scared of its non-durability.

### 1.2 *ABARI (Adobe and Bamboo Research Institute)*

As an architect, I had been designing with adobe (sun dried bricks) in New Mexico, USA and Mongolia. Due to the lack of wood in either of the deserts, I was promoting woodless dome construction technique. However, after coming back to Nepal, I had to make changes in the construction technique because of the different climatic conditions. I could not use adobe alone because of the wet climate and the seismically active terrain. However, I was fortunate enough to have bamboo at my disposal.

Impressed by its economic, ecological, structural and aesthetical qualities, I began promoting bamboo. Though people were aware of bamboo's superior strength and its beauty, people were reluctant to use it because it decayed fast. Even if they did, the middle class people only built temporary structures, as an annex to their existing concrete house and the poor people did not want to use it altogether because the high maintenance symbolized poverty.

It is in this context, with an engineer partner Shishir Gairhe, I initiated a specialized research and design institution (ABARI Adobe and Bamboo Research Institute http://www.abari.org), that would systematically investigate these material, so they could address the modern housing need of Nepal. Our main focus has been to promote a sustainable housing by mobilizing local human and natural resources in order to provide safe and sanitary living condition.

Before ABARI could push the bamboo-adobe design concept, I knew, we had to find a solution for the fast decaying bamboo. The traditional wisdom of soaking in water, using mature bamboo or drying did not suffice. A more efficient technique for treatment was need. Therefore, we initiated a project whose main objectives were:

## 2 OBJECTIVE

1. To find a fast and efficient treatment method, that would take care of the common termite and powder beetle problem.
2. To find a system that is cheap and easy to construct, which a poor can emulate.
3. To find a system that can be developed locally.
4. To develop a system that is portable, so it can be taken to the remote parts the country which are not accessible by road.

## 3 METHODOLOGY

### 3.1 *Vertical Soak Diffusion (VSD) Method*

It is a method, where all the nodes except the last one are penetrated with a long iron rod with a spearhead welded on one end and a T-shaped handle on the other. After which, the bamboo are vertically placed, and preservative are poured on to them.

### 3.2 *Results*

VSD method was not feasible because,

1. It is hard to penetrate bamboo if they are curved or long.
2. It is time consuming. One has to soak the bamboo in a rain-protected area for at least 2 weeks.
3. To make an elevated platform is sometimes expensive and not feasible.
4. One 10 meter bamboo requires about 6 liters of boron compound. It cost Nepali Rs. 300 (5 USD) for 6 liter solution, while the bamboo only cost Rs. 70 (1 USD). The cost ratio is too high and not affordable to many.

Therefore, mainly considering the cost issue, this technique was abandoned.

Then we tried the traditional soaking method.

### 3.3 *Traditional soaking method*

In this technique bamboo are submerged in water for about 6 weeks, see Figure 1. This method increases the durability of bamboo, according to a local belief, by 10 years. It is believed that since starch is soluble in water, by submerging the starch gets dissolved.

### 3.4 *Advantages*

1. Safe and effective non-technical approach.
2. Economical.
3. Time tested treatment method.

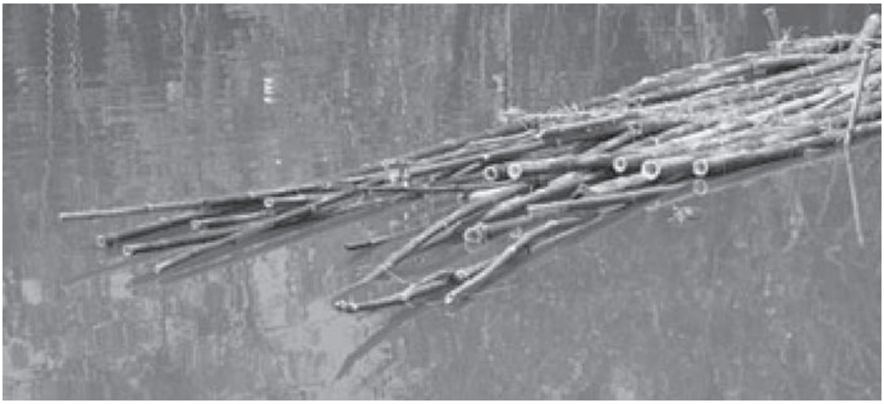

Figure 1. Bamboo are submerged for 6 weeks.

### 3.5 *Limitations*

1. Leaving bamboo for about 6 weeks under water was not always safe.
2. Time consuming.
3. Very resource consuming when done in a large scale.
4. Transportation to the water source is not always easy.

However, I do endorse this technique, if all the resources are available and the alternative is not there.

## 4 MODIFIED BOUCHERIE TECHNIQUE

With the impracticality of VSD method, we experimented with a modified Boucherie Technique. In Nepal, Abari was the first organization to try this technique in a local scale, so there was very little literature or help to ask for. Our main resources was INBAR's website and other resources on the web. From the web resources we could get the general concept of the Boucherie technique, but we had to basically design and build everything on our own since we did not find a detailed manual on its construction. Everything in this plant was built and improvised by a local technician.

### 4.1 *Physiological characteristics*

Bamboo culms are divided into nodes and internodes and are composed of two types of tissue; parenchyma cells and vascular bundles. The latter consist of vessels, thick walled fibers and sieve tubes and it is through these that water movement takes place in the living plant. (Rao 17) In Modified Boucherie Technique, (aka. sap displacement technique), pressurized preservative solution is applied on the basal end, which pushes the sap contained in the vascular bundle out and then replaces it with a preservative solution. This technique is only possible on a freshly cut bamboo because vascular bundle is still wet.

### 4.2 *Equipments*

1. A big cylinder, fitted with:
   - A pressure gauge: The pressure inside the cylinder is always kept at 20–25 psi, which is enough to send the solution inside the bamboo.
   - Solution inlet: a mixed solution is poured through this inlet.
   - Solution regulator: it regulates how much solution is to be let out of the cylinder.

- Hand pump: a simple manual pump to put pressure into the cylinder. An electric compressor can be used if labor is expensive.
- Pressure regulator: to regulate how much pressure is to be let inside the cylinder.
- Solution outlet, which was later, split into 7 outlets, to let the solution out. See the fig.

## 4.3 *Procedure*

This is a very simple technique, which can be operated by almost anyone. We have taken our treatment plant to the rural areas and more then 50% of the operators have been women.

## 4.4 *Steps*

- The cylinder is ¾ filled with preservative. We are now using boron compound, and we are testing neem and cow urine.
- The cylinder is pressurized (up to 20–25 psi) using a simple manual pump.
- Valve in the nozzle is open for a split second to let the air out.

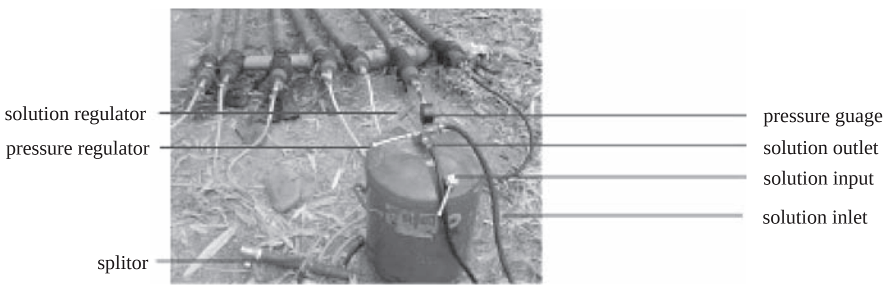


Figure 2. Modified boucherie treatment plant.

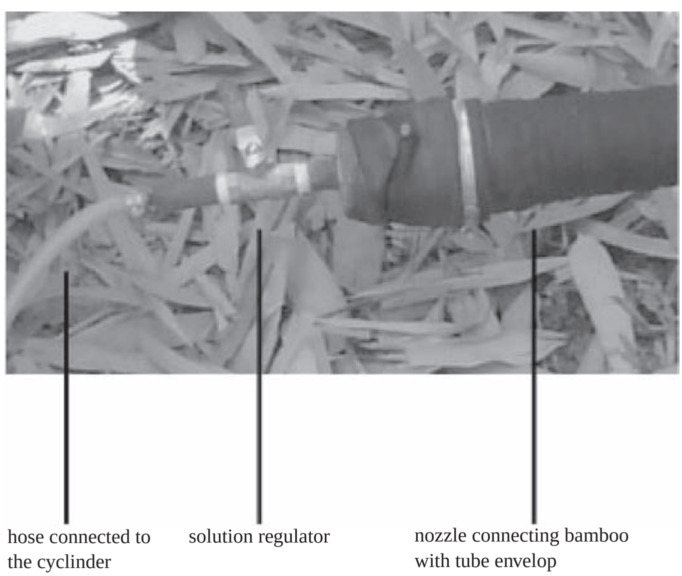


Figure 3. A nozzle connecting bamboo.

- Nozzle is connected to the bamboo, which is made airtight using rubber tube. Figure 5.
- Sap starts dripping from the branch in almost 5 minutes. It takes about half hour for the preservative to come out from the opposite end.
- Treatment is done for atleast an hour so that the preservative can reach all parts of the bamboo.
- Bamboo is then stored horizontally in a rain-protected area till it dries.

### 4.5 *Bamboo*

- We have tried this process only on three kinds of bamboo: Bambusa Tulda, Bambusa Nutan and Bambusa Balcooa locally known as Mal, Chanp, and Harot respectively.

Figure 4. Nozzle: a closer look.

Figure 5. Men and women using the treatment plant.

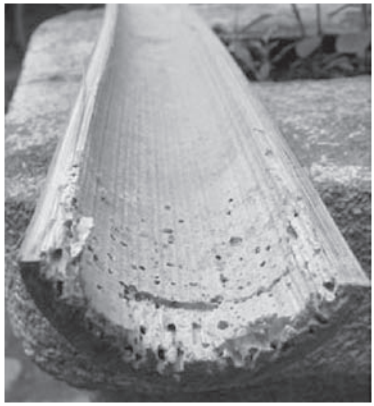

Figure 6. Example of bamboo being infected.

- All these bamboo were between 3–5 years of age and they were treated almost immediately after felling.

### 4.6 *Preservative*

- We are currently using Boron Compound, i.e. Borax, boric acid and water were used in 1:1:10 ratio.
- We have also used neem.

### 4.7 *Results using boron compound*

Six months after the treatment, we found the following results:

- Molds were formed on the outside and the inside of the ends in almost all the bamboo.
- If the parts where molds were formed were split open, they were found to be clean and unaffected. Thus mold were only limited to the outside.
- Most of the bamboo had white termite like bugs, but they did not penetrate inside. They seemed to content living in the mold.
- 30% of the bamboo's end where attacked by powder beetle, however they were limited only to the top ends. Only 6 out of 50 bamboos were infected inside. See Figure 6.

### 4.8 *Conclusion*

The reason most of the bamboo had mold in it is because they were not properly dried. They were dried in a closed environment, which had very little sunlight and air circulation. So a new kind of storage was built for another batch of treated bamboo, which had enough air circulation and sunlight yet they were protected against the rain (see Figure 7). In the treated batch the mold were not formed but they still had beetle infection, but yet again they were only in the top ends.

## 5 RESULTS USING NEEM

- One and half kilo neem was first boiled in 10 liters water for about half an hour. It was then cooled down; the result was a very thick black neem concentrate. However, it was very difficult to penetrate the solution through the treatment plant so the solution was again diluted at 1:5 ratio with water.

Figure 7. Storage space for freshly treated bamboo.

- The solution was forced into the bamboo using boucherie treatment plant. The solution started coming out from the other end but not through the branches. The explanation was that vascular bundles are wider on the inner part compared to the periphery; therefore the solution could only penetrate on the inner part.
- The solution was then filtered to get rid of the particles, after which the solution easily penetrated the bamboo!

The experimented was successful in terms of penetrating the neem solution into the bamboo. The effect of the solution on preservation has yet to be studied. We are also planning on using cow urine because traditionally it has been used to treat wood.

## 6 ADVANTAGES USING BOUCHERIE TREATMENT METHOD

- The treatment plant can be locally and economically constructed.
- Our three treatment plant successfully treated 1200 bamboo in a month.
- Traditional treatment preservative can be used with this technique: for example neem and cow urine.
- It can be operated with a simple instruction by almost anyone.
- Since this can be taken to rural areas, it can be provide employment to the locals.
- It is a fast and effective process.

## 7 LIMITATIONS

- The treatment can only be done for freshly cut bamboo.
- It is only cost effective (compared to VSD) when one is treating more then 25 bamboo.
- Boron compound is not available everywhere, and the alternative like neem and cow urine have to be explored.

## 8 CONCLUSION

As per our objective we have found a simple and effective way of treating bamboo Modified Boucherie Technique. We have successfully treated more then 2000 bamboo using this technique and have trained many people in the process. If we get enough funding we will further explore neem and cow urine solution. However, with the success of the technique, we have already started design and construction in many parts of Nepal. After seeing the technique and our bamboo craftsmanship, more people are interested in using bamboo. Let bamboo prevail. Please check www.abari.org to see our projects.


## ACKNOWLEDGEMENT

I would like to thank our dedicated technician Ram Krishna Thapa, who whole-heartedly helped in realizing this project. And also my parents Shova Adhikary and Basanta Adhikary who financially sponsored this project. And all the bamboo lovers who sent regular emails to encourage the project.


## REFERENCES


Adamson, Marcos & Lopez. 2001. Socioeconomic study for the bamboo sector in Costa Rica.

Adhikary N. 2007. Love of Mud Kantipur.

Bhattarai T.R., Dahal, Pramod., Khem B.K. et al. 2002. Participatory Action Research on Chiuri Tree: A Cornerstone for Understanding Community Forestry through Management of Non-Timber Forest Products in Central Nepal FAO.

Bista, Dor Bahadur. 2004. People Of Nepal, Kathmandu, Nepal.

Dharmananda S. 2004. Bamboo as medicine. Institute for Traditional Medicine Dec. http://www.itmonline.org/arts/bamboo.htm

Janssen J.J.A. 2000. Designing and Building with Bamboo Technical report No. 20.

Kumar, Satish., Shukla K.S., Dev, Indra. et al. 1994. Bamboo preservation techniques: A review, inbar.

Karki, Madhav B., Sherchan, Gopal R., Karki, Jay Bahadur S. 1998. Extensive Bamboo Production-to-Consumption Systems in Eastern Nepal: a Case Study INBAR Working Paper No. 17, INBAR.

Larasati, Dwinita. 1999. Uncovering the green gold of Indonesia: A Design Research on Bamboo's Potential, Eindhoven.

Nayar, Lola. Bamboo is India's 'green gold' Indo-Asian News Service.

Poudyal, Punya. 2006. Bamboos of Sikkim (India) Bhutan and Nepal, Kathmandu, Nepal.

Storey, Peter. 1990. Bamboo: A valuable crop for the hills Volume I.

*Modern Bamboo Structures – Xiao et al. (eds)*


# Patent analysis of bamboo exploitation and utilization in China

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ABSTRACT: In this paper, based on the complete Patent database of SIPO (State Intellectual Property Office of P.R.C) and ESPACENET (Europe's Network of Patent Databases), using the analysis tools of Patentmap theory (PM), the main characters, distribution and research states in the field of bamboo patented technology innovation were analyzed quantitatively, The present hot core and the main characters about the patent application were focused clearly, and the further development of the use and study of bamboo field were also proposed.

## 1 INTRODUCTION

Bamboo is the important part of the forest resources, and the People had made use of the bamboo resources in ancient times. In recent years, bamboo industry is developing rapidly, meanwhile the development of the bamboo resources become more deep and wider. Firstly the varieties of bamboo products are complete, which is widely applied in architecture, papermaking, furniture, light-industry, food, medicine, health product, package, transportation, tourism, environment protection and the other new material field. The products of bamboo made in china have been exported to the other countries and regions in the world. With the further development of competition globalization, different countries realize gradually the importance of the intellectual property protection of bamboo. The figure of patent application and grand can directly reflect the development status in the field. The quantity of patent application and grand is more, which shows that, in this field, the research activity is active and the speed of the development and the production renewal is faster (ZHANG, Y et al. 2007).

According to the data of WIPO, although Patent Literature is only about 10% of the Periodical Literature, it contains about 40% information of the new production. From 90% to 95% of new technology in the world was opened by Patent Literature (SHENG, G.C. 2002). Tracing, researching and analysing the patents became an important mean to get the advance technology in some field. Based on the analysis on patent information, we can explore its rich content,which serves for the research and application of the patent strategy (DING, Y.H. et al. 2005). This paper, using the analysis tools of Patentmap theory (PM), analyze the main characters, distribution and research status in the field of bamboo patented technology innovation quantitatively. The present hot core and the main characters about the patent application were focused clearly, and the further development of the use and study of bamboo field were also proposed.

## 2 DATA SOURCE

It has counted and analyzed the bamboo patent application information of ESPACENET (since 1978) and Chinese patent (since 1985). Patent application keeps a well linear correlation with patent grand, meanwhile patent grand is time-lagging, so that, I choose patent application as my data to analyze, the deadline is August, 2007.

## 3 PATENT APPLICATION STATUS OF BAMBOO IN THE WORLD

Bamboo is the important part of the forest resources, which is rich in tropical and subtropical zone. It can be depart into three regions: Asia-pacific, American, Africa. The richest region in the three is Asia-pacific, including China, Japan and some Southeast Asian Countries (ZHANG, Z.H. 2002). There are also a few bamboo in Europe and Australian Continent. The distribution of bamboo and the local economic development level have a great effect on the patent application (Table 1). The quantity of the patent application was 7722 pieces before April, 2007, all over the world. China has 2807 pieces,which is the world second largest country in bamboo patent application (lower than Japan). In recent years, although there are only a small few of bamboo resource in Europe and Australian, they also improve the cooperation in utilization studies of bamboo resource. The countries of EC have developed some major project, such as “Sustainable Management and Quality Improvement of bamboo” and “European Action Plan for bamboo”, which improve the processing and application technology of bamboo and patent application in these areas.

## 4 DEVELOP TREND OF PATENT APPLICATION IN CHINA

In China, the patent needs 5 or 6 years from application to implementation. Searching the Patent Literature and counting the quantity of patent application can predict the developmental trend effectively. Since 1985, there are 4005 pieces of patent application in China (invention patent 1072, new practical type patent 1553, design patent 1380). Figure 1 shows the quantity of patent application ordered by years.

$$\gamma = \frac{a}{A} \tag{1}$$

$$\alpha = \frac{a}{a+b} \tag{2}$$

$$N = \gamma^2 + a^2 \tag{3}$$

where [LIU, L. 2007]: $\gamma$ is the growth rate of the technology; $\alpha$ is maturity coefficient of technology; $N$ is the new technical features index; $a$ is the number of invention patent applications of the

Table 1. The quantity of bamboo patent application all over the world.

| Rank | Nation | Abbreviation | Number | Rank | Nation | Abbreviation | Number |
|---|---|---|---|---|---|---|---|
| 1 | Japan | JP | 3108 | 9 | French | FR | 30 |
| 2 | China | CN | 2807 | 10 | Austrilia | AU | 26 |
| 3 | Korea | KR | 792 | 11 | Heloon | NL | 9 |
| 4 | Britain | GB | 423 | 12 | Philippines | PH | 7 |
| 5 | America | US | 283 | 13 | Indian | IN | 3 |
| 6 | Taiwan, China | TW | 131 | 14 | Mexico | MX | 3 |
| 7 | Germany | DE | 56 | 15 | Hongkong of China | HK | 1 |
| 8 | Canada | CA | 39 | 16 | Singapore | SG | 1 |

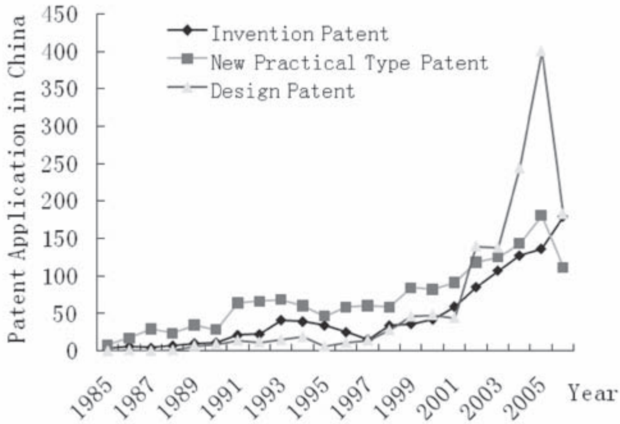


Figure 1. Developmental trend of patent application in China.

current year (or patent grand); *A* is the cumulative number of invention patent applications over the past 5 years (or cumulative patent grand); *b* is the number of new practical type patent of the current year (or patent grand).

Data statistical analysis shows that bamboo patent application in China can be divided into two phases: First phase (1985~1993), the technology infant period. The growth rate of the technology (γ) was continuously increasing in those years (GUANG, M.J. et al. 2001), but the total development of bamboo industry still depressed and steady, and the quantity of patent application is increasing from 11 pieces in early years to124 pieces. Second phase (1997~2006), the rapid increasing period. The industrial technology achieved significant breakthrough, meanwhile enterprises and society gradually realized the market valueand development potential of bamboo, which increased the quantity of patent application rapidly. During this phase, the quantity of patent application is 3157 pieces, 78.8% of the total, which indicated the booming development. From 1997 to 2006, the new technical features index(N) was increasing from 0.04 to 0.50,which showed that the new technical features of bamboo patent was continuously increasing and had a great potential for development (HUANG, Y.Y. et al. 2006).

## 5 REGIONAL DISTRIBUTION OF PATENT APPLICATION IN CHINA

Most of the opened bamboo patents in China was applied by domestic (including Taiwan) enterprises or individuals, which are widely distributed in 22 provinces, 4 autonomous regions, 3 municipalities directly under the Central Government and Hong Kong Special Administrative Region. As shown in Table 2, it mainly concentrated in Changjiang River-Nanling Mount and South China, such as Zhejiang, Hunan and Guangzhou where bamboo resources are abundant. In some provinces without bamboo resource, such as Ningxia Autonomous Region, Qinghai, Tibet Zhang Autonomous Region, there are no distributions. It seems that there is a close correlation between the quantity of patent application and bamboo distribution. The quantity of Zhejiang is 1114 pieces, taking 27.8%. Exploitation and utilization of bamboo in this region is quite developed. The second province Hunan has 389 pieces. Then Guangdong has 317 pieces, Sichuan has 306 pieces and Fujian has 288 pieces. Moreover, the entities from other regions and countries also applied Chinese patent, for protecting their right in China.

Table 2. Regional distribution of patent application in China.

| Rank | Provence | Num | Rate (%) | Rank | Provence | Num | Rate (%) |
|---|---|---|---|---|---|---|---|
| 1 | Zhejiang | 1114 | 27.8 | 15 | Guizhou | 49 | 1.2 |
| 2 | Hunan | 389 | 9.7 | 16 | Chongqing | 39 | 1.0 |
| 3 | Guangdong | 317 | 7.9 | 17 | Liaoning | 38 | 0.9 |
| 4 | Sichuan | 306 | 7.6 | 18 | Hebei | 38 | 0.9 |
| 5 | Fujian | 288 | 7.2 | 19 | Henan | 27 | 0.7 |
| 6 | Shanghai | 181 | 4.5 | 20 | Tianjin | 27 | 0.7 |
| 7 | Jiangsu | 172 | 43 | 21 | Heilongjiang | 27 | 0.7 |
| 8 | Jiangxi | 149 | 3.7 | 22 | Jilin | 24 | 0.6 |
| 9 | Beijing | 145 | 36 | 23 | Shanxi | 23 | 0.6 |
| 10 | Shandong | 107 | 2.7 | 24 | Shaanxi | 22 | 0.5 |
| 11 | Guangxi | 106 | 2.6 | | Taiwan | 90 | 2.2 |
| 12 | Hubei | 77 | 1.9 | | Japan | 29 | 0.7 |
| 13 | Yunnan | 70 | 1.7 | | Korea | 16 | 0.4 |
| 14 | Anhui | 50 | 1.2 | | America | 7 | 0.2 |

Table 3. Types of bamboo patent applicants in China.

| Type | Invention patents | Practical type patents | Design patents | Total | Rate (%) |
|---|---|---|---|---|---|
| Individual | 633 | 1204 | 1049 | 2886 | 73.8 |
| Enterprise | 255 | 169 | 326 | 750 | 19.2 |
| University | 128 | 42 | 4 | 174 | 4.5 |
| Scientific & research institute | 63 | 33 | 1 | 97 | 2.5 |
| Organization & group | 1 | 0 | 0 | 2 | 0.1 |
| Sum | 1072 | 1553 | 1380 | 4005 | 100 |

## 6 PATENT INVENTORS AND PATENT APPLICANTS

The analysis of the patent application of patent can show the research and development ability of company some time and the proportion in the investment on scientific research. Table 3 shows that patent applicants mainly belong to individuals. The quantity of individuals' invention patents, practical type patents, design patents and the total are all father more than enterprises, universities, scientific & research institutes and the organizations & groups. Individuals are the main force of the patent applicants. It almost take 73.8% of the total. The next are enterprises taking 19.2% with 750 pieces. Universities, less than enterprises, have 128 pieces. Scientific & research institutes only have 63 pieces, which is almost a half of universities.

We can obtain the main mechanism and core personage (who applied patent much more than others) of bamboo patent applications (SHAO, B. et al. 2006) from the ranking of the number of invention patents (Table 4). The result shows that the enterprises in developing areas pay more attention to patent applications for keeping there advantages, such as Guangdong Shennanpeng (Yunan) Bamboo-wood Plant who applied 45 pieces of patents is the most. Some Forestry Colleges and Universities also applied many patents. For example, Nanjing Forestry University with 41 pieces and Zhejiang Forestry College with 29 pieces respectively dominated the second and the third. Moreover, most of the whole shows were from Zhejiang.

Table 4. The main mechanism and whole show of bamboo patent applications in China.

| Rank | Main mechanism | Num | Rank | Whole show | Num |
|---|---|---|---|---|---|
| 1 | Shennanpeng (Yunan) Bamboo-wood plant | 45 | 1 | Yu-qiang Chen | 90 |
| 2 | Nanjing Forestry University | 41 | 2 | Yong-jin Chen | 82 |
| 3 | Zhejiang Forestry College | 29 | 3 | Ming-jiang Xu | 49 |
| 4 | Shanghai Jiazi Bed Clothes Co. Ltd. | 20 | 4 | Zhao-ping Chen | 45 |
| 5 | Yibin Siliya Ltd. | 20 | 5 | Ming-rong Wang | 37 |
| 6 | Xiamen Wanxie Bamboo-wood handicraf Co. Ltd. | 16 | 6 | Wei-ping Shen | 32 |
| 7 | Zhejiang University | 16 | 7 | Jian-zhong Wang | 25 |
| 8 | Shanghai Chundewudao Co. Ltd. | 15 | 8 | Wen-xun Li | 23 |
| 9 | Donghua University | 12 | 9 | Qi-sheng Zhang | 23 |
| 10 | Hunan Imp. & Exp. Co.-Xingzhu Company | 12 | 10 | Dan-ren Wu | 21 |
| 11 | Xiamen Tianmao Imp. & Exp Trade Co. Ltd. | 12 | 11 | Fu-zhen Xu | 19 |
| 12 | Research Institute of Wood Industry, Chinese Academy of Forestry | 11 | 12 | Hui-mu Yao | 19 |
| 13 | Lijiang Shiguxiangcun Grass and Bamboo Weaving Ltd. | 11 | 13 | Miao-jin Lang | 18 |
| 14 | Wuhan Chutianjiguan (Group) Co. Ltd. | 10 | 14 | Xiao-ya Cao | 18 |
| 15 | Zhejian Deqing County Mount Mogan Bamboo Plywood Plant | 10 | 15 | Tao Feng | 18 |

Table 5. Types of Bamboo Patent Technology in China.

| Invention patents Rank | Type | Num | Practical type patents Rank | Type | Num | Design patents Rank | Type | Num | Total | Type | Num |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | C | 279 | 1 | A | 763 | 1 | A | 1269 | 1 | A | 2178 |
| 2 | B | 242 | 2 | B | 421 | 2 | B | 32 | 2 | B | 695 |
| 3 | E | 152 | 3 | D | 210 | 3 | E | 27 | 3 | C | 334 |
| 4 | A | 146 | 4 | E | 62 | 4 | G | 19 | 4 | D | 247 |
| 5 | F | 109 | 5 | C | 51 | 5 | H | 15 | 5 | E | 241 |
| 6 | G | 40 | 6 | G | 24 | 6 | F | 13 | 6 | F | 143 |
| 7 | H | 40 | 7 | F | 21 | 7 | C | 4 | 7 | G | 83 |
| 8 | D | 36 | 8 | I | 1 | 8 | D | 1 | 8 | H | 55 |
| 9 | I | 28 | 9 | H | 0 | 9 | I | 0 | 9 | I | 29 |
| Sum | | 1072 | | | 1553 | | | 1380 | | | 4005 |

*Main types: A. Bamboo furniture, handicraft, daily used products; B. Bamboo-based panels; C. Bamboo medicine and healthy curative function; D. Bamboo processing machines and equipment; E. Bamboo charcoal, bamboo activated carbon and extracts from bamboo; F. Bamboo fiber; G. Crude bamboo; H. Bamboo shoots and its products; I. Cultivation of bamboo.

## 7 ANALYSIS OF PATENT TECHNOLOGY

According to the classification analysis of technological classification about the 4005 pieces of patent, we can get the achievements, developments, technology level and the key research direction in scientific research (SHENG, G.C. et al. 2002). bamboo patent application are divided into 9 types, as follows: bamboo furniture, handicraft, daily used products; bamboo-based panels; bamboo medicine and healthy curative function; bamboo processing machines and equipments; bamboo charcoal, bamboo activated carbon and extracts from bamboo; bamboo fiber ;crude bamboo; bamboo shoots and its products; cultivation of bamboo (XU, Y.M. et al. 2003).

From the aspect of the total application quantity, we can obtain some results. Daily used bamboo products are the hot spot of the patent application, up to 2178 pieces, including bamboo mats, furniture, chopsticks, stickers and so on. The second patent application quantity is bamboo-based panels, up to 695 pieces. The third is bamboo medicine and healthy curative function patent, up to 334 pieces. In addition, there are 247 pieces of patents in the type of bamboo processing machines and equipments. From the aspect of the invention patents, the patents quantity of bamboo medicine and healthy curative function is more than others, which is 279 pieces. From the aspect of the design patents, the patents quantity of bamboo furniture, handicraft and daily used products are much more than other types, up to 1269 pieces.

## 8 CONCLUSIONS

By counting and analyzing 7722 pieces of bamboo patent applications of ESPACENET and 4005 pieces of Chinese patent, I got some conclusions, as follows:

Development and utilization of bamboo in China reaches the advanced world level. The distribution of bamboo and the local economic development level have a great effect on the patent application. China has 2807 pieces of bamboo patent applications, which is the world second largest country in bamboo patent application, lower than Japan and father more than some developed countries, such as: Britain, America and Germany. We have applied 4005 pieces of bamboo patents since 1985. After the technology infant period and the rapid increasing period, the new technical features index (N) was up to 0.50 in 2006, which shows the new technical features of bamboo patent is continuously increasing and has a great potential for development.

Bamboo patent applications mainly concentrate in the place where bamboo resources are abundance or economy is developed. in Changjiang River-Nanling Mount and South China, such as Zhejiang, Hunan an Guangzhou where bamboo resources are so abundance to supply the base of further development and utilization, and the focus of Bamboo technology has also begun to tilt in these areas. The core patent applications and most of the core figures from the coastal provinces, reflecting the enterprises and individuals more emphasis on the protection of intellectual property in those regions, but also mapping out these areas with a more active atmosphere for technological innovation and fruitful innovations.

In China, the whole patent quality bamboo needs to be raised continuately. The area of bamboo patent mainly concentrated in the everyday life of people with bamboo products, primarily institutions and core personage emphasis on the design patent applications patents, the overall quality is not high. From the overall situation, the needs of people's daily life in the bamboo products are patent applications for the hot of Patent applications, amounted to 2178 pieces, including bamboo mat, bamboo furniture products, chopsticks, bamboo and other living necessities. and patent applications reflecting the level of deep processing of bamboo plywood are 695 pieces, only 17.4%.

The above statistics and analysis show that the future should focus on bamboo patent applications with high applicability, high value-added and high-tech, further to strengthen Panel bamboo, bamboo paper and deep processing of bamboo product development, bamboo patent further enhance the overall quality and improvement (MAO, Y.Q. 2006) . Related departments should fully play its role and actively guide the healthy development of bamboo patents, increase the bamboo processing depth of the development of new products, and strive to play a bamboo resource advantages, further expand the areas of bamboo, bamboo industry to embark on the road of sustainable development (WANG, K.H. et al. 2000).

## REFERENCES

Ding, Y.H.; Li, C.X.; Wen, G.H.; et al. Design and Realization of Strategy Patent Analysis System, *Computer Engineering*, August, pp. 211–213.

Huang, Y.Y.; Zhu, D.H.; Ren, Z.J.; et al. 2006. Patent Information Analysis and Case Study, *Science and Technology Management Research*, December, pp. 121–124.
Liu, L.; Zhu, D.H. 2007. Analysis of the Patent Information Theory and Empirical Research, *Commercial Time*, January, pp. 96–97.
Mao, Y.Q. 2006. Development and utilization of bamboo research, *East china Forest Management*, February, pp. 35–37.
Shao, B. 2006. The Patent Analysis of Enterprise Competitive Intelligence and Counterintelligence, *Information Science*, March, pp. 361–364.
Sheng, G.C. 2002. The course book of Information Retrieval, Higher Education Press.
Guang, M.J.; Zhang, Q.S. 2001. Literature analysis of the topic of Bamboo, *Journal of Bamboo Research*, March, pp. 69–72.
Wang, K.H.; Li, Q. 2000. Present Utilizational Situation and Deep Exploitation of Bamboo Resources, *Journal of Bamboo Research*, April, pp. 69–72.
Xu, Y.M.; Hao, P.Y.; Liu, Q.P. 2003. Advances of Bamboo Properties and Their Resources Exploitation and Utilization, *Journal of Northeast Forestry University*, May, pp. 71–77.
Zhang, Y.; Zhang, W.M. 2007. Patent Information Analysis, *Modem Information*, March, pp. 185–186.
Zhang, Z.H. 2002. Bamboo and rattan in the world, Liaoning science and technology publishing house.

*Material properties*

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# Mechanical properties of Colombian glued laminated bamboo

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ABSTRACT: A study is conducted to establish the suitability of Colombian glued laminated bamboo (Guadua Angustifolia Kunt) for structural applications. As part of this study, selected mechanical properties of glued laminated guadua (GLG) were investigated and they are reported in this paper. Results confirm that GLG has similar mechanical properties to best structural woods in Colombia. A comparison of the mechanical properties obtained in this research with the corresponding data reported around the world indicates that GLG can be suitable as a material for construction of structural elements.

## 1 INTRODUCTION

About 52,000 hectares of specie of bamboo called G*uadua Angustifolia Kunt* grows naturally in some regions in Colombia. Only 40% of the Guadua bamboo is used in structural applications, mainly as material for falsework in the construction of concrete floors. In the Country, there has been some intent to use guadua bamboo as structural material with a relative good success. Nevertheless, one of the problems with the guadua culm is the variability of the mechanical properties since it is used in its natural form. Hence, glued laminated Guadua (GLG) has surged as an alternative solution in which guadua is used as standardized material for construction of structural elements. GLG has been studied only to a limited extent. Preliminary research (Duran 2003, Vanegas 2003) indicated that the GLG has an excellent mechanical properties and it is as good as the best structural wood in Colombia.

The Universidad de Los Andes in Bogotá is conducting for the first time in Colombia a detailed study of the structural performance of the GLG. This research consists of physical and mechanical characterization, strength verification of structural elements, and behavior of typical connections and seismic validations of construction systems. Selected mechanical properties of the GLG like: compressive strength perpendicular and parallel to grain, tensile strength perpendicular to grain, flexural strength, shear strength parallel to grain and internal bond strength are presented in this paper. A comparison of the mechanical properties obtained in this research with the corresponding data reported in the literature is shown.

## 2 MATERIAL AND PRODUCTION METHOD

### 2.1 *Material*

Guadua bamboo culms are obtained from Caidedonia-Valle in Colombia. The average top and base diameter of the bamboo are 7 cm to 14 cm, respectively with an average height of 30 m. The average thickness of the culm wall varies from 0.8 cm to 2.0 cm. The age of the bamboo varies from 4 to 6 years.

## 2.2 *Production method*

The manufacture of the GLG is carreout in Colguadua Ltda factory. The culms are cut into 2 to 3 meters lengths and they are taking into the warehouse of the factory. The culms sections are cut again into 1 m to 1.5 m in order to have straight pieces. Each piece is split in the radial direction into proper number of slices and the node sections are removed. The slices are dried in oven to an average moisture content of 6% to 8%. Once the slices are dried, they are immersed in a chemical solution to protect bamboo against insects attack. Each slice is machined by cutting off the inner and outer faces and form guadua lamina with thickness varying from 7 mm to 10 mm. All laminas are impregnated with polyvinyl acetate (PVA) adhesive and staked to form laminated Guadua sheeting. Each laminated Guadua is cold pressed in hydraulic press at a pressure of 2 MPa for 15 minutes.

# 3 EXPERIMENTAL PROGRAM

Temperature, moisture content and relative humidity were recorded for all specimens. Tests were conducted on a MTS Universal Testing Machine at the Material Lab at the Universidad de Los Andes in Bogotá, Colombia. All the specimens follow the specifications of the Colombian Institute of Standards (ICONTEC) for woody materials which are based on the ASTM D143-52 -1997 standards. Test procedures are summarized as follows:

## 3.1 *Compression parallel to grain- ICONTEC 784*

The specimens were 50 mm by 50 mm in section and 200 mm in length. A continuously compression load with load rate of 0.6 mm/min was applied. The load-displacement curve is recorded and the modulus of elasticity (MOE), the proportional limit and the ultimate stress are determined.

## 3.2 *Compression perpendicular to grain- ICONTEC 785*

The specimens were 50 mm by 50 mm in section and 150 mm in length. MTS load frame with a bearing metal plate 50 mm wide was used to apply a continuously compression load with a load rate of 0.3 mm/min. The load was applied up to a deformation equal to 5% of the specimen thickness and the proportional limit stress is calculated.

## 3.3 *Flexural strength- ICONTEC 663*

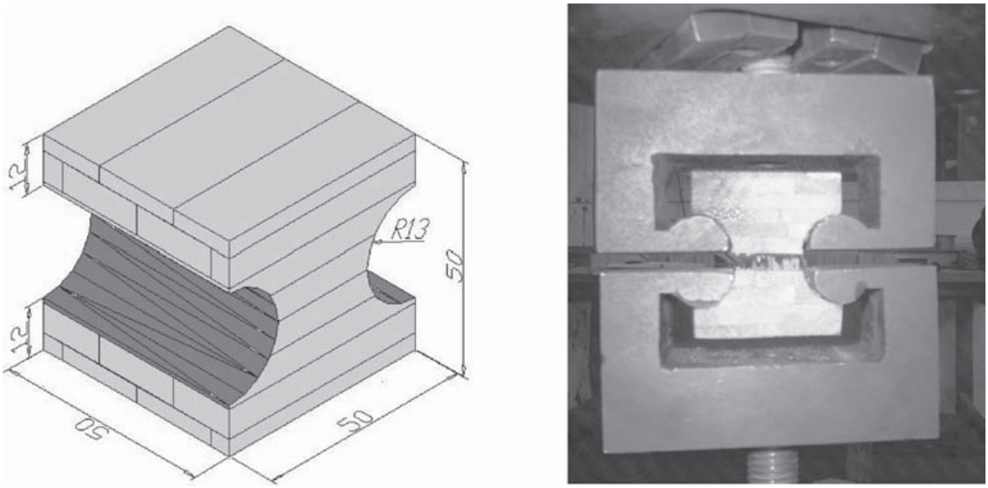
The specimens were 25 mm by 25 mm in section and 410 mm in length. The load was applied at the center of a 350 mm span with a load rate of 2.5 mm/min. The failure load is recorded and the module of rupture (MOR) is calculated.

## 3.4 *Tensile strength perpendicular to grain- ICONTEC 784*

Figure 1 presents the dimensions of the tensile test specimen. The load was applied continuously throughout the test at the rate with a movable crosshead of 2.5 mm/min. Ultimate tensile stress is calculated.

## 3.5 *Shear strength parallel to grain- ICONTEC 775*

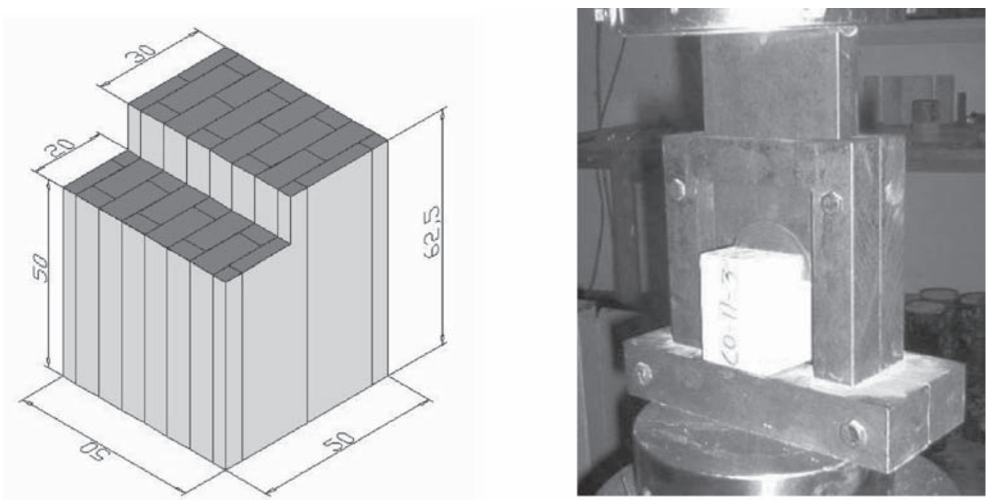
Dimensions of the specimen as well as the test setup are shown in Figure 2. The load was applied continuously throughout the test at the rate of 0.6 mm/min. Ultimate shear stress is calculated.




(a) Specimen Dimensions [mm]

(b) Test Setup

Figure 1. Tensile test.




(a) Specimen Dimensions [mm]

(b) Test Setup

Figure 2. Shear parallel to grain test.

### 3.6 *Internal bond strength*

The block-type glue-line shear test was used to evaluate internal bond strength and it is based on ASTM D1037. Figure 3 presents the dimensions of the test specimen and the test setup. The load was applied through a self aligning seat with a continuous motion of the movable head of the testing machine of 0.6 mm/min. Shear stress at failure based on maximum load is determined.

Table 1. Summary of test results of Glued Laminated Guadua (GLB).

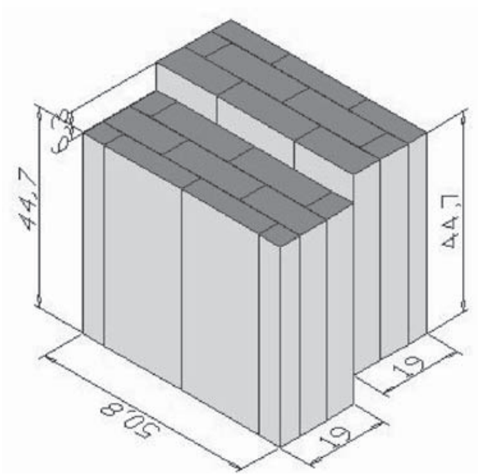
| | Glued Laminated Guadua | | | | | | | NSR-98 wood grade | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 5% Percentil (MPa) | | |
| Test | N | T (C) | MC (%) | RH (%) | Result (MPa) | VC (%) | 5% Percentil (MPa) | A | B | C |
| Compresion parallel to grain | 33 | 20.5 | 10.44 | 63.06 | $\sigma_{ult} = 47.6$ | 5.42 | $\sigma_{ult} = 43.59$ | $\sigma_{ult} = 29.59$ | 22.45 | 16.33 |
| | 32 | | | | $\sigma_{pl} = 35.71$ | 5.48 | $\sigma_{pl} = 32.79$ | $\sigma_{pl}$ = ND | ND | ND |
| | 31 | | | | MOE = 19,140 | 8.49 | MOE = 16,000.0 | MOE = ND | ND | ND |
| Compresion perpendicular to grain | 29 | 19.23 | 10.15 | 67.57 | $\sigma_{pl} = 5.4$ | 14.66 | $\sigma_{pl} = 2.63$ | $\sigma_{pl} = 6.5$ | 4.57 | 2.45 |
| Tension perpendicular to grain | 17 | 20.18 | 12.64 | 62.59 | $\sigma_{ult} = 1.49$ | 29.9 | $\sigma_{ult} = 0.76$ | $\sigma_{ult}$ = ND | ND | ND |
| Static bending | 21 | 21.03 | 12.76 | 66.4 | MOR = 81.9 | 14.79 | MOR = 60.66 | MOR = 68.45 | 48.89 | 32.6 |
| Shear parallel to grain | 30 | 18.08 | 10.79 | 70.18 | $\sigma_{ult} = 9.32$ | 12.63 | $\sigma_{ult} = 7.68$ | $\sigma_{ult} = 6.12$ | 4.9 | 3.27 |
| Glue-line shear test | 32 | 19.25 | 13.44 | 70.56 | $\sigma_{ult} = 7.92$ | 12.29 | $\sigma_{ult} = 6.64$ | $\sigma_{ult}$ = ND | ND | ND |

N°: Number of Specimens, T: Temperature, MC: Moisture content, RH: Relative Humidity, $\sigma_{ult}$: Ultimate Stress, $\sigma_{pl}$: Proportional Limit Stress, MOE: Elasticity Modulate, MOR: Modulus of rupture, VC: Variation Coefficient.

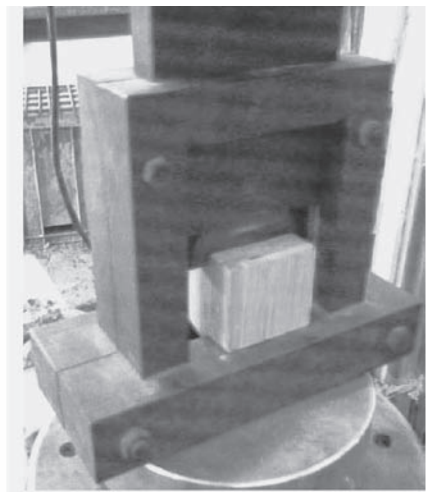
4 RESULTS AND DISCUSSION

Test average results with the corresponding number of specimens, temperature, average moisture content and relative humidity are shown in Table 1. An average of 19.7°C, 11.7%, and 66.7% of temperature, moisture content and relative humidity were recorded at the moment of the tests. Also in Table 1, the 5th percentiles of the results and the corresponding mechanical properties of the structural wood according to Colombian Seismic Regulations (NSR, 1998) are shown for comparison.

The compression parallel to grain (CPAG) test showed a combination of crushing and buckling failure for most of the specimens. The 5th percentile value of the ultimate stress for CPAG is 47% higher than the best Colombian wood (grade A). The compression perpendicular to the grain test was performed with the adhesive line horizontal respect to the load application. The failure mode of the CPEG test was crushing of the material. Relatively low value of the 5th percentile was achieved in CPEG test compared to Colombian wood. In order to know the effect of the orientation of the adhesive line (horizontal vs. vertical), an additional CPEG test was performed with load




(a) Specimen Dimensions [mm]



(b) Test Setup

Figure 3. The block-type glue-line shear test.

Table 2. Comparison of compression parallel to grain stress of GLB.

| Author | Year | Bamboo | Adhesive | Compression parallel to grain (MPa) |
|---|---|---|---|---|
| BARRETO C.W. | 2003 | Guadua angustifolia kunt | Urea Formaldehyde Resin | 47.2 |
| | | | Polychloroprene | 46.5 |
| | | | Urea Formaldehyde Resin | 34.0 |
| DURAN G.L | 2003 | Guadua angustifolia kunt | Polychloroprene | 46.5 |
| CORREAL D.J.F., LOPEZ M.L.F. | 2007 | Guadua angustifolia kunt | Polyvinyl of Acetate (PVA) | 47.6 |

applied to specimens with vertical adhesive line. As a result, the ultimate stress for CPEG with vertical adhesive line increased 41% compared to CPEG with horizontal adhesive line.

Adhesive failure was observed in all the specimens of the tension perpendicular to grain (TPG) tests. It seems that the adhesive spread rate was not constant during the construction process of these specimens which could explain the high variation coefficient obtained in the TPG test. Delimitation failure was presented in most of the specimens of the static bending (SB) test. MOR obtained from the SB test is comparable to grade B Colombian wood. The failure mode observed in the shear parallel to grain (SPG) test was shear-off the specimen. The shear strength from SPG test is 25% higher compared to Colombia wood grade A. The glue-line shear test specimens failed in the interlaminate adhesive as expected.

A comparison of compression parallel to grain (CPAG) stress of GLG with different adhesive is shown in Table 2. There was no difference between the CPAG stress of GLG with Polychloroprene and with PVA. In addition, the CPAG stress of GLG with PVA is similar in magnitude compared to the higher stress obtained with urea-formaldehyde resin (UFR) adhesive.

Moso bamboo grows in the southern of the United States. A previous study (Lee A 1998) has been performed in glued laminated moso bamboo (GLM). Table 3 shows a comparison of internal bond (IB) strength and MOR of glued laminated Guadua (GLG) and glued laminated moso bamboo (GLM). The IB strength for PVA adhesive is higher compare to UFR adhesive when it is used in GLG. Disregarding the adhesive type, the IB strength is higher in GLG compare to GLM. The difference in IB strength in GLB and GLM can be associated with different adhesive spread rates. Nonetheless, it seems that the differences in IB strength between GLG and GLM did not affect the MOR. Whereas the difference between GLG and GLM in IB strength is about 372% and in MOR is only 20%. It appears that once the optimum amount of adhesive is achieved, the IB strength do not have a significant affect on the MOR (Nugroho and Ando 2001).

Table 3. Comparison of internal bond strength and MOR for GLB and glued laminated moso bamboo.

| Author | Year | Bamboo | Adhesive | Internal bond (MPa) | Beam Type | Static bending MOR (MPa) |
|---|---|---|---|---|---|---|
| BARRETO C.W. | 2003 | Guadua angustifolia kunt | UFR | 3.91 | ND | ND |
| DURAN G.L | 2003 | Guadua angustifolia kunt | UFR | 3.01 | | |
| | | | PCP | 5.67 | | |
| | | | PVA | 4.22 | ND | ND |
| CORREAL D.J.F. | 2007 | Guadua angustifolia kunt | PVA | 7.92 | ND | 81.9 |
| LEE W.C.A., BAI X., BANGI A.P. | 1998 | Moso Bamboo | RFR | 2.13 | H-beam | 98.6 |
| | | | | | V-beam | 104.8 |
| NUGROHO N., ANDO N. | 2000 | Moso Bamboo | E-MDI | 0.81 | ND | 76.84 |
| NUGROHO N., ANDO N. | 2001 | Moso Bamboo | RFR | 0.59 | H-beam | 70.31 |
| | | | | | V-beam | 77.04 |

UFR: Urea Formaldehyde Resin, PCP: Polychloroprene, PVA: Polyvinyl of Acetate, RFR: Resorcinol Formaldehyde Resin, E-MDI: Emulsion methyldiisocayanate resin.

## 5 CONCLUSIONS

Based on the preliminary results of this research, the following conclusions are drawn:

1. Glued laminated Guadua (Colombian Bamboo) has comparable mechanical properties to structural Colombian wood. In some cases, the mechanical properties of the GLG are better than those of the best structural wood in Colombia.
2. The compression parallel to grain stress is not affected by the type of adhesive and the internal bond strength in glued laminated Guadua.
3. Modulus of rupture for glued laminated Guadua and glued laminated Moso is not affected by the internal bond strength once the optimum amount of adhesive is achieved. In general the MOR of the glued laminated Guadua is comparable to glued laminated Moso.
4. Based on the comparison of glued laminated Guadua (GLG) to structural Colombian wood and glued laminated moso bamboo, GLG can be suitable as a material for construction of structural elements.

## ACKNOWLEDGEMENT

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## REFERENCES

ASTM. 1997. *Standard methods of testing small clear specimens of timber*. Part 22. D143–52. Philadelphia, PA.

Barreto C.W. 2003. Evolución de guadua laminada pegada aplicada a propuesta de reticulado plano. t*esis de grado arquitectura*. Universidad Nacional de Colombia sede Bogota.

Duran, L. 2003. Estudio de Guadua Laminada y su Aplicación al Sistema Tensegrity. *Thesis Work in Architecture*, Universidad Nacional de Colombia sede Bogotá.

Instituto Colombiano de Normas Técnicas y Certificación, ICOTEC 663, 775, 784 y 785, Maderas, 1974, Bogotá-Colombia.

Lee A. Bai X. Bangai A. 1997. Flexural Properties of Bamboo-Reinforced Southern Pine OSB Beams. *Journal Forest Products* 47(6): ABI/IMFORM Global Pg 74.

Lee A. Bai X. Bangai A. 1998. Selected Properties of Laboratory-Made Laminated-Lumber. *Journal Holzforschung* Vol 52, N°2.

Normas Colombianas de Diseño y Construcción Sismoresistente, NSR-98, Ley 400 de 1997 y Decreto 33 de 1998, publicada y distribuida por la Asociación de Ingeniería Sísmica, AIS.

Nugroho N. Ando N. 2000. Development of Structural Composite Products Made From Bamboo I: Fundamental Properties of Bamboo Zephry Board. *Journal Wood Sci* 46: 68–74.

Nugroho N. Ando N. 2001. Development of Structural Composite Products Made From Bamboo II: Fundamental Properties of Laminated Bamboo Lumber. *Journal Wood Sci* 47: 237–242.

Vanegas G. 2003. Guadua Laminada Investigación, Experimentación y Aplicación. *Thesis Work in Architecture*. Universidad Nacional de Colombia sede Bogotá.

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# Manufacture of drift pins and boards made from bamboo fiber for timber structures

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ABSTRACT: The law concerning the construction recycling was enforced in Japan in 2002. Therefore, the discretion dismantlement of the building and housing was obligated. As a result, the discretion dismantlement with a wood, wood-based material and metallic joint tools is becoming a problem now. If the joint materials and the whole building materials can be composed of the wood-based material, it is very effective for the dismantlement of building. In addition, wood-based materials have a big advantage to earthquake-proof because of light materials. Bamboo having high-strength fiber is a quick grower, and has received attention as a lingo-cellulosic material. In this research, the drift pin and the plate were made by using the long fiber of the bamboo. The fiber was obtained by alkali treatment. The drift pin was made for the direction of one axis. The plate has three layers, the surface layers were composed of short fibers and the core layer was composed of long fibers. The performance of these joint materials was evaluated by bending and two types of shear tests. The bending strength and young's modulus of the φ12 mm drift pin were 350–400 MPa and 50 GPa, respectively. The bearing strength of the plate which is parallel to the grain for the force direction was about 10 kN. Moreover, the two types of connection were proposed and each tensile strength of both types exceeded 15 kN.

## 1 INTRODUCTION

In timber structures which are between housing and heavy timber structure, nails, drift pins, bolts and steel plates are typically used. A law concerning construction recycling was passed in Japan in 2002 which placed specific restrictions on the dismantlement of buildings and housing. As a result, the dismantlement of buildings containing wood, wood-based materials and metallic joint tools has become complicated. Dismantlement is much simpler if joint materials and all building materials are wood-based. In addition, wood-based materials, because they are lightweight, are more earthquake resistant. Bamboo, because it contains high-strength fiber and grows quickly, has received attention as a lingo-cellulosic material.

In ancient Japan, natural nails made from bamboo or *Utsugi* were used to fasten slumber boards and to anchor roof materials made of the skin of the Cypress. In recent years, Tomita developed a bracing connector for wooden shear walls using structural plywood, and Inoue developed a high-performance bamboo nail and a shear plate made of compressed wood. In addition, Nakata developed a drift pin and a board made of compressed plywood. Bamboo has received much attention as a biomass material because it contains high performance fiber and grows very quickly. On the other hand, it is known that bamboo encroaches on forest environments. Therefore, the effective use of bamboo should be the subject of further research. In the present study, a drift pin and plate were made by using the long fiber of the bamboo. The fiber was obtained by an alkali treatment. The drift pin was made for the direction of one axis. The plate has three layers. The surface layers were composed of short fibers, and the core layer was composed of long fibers. Also, we evaluated the strength performance of the drift pins and the boards. In addition, joint methods using the drift pins and boards were proposed and evaluated.

## 2 MAKING FIBER AND MATERIALS

### 2.1 *Alkali treatment*

We used 4-year-old bamboo (*Phyllostachys bambusoides*) from Oita, which is a prefecture in Japan widely known for its bamboo production. The bamboo was cut to 350 mm lengths to exclude knots, and the lengths were then divided into eight cross-sectional pieces. The pieces were treated with alkali solution in a stainless steel box for 5 hours at a temperature of about 70°C. As the alkali solution, 83.28 g (1 mol) of sodium hydroxide was dissolved in 1 *l* of water. After the treatment, the bamboo was washed with water and separated into long fibers and short fibers. The long fibers were bundles (Figure 1), and the short fibers were parenchyma cells. The long fibers were washed again and air-dried.

### 2.2 *Materials*

The drift pins were manufactured as follows. Bamboo long fibers with a mass of 210 g were impregnated with 300 g of acetone-diluted PMDI solution (30%). The impregnated fibers were put into a steel jig (13 × 40 × 300 mm) then pressed at 140°C for 20 minutes under 19.6 MPa of pressure. After being cooled, the fibers were removed from the press machine. Finally, the pressed bamboo long fibers were formed into pins of 12 × 12 × 260 mm.

As for the manufacture of the boards, 330 g bamboo long fibers were impregnated with 300 g of acetone-diluted PMDI solution (30%), and 150 g bamboo short fibers were sprayed with 45.3 g of acetone-diluted PMDI solution (30%) using a spray gun. The impregnated fibers and sprayed fibers were put into a wooden jig (10 × 300 × 300 mm). In this case, the board had three layers, the surface layers were composed of short fibers, and the core layer was composed of long fibers (Figure 2). The target density for this board was 1.2 g/cm$^2$. It was then pressed at 140°C for 10 minutes under 19.6 MPa. After cooling, it was removed from the press machine. This board was used as an insertion plate.

Outer layers are made of bamboo short fibers. Core layer is made of bamboo long fibers.

## 3 EVALUATION OF EACH CONNECTING TOOL

### 3.1 *Bending performance of drift pins*

The drift pin was evaluated in a three-point bending test in which a 200 mm span and a 2 mm/min. loading speed were used. Two types of specimens were tested, one whose cross-sectional shape

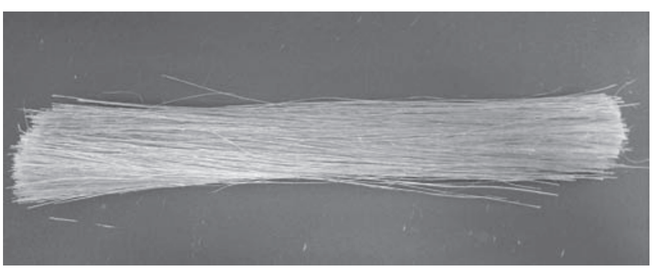

Figure 1. Bamboo long fiber.

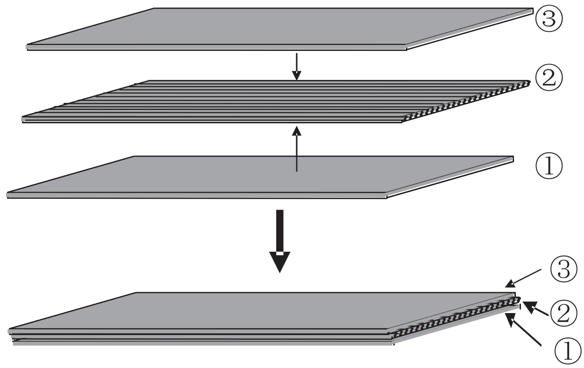


Figure 2. Layers of the bamboo board.

Table 1. Results of properties obtained from bending test.

| Specimen's name | MOR [MPa] | MOE [GPa] |
|---|---|---|
| SP–1 | 393 | 55 |
| SP–2 | 351 | 53 |
| SP–3 | 361 | 53 |
| Average | 368 | 54 |
| CP–1 | 448 | 55 |
| CP–2 | 411 | 48 |
| CP–3 | 385 | 47 |
| Average | 415 | 50 |

was square (12 × 12 mm), and another whose cross-sectional shape was round (φ12 mm). The round type was formed using a belt sander. Three specimens of each type were tested.

The results for all specimens are shown in Table 1. "SP" refers to the square specimens, and "CP" refers to the round specimens. The values shown in Table 1 are high, with MOR over 350 MPa and MOE of approximately 50 GPa. These drift pins thus showed a good bending performance, but were inferior to steel pins in terms of MOE.

The fracture mode of the drift pin is shown in Figure 3. In the SP type, all of the specimens failed due to shearing, but in the CP type two specimens failed due to bending and another failed due to shearing. As a result, it is clear that it is an anisotropic material, and that the shearing resistance of materials united by bonding should not be able to be expected high. Matsumoto's graduation thesis showed that, in a nail made from bamboo fibers, the PMDI was not sufficient for uniting the fibers, and the nail could not be driven as a nail because the fibers became separated and each fiber buckled.

### 3.2 *Shearing performance of the boards*

Shearing stress was applied to a hole in the board by pulling a bolt that was inserted in the board by the material testing machine. The board had two holes, one of φ12 mm and another of φ16 mm. We evaluated the shearing performance of the φ12 mm hole because we wanted to use a drift pin that was φ12 mm. The dimensions of the specimen used in the board-shearing test are given in Figure 4. The testing speed was assumed to be 2 mm/min. In two specimens, the stress was loaded parallel to the grain of the long fibers, while in one specimen the stress was loaded in another direction.

Figure 3. Failure mode of drift pin under bending stress. (upper: Round type, bottom: Square type)

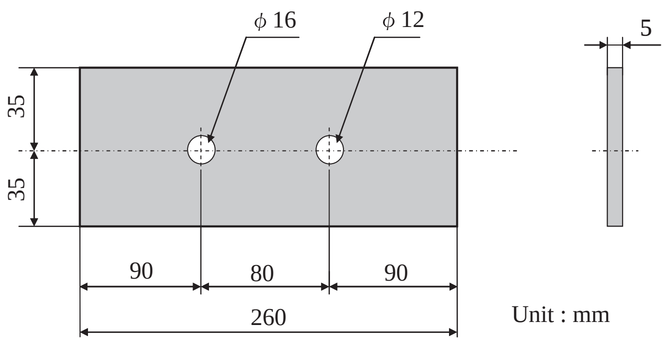


Figure 4. Dimensions of specimen used in board shearing test.

The relationship between load and deformation is shown in Figure 5. The specimen in which the stress was applied parallel to the grain showed high stiffness and bearing strength, but the specimen that received perpendicular stress did not perform well. The failure mode differed between specimens that underwent the two types of stress. Those receiving the parallel type failed from the outside layers, but those undergoing the perpendicular type failed from the core layer due to the splitting stress.

### 3.3 *Shearing performance of the joint constructed of drift pin and board*

These specimens were constructed of glulam (JAS Grade E105-F300) and bamboo boards connected by means of a φ12 mm drift pin. In this case, the glulam 5 mm boards named side member. The details of this specimen are shown in Figure 6. The testing speed was assumed to be 2 mm/min. The force was applied in two directions: parallel and perpendicular to the side member's grain.

The relationship between load and displacement obtained from the shearing test is shown in Figure 7. The results of all specimens are given in Table 2. ST1 refers to the specimens to which force was applied parallel to the grain of the side member, and ST2 refers to those receiving the perpendicular force. The specimens all performed similarly under the shear force. We expected

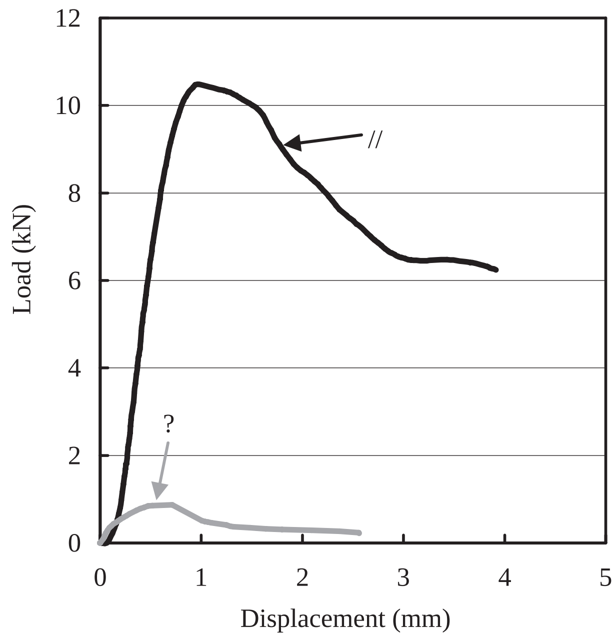


Figure 5. Relationship between load and displacement obtained from board shearing test (//: Parallel to the grain, ⊥: Perpendicular to the grain).

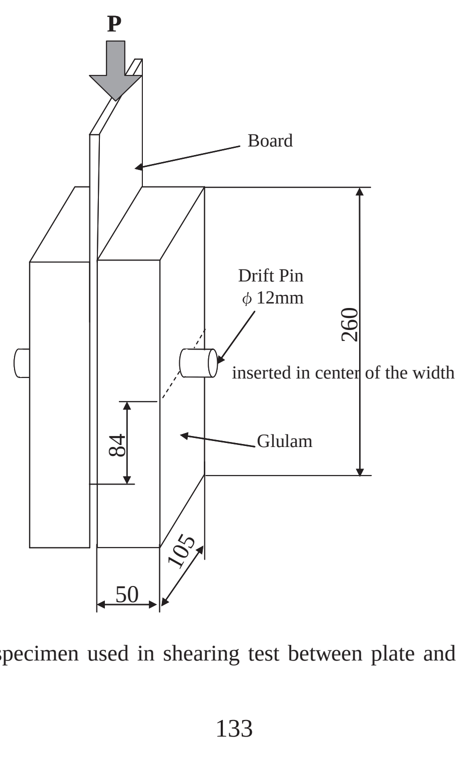


Figure 6. Dimensions of specimen used in shearing test between plate and side members with drift pin (Unit: mm).

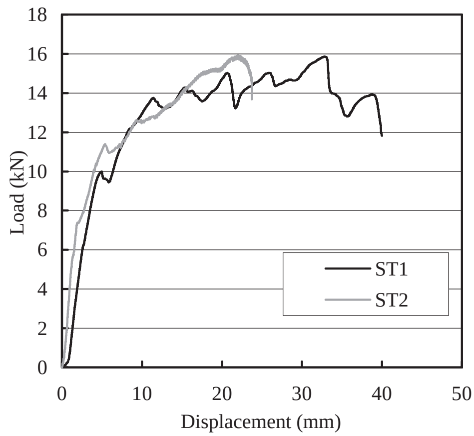


Figure 7. Relationship between load and displacement obtained from shearing test using board and drift pin (Black line: Glulam is parallel to the grain, Gray line: Glulam is perpendicular to the grain).

Table 2. Results of shearing test for connections using board and drift pin.

| Specimen's name | Bearing strength [kN] | Yield strength [kN] | Initial stiffness [kN/mm] |
|---|---|---|---|
| ST1–1 | 15.86 | 4.64 | 1.12 |
| ST1–2 | 15.77 | 4.86 | 1.27 |
| ST1–3 | 16.46 | 4.02 | 1.12 |
| Average | 16.03 | 4.51 | 1.17 |
| ST2–1 | 15.88 | 4.86 | 1.28 |

the initial stiffness of each type to be different, but the initial stiffness of ST1 and ST2 showed almost the same value, and the failure mode of ST2 occurred the bearing of the board same as ST1. In addition, the simple shearing performance of the board in the tensile test differed according to the grain direction of the board, but in this case, the boards had the same grain direction. So the failure mode of the board was the same as in the simple shearing test with the force applied parallel to the grain.

## 4 EVALUATION OF PROPOSED JOINT SPECIMEN

### 4.1 *Specimens and experiments*

The specimens were composed of glulam (JAS grade: E105-F345) made from Larch, an insertion board, and drift pins of φ12 mm as connectors. This specimen was a joint of the column and sill. The details of the specimen are shown in Figure 8. There were two types of specimen in which either one board or two boards were inserted, and three examples of each type of specimen were used in the experiment. A detail of the boards is shown in Figure 9. The direction of the long fiber was the same as the direction of the length axis. In the single-board specimens, the board's position was at the center, while in the double-board specimens, the boards were positioned 25 mm from each side. The column and sill members had the same size hole as the boards. This time, the sill was cut all of the length, but the sill will be cut a slit for inserting the board when we will use this joint.

Figure 10 shows the tensile test set-up. The column and the jig were connected by bolts, and the sill and the base of the testing frame were connected at 400 mm from the center of the sill using

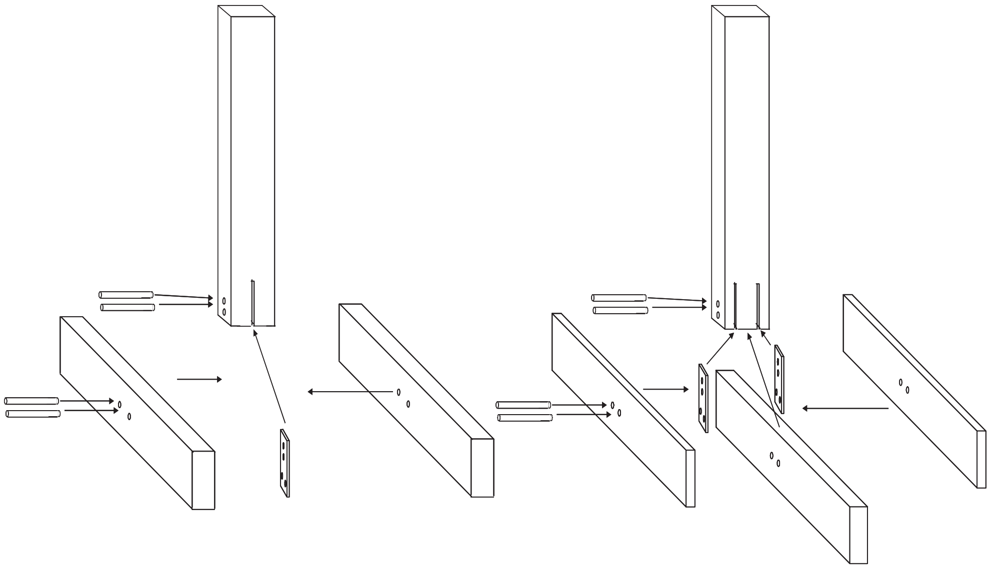

Figure 8.  Specimen composed using boards and drift pins (Left: single-board type, Right: double-board type).

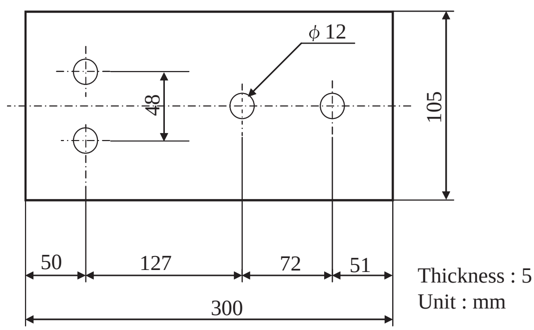


Figure 9.  Detail of the inserted board.

bolts. In the experiment, the column was pulled out from the sill, causing tensile stress in the joint part. The load was measured using the load cell and the relative displacement of the column and sill was measured with the transducers.

### 4.2 *Results of the tensile test of the column and sill joint*

The relationship between load and displacement obtained from the tensile test of the column and sill joint is shown on Figure 11. The maximum and yield strength were different between the single-board type and double-board type. We estimated the strength of the double-board type using the formula of Sawata and obtained a result of 17.2 kN per drift pin. We concluded that the specimen failed from the sill. The strength of the single-board was estimated to be twice that of the board shear test of parallel to the grain, because the single type used twice number of drift pins, and the failure mode of the board shearing test was not brittle. As a result, these estimations were good agreement.

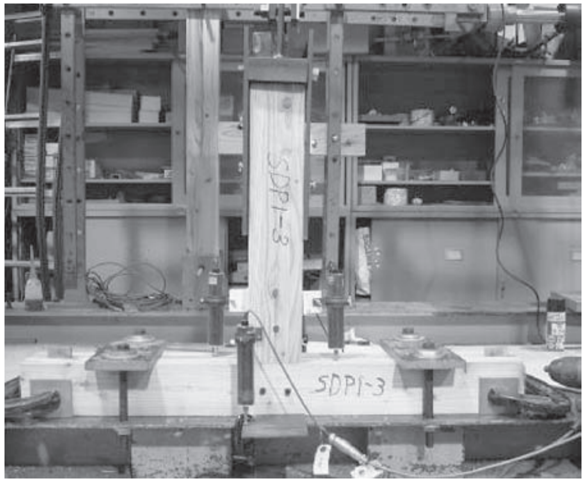


Figure 10. Set-up of the tensile test specimen.

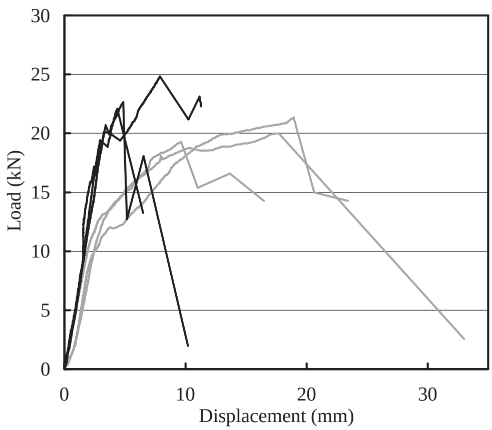


Figure 11. Relationship between load and displacement obtained from tensile test of column and sill joint (Gray line: single-board type, Black line: double-board type).

The failure modes are shown in Figure 12 and 13. The single type showed almost the same failure mode and deformation performance as shown in the board shearing test. The double type failed from the sill by bending and splitting. The value of the maximum strength of each type exceeded the strength of the steel connector CP-T, which is the connector used between column and sill in general housing.

## 5 CONCLUSIONS

In this research, the drift pin and the boards made of bamboo fiber showed high strength performance.

The drift pin showed good bending performance. The bending strength and Young's modulus of the φ12 mm drift pin were 350–400 MPa and 50 GPa, respectively.

Figure 12. Failure mode of the single-board type.

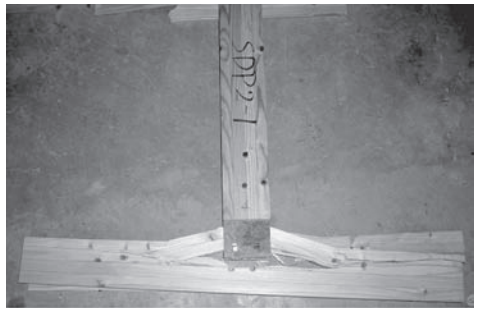

Figure 13. Failure mode of the double-board type.

The board to which force was applied parallel to the grain showed good bearing and shearing performance. The bearing strength of the board to which force was applied parallel to the grain was about 10 kN.

Moreover, two types of connection were proposed and the tensile strength of both types exceeded 15 kN. Therefore, it was shown that this material could be used to construct timber structures in the future.

## ACKNOWLEDGEMENT

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## REFERENCES

K. Nakata, H. Sugimoto, M. Inoue, S. Kawai, 1997. Development of Compressed Wood Fasteners for Timber Construction 1. Mechanical properties of phenolic resin impregnated compressed laminated veneer lumber. *Mokuzai Gakkaishi* 43(1): 38–45. (in Japanese).

K. Sawata, T. Sasaki, S. Kanetaka, 2006. Estimation of shear strength of dowel-type timber connections with multiple slotted-in steel plates by European yield theory. *Journal of Wood Science* 52(6): 496–502.

K. Shirasu, A. Sasagawa, H. Isoda, Y. Shionoiri, 1997. Cyclic load tests on bracing bearing wall for understanding hysteretic characteristics Part 2: Test on joint connection. *Summaries of technical papers of the annual meeting of the Architectural Institute of Japan, C-1, Structures 3*: 43–44. (in Japanese).

M. Inoue, T. Mori, 2003. High Performance Bamboo Nail. *Summaries of technical papers of the annual meeting of the Architectural Institute of Japan, C-1, Structures 3*: 43–44. (in Japanese).

M. Inoue, K. Tanaka, M. Inoue, S. Ukyo, T. Soma, M. Inayama, N. Ando, 2006. Connecting System Wood Based Shear Plate 1: Suggestions Regarding Wooden Shear Plates, Rods, and Fasteners. *Summaries of technical papers of the annual meeting of the Architectural Institute of Japan, C-1, Structures 3*: 55–56. (in Japanese).

M. Norimoto, 2006. Bamboo and Its Fiber. *Mokuzai Kogyo* 61(10): 430–433. (in Japanese).

M. Tomita, H. Nakatani, 1999. Shear strength of conventional wooden shear wall with brace jointed by structural plywood connectors. *Summaries of technical papers of [the] annual meeting of the Architectural Institute of Japan, C-1, Structures 3*: 203–204. (in Japanese).

T. Mori, K. Umemura, M. Sasada, M. Norimoto, 2007. Development of Drift Pins and Boards Made from Bamboo Fiber for Timber Structures. *Proc. of the 56th JSMS Annual Meeting*: 193–194. (in Japanese).

Unpublished, H. Matsumoto, 2007. Evaluation of joint using plate and nail made from bamboo fiber. *Graduation thesis* at the Faculty of Engineering of Doshisha University. (in Japanese).

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# Reinforcement using bamboo board and rod around bolt hole at fastener joint in timber structure

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ABSTRACT: Main objective of this study is to prevent brittle failure and to enhance the strength of fastener joint such as the bolt or drift-pin joints through local reinforcement or GIR (glued-in rod) system. The tension tests were carried out to confirm the effect of the strengthening method for fastener joints using bamboo plywood or bamboo GIR system. From test results, the local reinforcement members and the effect of the member size on the mechanical behavior of the joint were discussed. The performance of the strengthened joint was improved. From test results by the GIR system, the effect of the distance between the bolt and the GIR on the mechanical behavior of the joint was discussed. In addition, 3-D non-linear finite element models were developed to simulate structural behavior of the fasteners strengthened by typical local reinforcement and GIR system. Reasonably good correlation was obtained.

## 1 INTRODUCTION

The long span or large timber structures are constructed frequently. In the large structures, the higher strength performance is required. The long distance between the bolt or drift-pin hole and edge is necessary in the case of fastener joint. In this study, the method of strengthening joint and preventing the brittle failure at the joint with a short edge distance is proposed. In addition, the good design for joint is proposed. The edge distance will be reduced using the local reinforcement and GIR strengthening system.

## 2 TEST SPECIMENS

Table 1 shows the list of test specimen. Fig. 1 and 2 show the shape and size of specimen and the details of strengthening part of specimen. The distance from the center of bolt hole to the top end of metal rod is defined as “a”. The parameters are the type of strengthening method (the attached local reinforcing member, GIR system), edge distance (5d, 7d) in only specimens without strengthening, and “a” (1d~3d) (d: diameter of bolt). Six specimens (2 series × 3 specimens) without strengthening, nine specimens (3 series × 3 specimens ) with strengthening by the attached board member and nine specimens (3 series × 3 specimens ) with strengthening by GIR system were tested.

## 3 MATERIAL

Two by four dimension lumbers (SPF) were adopted as specimens. Young’s modulus of the specimen are 8.2~19.1 GPa. The moisture content of specimen is 18~31%. Densified bamboo plywood

Table 1. List of test specimen.

| Non-Strengthening | | | Strengthening (1) | | | | Strengthening (2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Name | L:End Distance | Number of specimen | Name | L:End Distance | Dimension | Number of specimen | Name | L:End Distance | a: Distance between bolt hole to metal rod | Number of specimen |
| N–51 | 5d (100) | 3 | BP-5l-S | 5d (100) | 88*88 | 3 | B-5l-1a | 5d (100) | 1d (20) | 3 |
| N–71 | 7d (140) | 3 | BP-5l-I | 5d (100) | 88*128 | 3 | B-5l-2a | 5d (100) | 2d (20) | 3 |
| | | | BP-5l-E | 5d (100) | 88*140 | 3 | B-5l-3a | 5d (100) | 3d (20) | 3 |

(d:Diameter of Bolt)

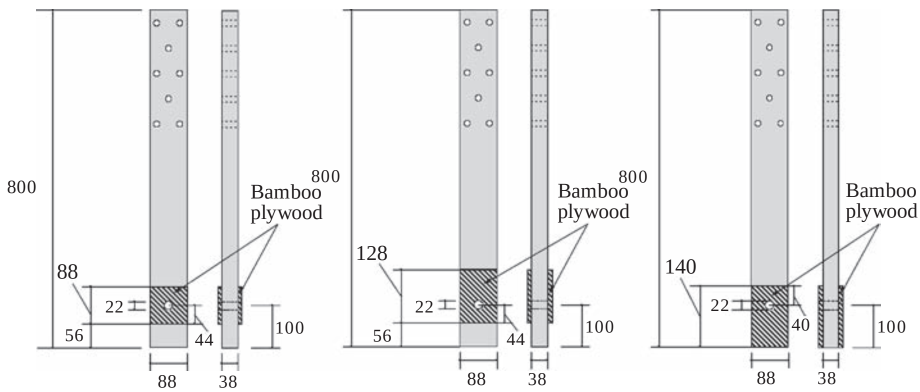



Figure 1. Shape and size of specimen (method of the local reinforcing member: unit in mm).

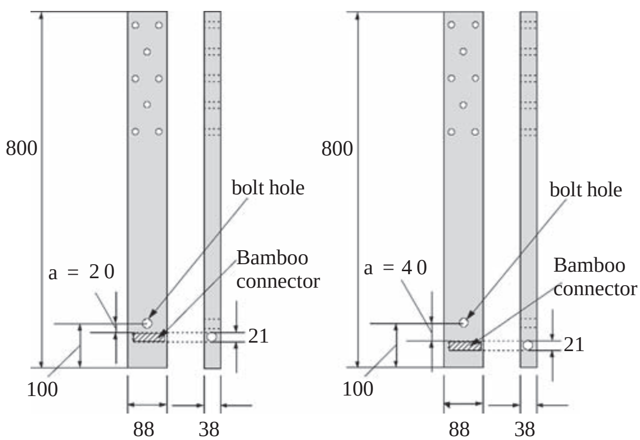



Figure 2. Shape and size of specimen (GIR system: unit in mm).

is adopted as the attached local reinforcing member (see Photo 1) and bamboo connector in GIR system (see Photo 2). Fig. 3 shows the production method of the densified bamboo plywood. The bamboo connector used in the GIR strengthening system is made of laminated bamboo.

## 4 STRENGTHENING METHOD USING GIR SYSTEM

Timber connecting system using adhesive and bamboo connector developed by authors is adopted as strengthening method of fastener joints.The size of bamboo connector used in 9 specimens is 18 mm in diameter and 70 mm in length.

The assembly processes of strengthening for this system is shown in Fig. 4 and are listed as follows.

1. Holes for S-type rods are drilled using an electric drill. Hole diameters are 3 mm larger than the diameter of bamboo connector.
2. Adhesive (urethane bond) is pumped into the cavities around the bamboo connector by a conventional caulking gun. Pumped adhesive reaches to the cavity through the inside hole of rod.

3. Filling up of adhesive is confirmed by watching the adhesive which comes up through the space around the outside hole of rod.
4. Small wood piece is driven into the hole for rod.

There is no specimen with poor filling up of the adhesive at the gap between the timber hole and the bamboo rod in all test specimens. In this strengthening method, the urethane bond was used as adhesive.

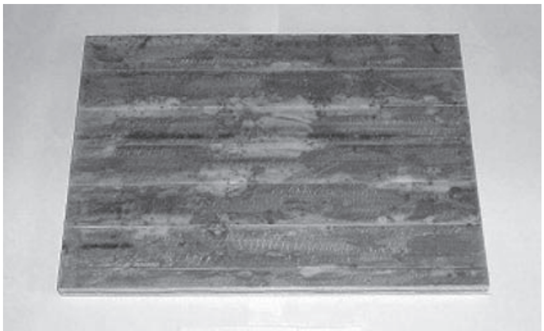


Photo 1. Densified bamboo plywood.

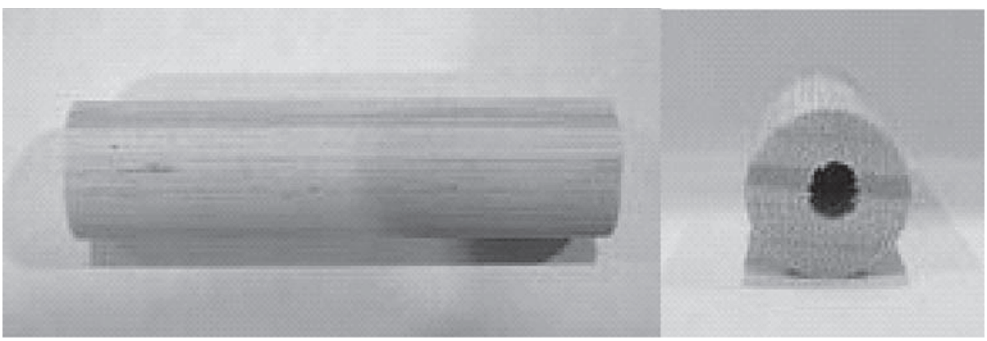


Photo 2. Bamboo connector.

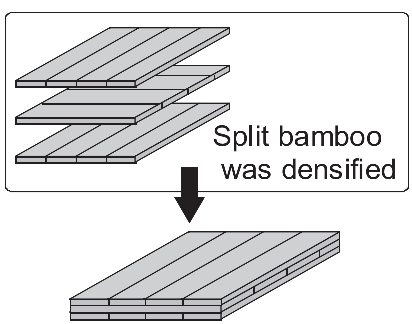



Figure 3. Production method of densified bamboo plywood.

## 5 TEST PROCEDURE

Fig. 5 shows the test set-up for tension test. Specimens are subjected to monotonous tension load by 200 kN capacity oil jack. The relative and vertical displacement of bolt is measured by two displacement transducers.

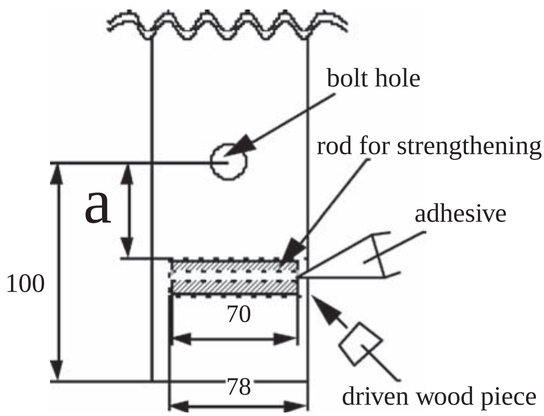



Figure 4. Assembly process of strengthening.

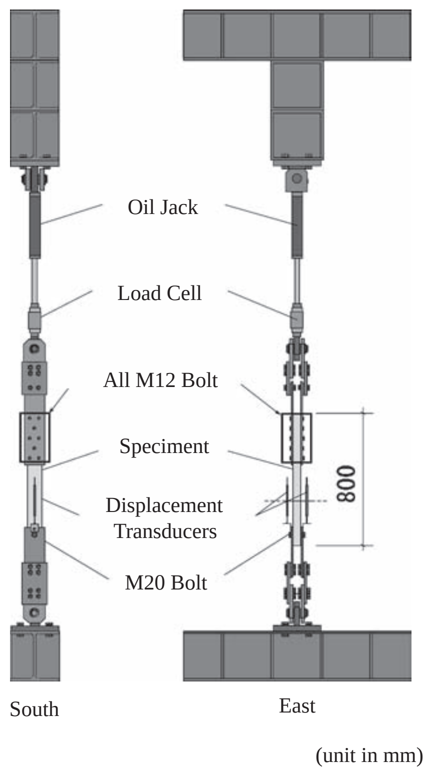



Figure 5. Test set-up for tension test.

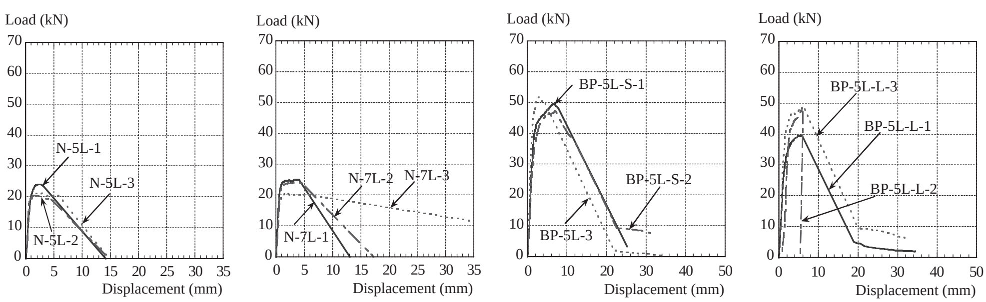
## 6 LOAD-DISPLACEMENT CURVE

Fig. 6 and 7 show the typical load-displacement curves. Curves in Fig. 5 (N-5L, N-7L series) show load-displacement relationship of non-strengthened specimens. The non-strengthened specimens broke suddenly after getting to the ultimate strength. Fig. 6 (BP-5L-S, BP-5L-L series) and Fig. 7 (BP-5L-E series) show load-displacement relationship of strengthened specimens by densified bamboo plywood. The load rose up rapidly to the loading point where the displacement is about 10 mm after yielding. Fig. 7 (except BP-5L-E series) shows load-displacement relationship of strengthened specimens by bamboo connector. Higher deformation performance is obtained in the specimen with the longer distance “a” between bolt and bamboo connector.

## 7 FINAL FAILURE MODE

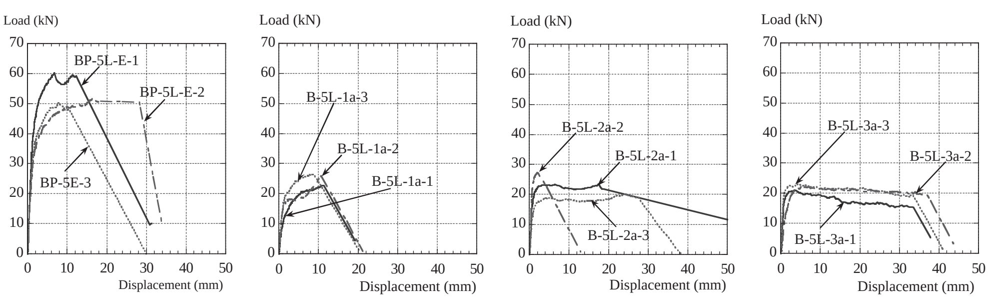
The splitting failure from bolt hole to the end of lumber (see Photo 3–(1)(2)) occurred in the non-strengthened specimen and strengthened by densified bamboo plywood specimen. There are two kinds of the final failure mode for the specimens strengthened. The specimens with long distance between bamboo connector and bolt broke in failure mode shown in Photo 3–(4). In this failure, the bamboo connector is pushed out the wood located under the bamboo connector. The specimens with short distance between bamboo connector and bolt broke in failure mode are shown in Photo 3–(3). In this failure, the specimens are torn apart.

Fig. 8 shows the maximum strength and the average values of the maximum strength for each series specimens. The effect of strengthening is confirmed in comparison with the average



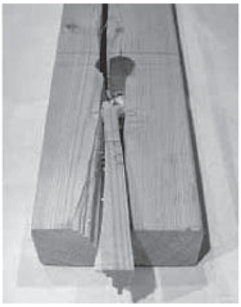

(N-5L series) (N-7L series) (BP-5L-S series) (BP-5L-L series)

Figure 6. Load-displacement curve.



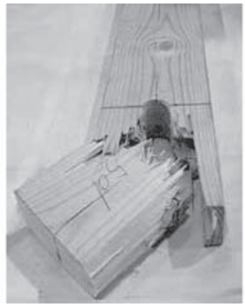

(BP-5L-E series) (B-5L-1a series) (B-5L-2a series) (B-5L-3a series)

Figure 7. Load-displacement curve.



(1) (N-7L-1)

(2) (BP-5L-E-2)



(3) (B-5L-la-1)

(4) (B-5L-3a-2)

Photo 3. Final failure mode of specimen.

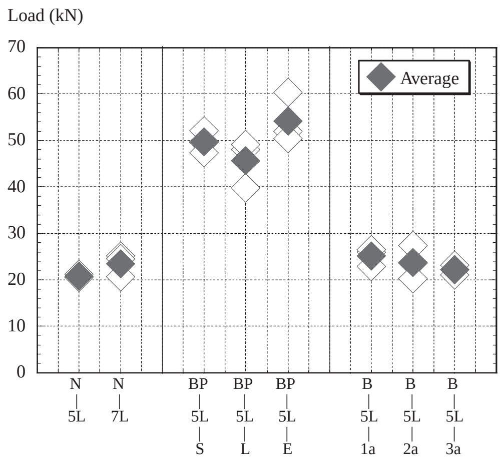



Figure 8. Maximum strength.

maximum strength of non-strengthened and strengthened specimens show the effect of strengthening. The highest strength is obtained in the specimen with densified bamboo board attached in wide range (see Fig. 1–(3)).

## 8 DUCTILITY FACTOR

Fig. 9 shows the ductility factor for all specimens and the average ductility factor for each series specimens. These figures for ductility factor of non-strengthened and strengthened specimen indicate the effect of strengthening. The ductility factor of the specimens with densified bamboo plywood is approximately equal to that of the non-strengthened specimens. The increase of the distance "a" between the bolt hole and the inserted bamboo connector promotes the ductility performance. The ductility of the specimen with the distance between bolt hole and bamboo connector which is 3d (d: bolt diameter) is about four times as that of the non-strengthened specimen.

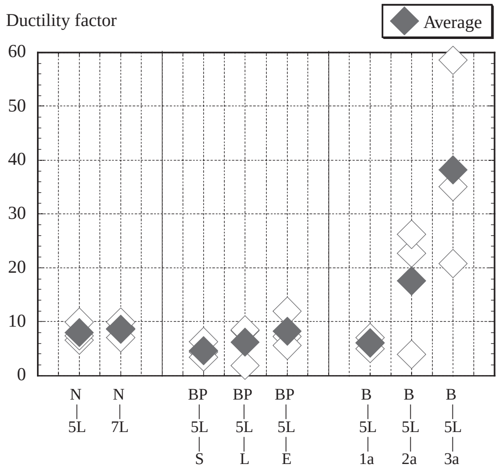



Figure 9. Ductility factor.

## 9 ANALYSIS

### 9.1 *Finite element modeling of locally reinforced timber fasteners*

3-D finite element models were developed using the commercial code Abaqus [1, 2]. For each joint, the timber member, two bamboo-plywood plates, the steel bolt and the GIR (dowel) were discretized using 8-node solid elements. The timber was modelled as an orthographic material in tension and an elasto-perfect plastic material in compression, bamboo-plywood as an isotropic material in tension and elasto-perfect plastic material in compression, and the GIR as an elasto-perfect plastic material. Since the bolt is made of high strength steel, there is hardly any deformation observed from tests. Therefore it is modelled as an elastic material with high stiffness.

Material properties used in the modelling were as follows.

Timber (Japanese Spruce): in tension:

E1 = 11700, E2 = 900, E3 = 500, G1 = 755, G2 = 38, G3 = 726 ($N/mm^2$)

$\upsilon 12 = 0.37$, $\upsilon 21 = 0.04$, $\upsilon 23 = 0.44$, $\upsilon 32 = 0.25$, $\upsilon 31 = 0.025$, $\upsilon 13 = 0.47$

and $\sigma y = 30\ N/mm^2$ for perfect plasticity under compression.

Bamboo-plywood:E = 15200 $N/mm^2$, $\upsilon = 0.2$ in tension

and $\sigma y = 75.8\ N/mm^2$ for perfect plasticity under compression.

Densified bamboo GIR: E = 54978 $N/mm^2$, $\upsilon = 0.28$ , Yield stress: 65 $N/mm^2$

Tensile strength: 365 $N/mm^2$, Compressive strength: 109 $N/mm^2$

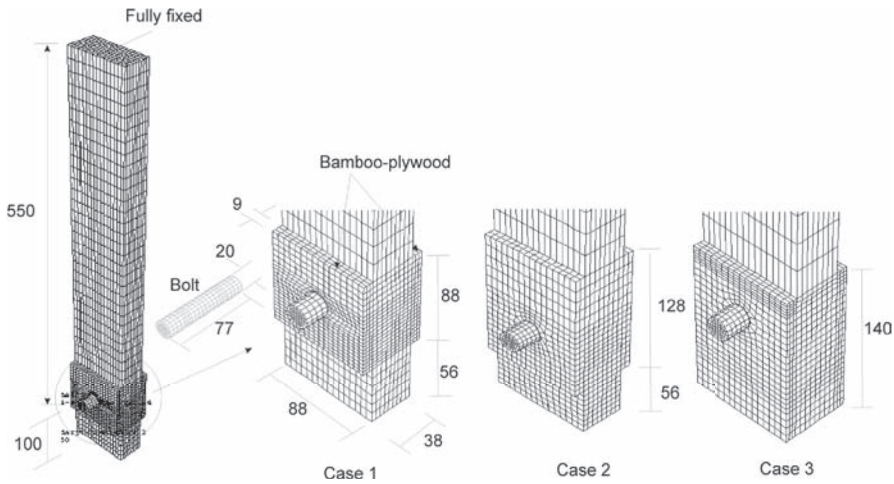
Shear strength: 25 $N/mm^2$

Bolt: E = 250000 $N/mm^2$, $\upsilon = 0.3$

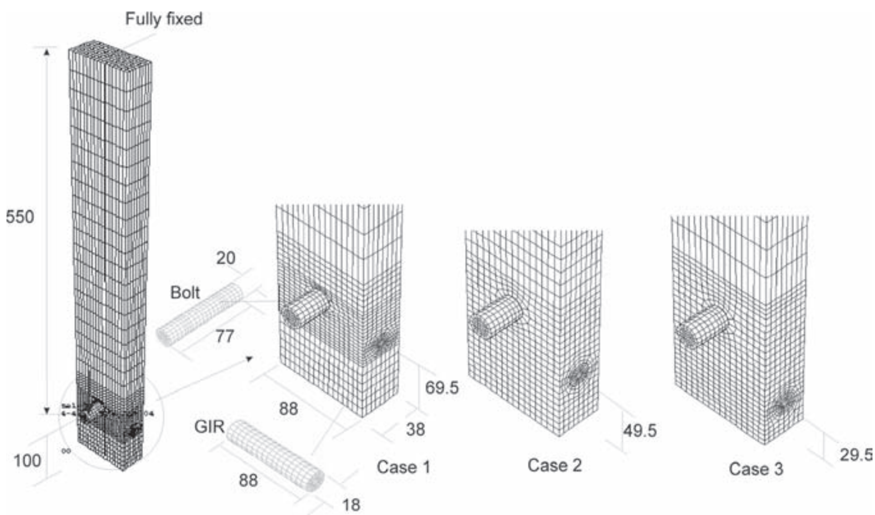
Modelling of interaction between different members is challenging, which has to be properly dealt in order to obtain convergence in numerical modelling. There are two types of interface in the fastener, i.e.

1. Timber-to-bolt and bamboo plywood-to-bolt. Slippage and separation are allowed in this type of contact with friction coefficient of 0.3.
2. Bamboo plywood-to-timber and timber-to-GIR. Rough contact is set to this type of contact, i.e. no separation is allowed. As resin was applied to the above interfaces, de-bonding usually occurred in the ultimate failure.

Six joint configurations were modelled, which involve three size of the bamboo plywood reinforcement and three locations of the GIR, respectively. Fig. 10 shows the mesh generation for one




(a) With local reinforcement, but without GIR




(b) with GIR, but without local reinforcement

Figure 10. Mesh generation with geometric, loading and boundary conditions.

of configurations of the fastener, including geometric, loading and boundary conditions. Other two configurations are also shown in the same diagram. The position of the steel bolt is fixed, i.e. 100 mm from the bottom. Sizes of the bolt and GIR are also kept as constants (see Fig. 10). Sizes for accommodating the bolt and the GIR are 22 mm and 21 mm, respectively. The only differences for the case 2 and case 3 are the size of the bamboo-plywood reinforcement or the location of the GIR.

## 9.2 *Modeling results and discussion*

Numerical modeling results are presented to cover load-displacement relationships, deformation/failure modes and stress distributions at the critical loads for typical fasteners. The cases presented here are the Case 2 with bamboo plywood reinforcement, but without the GIR, and the Case 2 with the densified bamboo GIR, but without reinforcement. Comparison between the experimental results and the finite element simulations in terms of load-displacement relationship is also given to show validation. Fig. 11 shows load-displacement curves for the fasteners of those two cases.

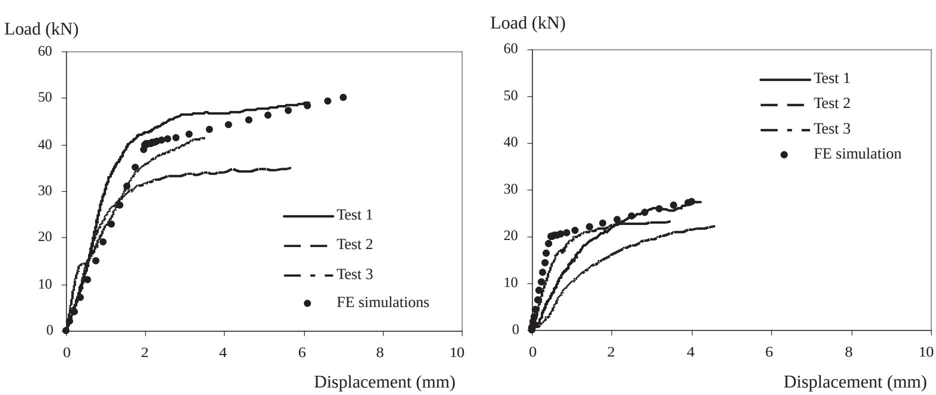
In general, FE simulations correlate the corresponding test results for the cases reasonably well, especially for the ultimate failure load and displacements. However, FE simulations give overestimate of the initial stiffness of the fastener without local reinforcement. This may be caused by perfect contact set in the numerical modeling. In testing of real fasteners, there are always small gaps between some members, such as bolt-to-timber, which will reduce the initial stiffness through gradual engagement. This is specifically true for the fastener without local reinforcement. Another reason is local crush of timber under embedding deformations, which needs to be considered in future modeling.

Fig. 12 shows the deformation modes, Mises stress, contact stress and shear stress contours at failure for those two cases. It can be seen clearly that a large gap is created above the top of the steel bolt, which was observed in the test. Timber underneath the bolt was crushed due to very high localized contact stress. This contributed to the creation of the gap. Simply a circular hole was changed to an oval one due to large embedding deformations. Influenced stress areas underneath the bolt for the fastener with local reinforcement are much smaller than the fastener without the local reinforcement, i.e. the latter is in much more critical situation. This is verified by the failure load, which is twice for the former in comparison with the latter. It will be interesting to see how the combined the local reinforcement and the GIR affect the load carrying capacity of such fastener.

## 10 CONCLUDING REMARKS

In this paper, the effect of strengthening method by using the bonded local reinforcing member made with densified bamboo plywood or GIR (glued-in rod) system with bamboo connector on the mechanical behavior of the fastener was investigated and assessed. The final failure mode is affected by the distance between the bolt and the strengthening bamboo connector. The improvement of ultimate strength capacity is obtained by attaching local reinforcing members around the bolt hole. The improvement of deformation capacity is also realized by using bamboo GIR system. The end distance for the fastener joint can be reduced by the attached reinforcing member or GIR system.

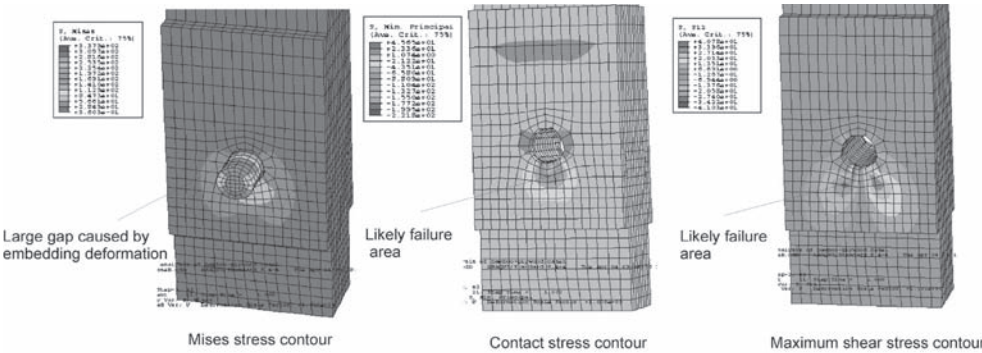
3-D nonlinear finite element models have been developed to simulate load-displacement relationships for the newly designed fasteners with different configurations of the local reinforcement and the location of the GIR. Reasonably good correlation has been obtained between the



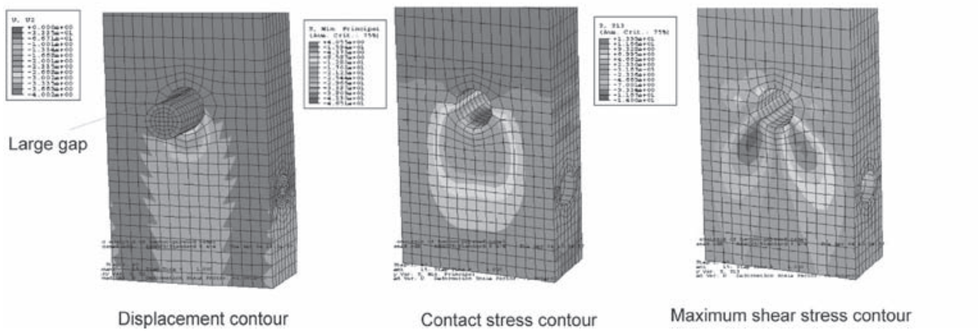

(a) Case 2 with reinforcement

(b) Case 2 without reinforcement

Figure 11. Load-displacement curves for two typical fasteners.




(a) Case 2 with the local reinforcement




(b) Case 2 without the local reinforcement

Figure 12. Contour images for two typical fasteners.

test results and numerical simulations. In addition stress contours were presented which show the critical stress distributions in the fastener. The model is ready to be used to cover variation of reinforcement and GIR. However, more work needs to be undertaken to take local timber crush into account.

## ACKNOWLEDGEMENTS

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## REFERENCES

Inoue M. et al. 1996. Introduction of Timber Structures Constructed by New Connecting System, *Proceedings of International Conference on Effective Utilization of Plantation Timber '99*, Chi-Tou, R.O.C, May, 1999, pp. 555–560.

Inoue M. et al. 2001. Strengthening Method of fastener joints by glued-in rod system in timber structures, *Joint in Timber Structures, Proceedings of International RILEM Symposium*, Stuttgart, Germany, September, 2001, pp. 223–232.

ABAQUS, Theory Manual, Version 6.0, Hibbitt, Karlsson & Sorensen, Inc. 2000.

ABAQUS, User Manual, Version 6.0, Hibbitt, Karlsson & Sorensen, Inc., 2000.

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# Flexural properties of bamboo sliver laminated lumber under different hygrothermal conditions

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ABSTRACT: To investigate the hygrothermal effect on the flexural properties of the bamboo sliver laminated lumber in different temperatures and moistures, the flexural properties of Moso bamboo *(Phyllostachys pubescens*) sliver laminated lumber were tested under five conditions in this paper: freezing (−50°C, 4 hrs); high-temperature drying (150°C, 4 hrs); normal (20°C, RH of 65%), cold water (20°C, 24 hrs) and hot water (90°C, 4 hrs). Test results show that the modulus of elasticity of bamboo sliver laminated lumber in high-temperature, hot water and cold water, respectively, decreases, while the modulus of elasticity increases under the freezing condition, all in comparison with that under normal conditions. Bamboo sliver laminated lumber was also tested in alternating hygrothermal conditions and the results show that decrease in the flexural properties in different conditions was more significant than that in the four temperatures and moistures, respectively.

## 1 INTRODUCTION

Bamboo, a natural composite, named as "green gold" for its fast growing, short harvesting period and excellent properties such as longitudinal strength, is widely used as a substitute material of wood due to the fact that rainforests are destroyed so seriously in modern times (Liese 1987; Zhang, Jiang and Tang 2002). There are many kinds of engineered bamboo products developed and utilized, such as bamboo flooring, bamboo-based panels (Zhang, Jiang and Tang 2002), bamboo/aluminium laminates (Li, Fu, Zhou, Zeng and Bao 1994) and bamboo sliver laminated lumber, etc. Bamboo sliver laminated lumber is made of bamboo slivers that are hot-pressed with phenol formaldehyde. Like parallel stand lumber, the slivers are mainly oriented longitudinally. This engineered bamboo product is particularly suitable for use as a structural material, making use of the natural longitudinal high strength of bamboo, and utilizing the abundant bamboo resource (Zhang, Jiang and Tang 2002; Bai 1996; Lee, Bai and Bangi 1998; Lee, Bai and Peralla 1996).

Bamboo sliver laminated lumber is often used outdoors, the hygrothermal conditions have important effect on its functions. So far, only the properties of bamboo sliver laminated lumber under normal temperature and humidity conditions are well known, while the properties under lower and higher temperatures remain largely unknown, although hygrothermal aging of bamboo/aluminium laminates was investigated according to different standards (Zhang Zeng, Yu and Kim 2001).

Simple hygrothermal conditions and alternating hygrothermal conditions were used to treat the bamboo sliver laminated lumber, in order to investigate the change of the flexural properties. Simple hygrothemal conditions included five conditions, freezing (−50°C, 4 hrs), high-temperature drying (150°C, 4 hrs), normal (20°C, RH of 65%), cold water (20°C, 24 hrs) and hot water (90°C, 4 hrs). Alternating hygrothemal conditions were from three different standards, ASTM D 1037-2005, GB/T 17657-1999 and GB/T 13123 -2003.

## 2 EXPERIMENTAL PROCEDURES

### 2.1 *Material and specimens*

The bamboo sliver laminated lumber was made of Moso bamboo of 3-year old culms (*Phyllostachys pubescens*) grown in Zhejiang Province, China, with phenol formaldehyde resin (PF) produced by Zhejiang Zhuji Bamboo Panel factory. Bamboo culms were split into slivers of 05–1.0 mm in thickness and about 0.5–3 cm in natural width. Bamboo slivers were dried to a moisture content of 6–9%, were then impregnated in PF resin for 3–5 minutes and drawn out to be dried again to the moisture content of 6–9%. The impregnated slivers were assembled mainly in the longitudinal direction of lumber and hot-pressed into bamboo sliver laminated lumber. Density of the lumber was 0.9–1.02 g/cm$^3$.

The specimens were sawn from the products in accordance with GB/T1767-1999, with a size of $50 \times 10 \times 250$ mm. 50 specimens were for each set of experimental conditions.

### 2.2 *Simple hygrothemal treatment conditions*

The basic specimens were treated in normal conditions (20°C, RH of 65%), and other specimens were treated in freezing (−50°C, 4 hrs) to simulate severe winter temperatures; high-temperature drying (150°C, 4 hrs) to simulate the insulating plywood which can be used in very high temperatures; cold water (20°C, 24 hrs) and hot water (90°C, 4 hrs), respectively.

### 2.3 *Alternating hygrothemal treatment conditions*

Considering the alternative temperature and moisture changes in service environment of bamboo sliver laminated lumber, the flexural characteristics and potential applications of bamboo sliver laminated lumber in alternating hygrothermal conditions were tested according to different standards. The details of conditions are shown in Table 1. Three standards were mainly used to accelerate?? the wood-based products (ASTM D1037, GB/T 17657-1999) and GB/T 13123 -2003 is for bamboo-based products).

Treated specimens were tested in bending immediately on the mechanical testing machine (Sanshi universal mechanical test machine, Shengzhen, China). The specimen was simply supported,

Table 1. Alternating hygrothermal treatment conditions.

| Reference standard | I | II | III |
|---|---|---|---|
| | GB/T 17657-1999 | GB/T 13123 -2003 | ASTM D1037-2005 |
| Treating condition | 1. Boiled in water at 100 ± 2°C for 4 h | 1. Soaked in water at 63 ± 2°C for 6 h | 1. Boiled in water at 49 ± 2°C for 1 h |
| | 2. Placed in a chamber at −12 ± 2°C for 6 h | 2. Dried in an oven at 100 ± 2°C for 6 h | 2. Placed in water steam at 93 ± 3°C for 3 h |
| | 3. Dried in oven at 100 ± 2°C for 6 h | 3. Stored at room temperature for 10 min | 3. Placed in a chamber at −20 ± 2°C for 20 h |
| | 4. Stored at room temperature for 10 min | | 4. Dried in oven at 99 ± 2°C for 3 h |
| | | | 5. Placed in water steam at 93 ± 3°C for 3 h |
| | | | 6. Dried in oven at 99 ± 2°C for 8 h |
| | | | 7. Repeat steps 1–6 |

with a span of 200 mm, the load was applied to the mid-span via a bearing block of 15 mm in diameter and at a cross head speed of 10 mm/min.

## 3 RESULTS AND DISCUSSION

### 3.1 *Results from simple hygrothermal treatment conditions*

The flexural properties of samples in five hygrothermal treating conditions were tested and the results are listed in Table 2.

As shown in Table 2, the modulus of rupture and the modulus of elasticity of bamboo sliver laminated lumber changed with different treating conditions, from the largest values in freezing (−50°C, 4 hrs) to the smallest values in cold water (20°C, 24 hrs). In order to compare the flexural properties in normal conditions with that in other treating conditions, the retention ratio, the value in other treating conditions to the value in normal conditions, of the flexural properties is shown in Fig.1.

It can be seen from Fig.1 that the freezing treatment and drying treatment enhanced the flexural properties of bamboo sliver laminated lumber, with the retention ratio of MOR and MOE being greater than 1.2. The other two retention ratios were below 1.0, showing the hygrothermal aging behaviour of bamboo sliver laminated lumber. The flexural properties in cold water for 24 h deceased to 60% and 40% in MOR and MOE, respectively, partly because the moisture content of bamboo sliver laminated lumber was higher than in the normal conditions, cold water softened the material and led to larger deformations than in normal conditions. Hot water also had similar effect but the treating time was only 4 hours which was not long enough for bamboo

Table 2. Flexural properties of bamboo sliver laminated lumber in different treating conditions.

| Treating conditions | Flexual properties | |
|---|---|---|
| Freezing (–50°C, 4 h) | 213(24)[a] | 15832(2001) |
| Drying (150°C, 4 h) | 182(16) | 13606(1291) |
| Normal (20°C; 65%) | 157(10) | 12824(1115) |
| Hot water (4 h) | 137(15) | 11739(843) |
| Cold water (20°C, 24 h) | 99(15) | 5217(1480) |

[a] Figures are average value and figures in parenthese are the standard deviation.

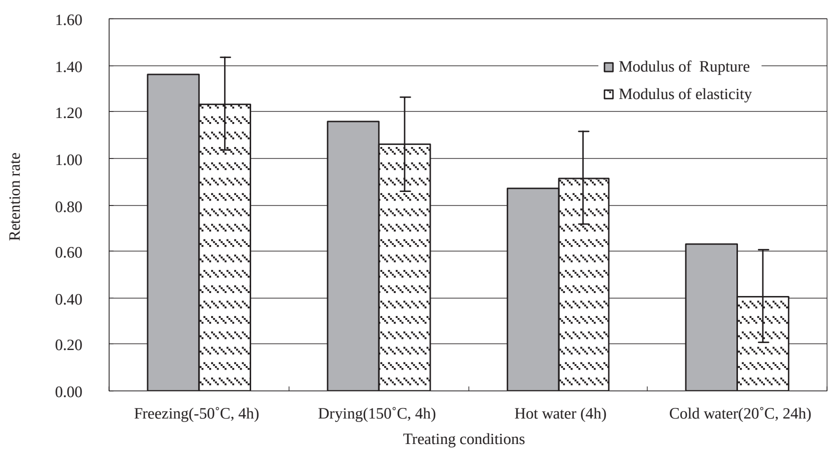



Figure 1. Retention rate of flexual properties of bamboo sliver laminated lumber.

sliver laminated lumber to absorb some more water. The hot-water treated material had a moisture content gradient, the inner part was still in high performance with a low moisture content and its retention ratio was larger than in cold water with retained MOR and MOE being more than 80%.

Typical load-deflection curves of bamboo sliver laminated lumber in relation to the above conditions are shown in Fig.2. It indicates that deformation of specimens increased with increase in

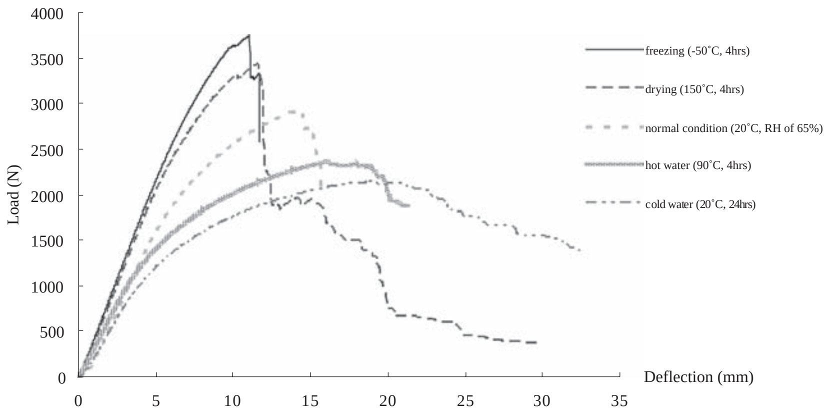
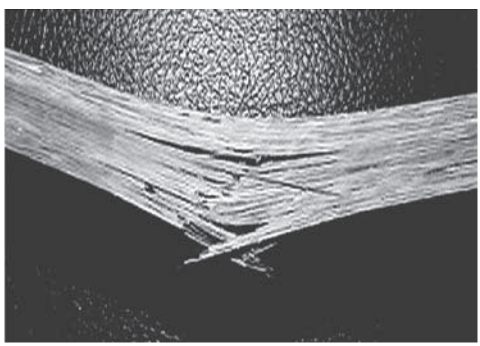
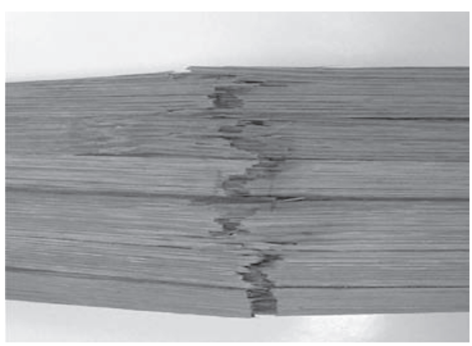



Figure 2. Load-deflection curves of bamboo sliver laminated lumber in different conditions.



(a) Side view



(b) View of tension surface

Figure 3. Typical failure mode in the dry conditions.

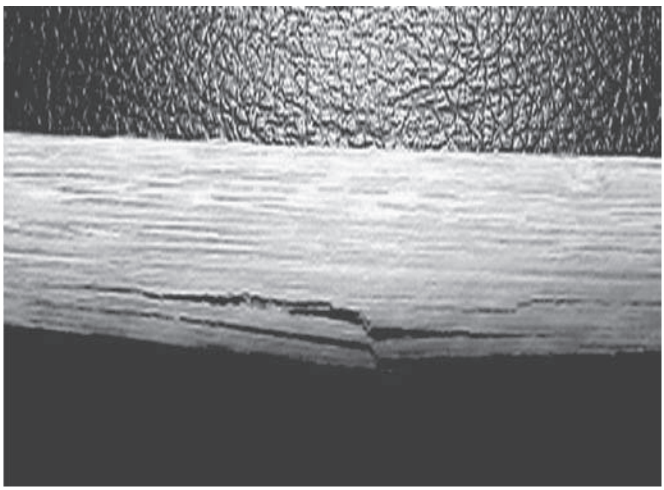
the moisture content. The figure also indicates that the bending properties decreased with temperature, though the trend is not as obvious as the change with the moisture content.

Typical failure modes of specimen in dry and freezing conditions are shown in Fig.3 and Fig.4, respectively. The failure modes of specimen in hot water, cold water and normal conditions were similar to the mode in Fig.4, they are not shown here for the sake of brevity.

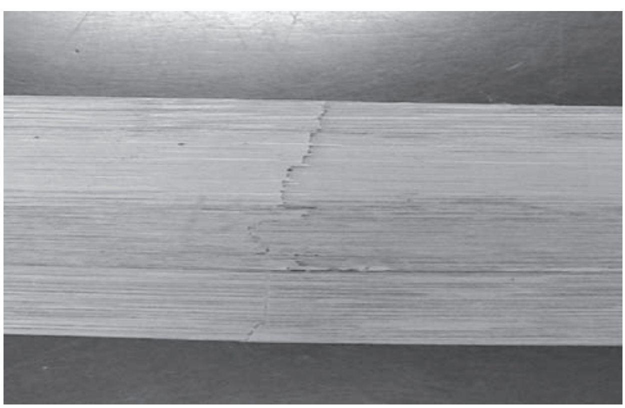
### 3.2 *Results from alternatively hygrothermal conditions*

The results from the three alternatively hygrothermal treatments specified in Table 1 are shown in Fig.5. In general, the bending properties of bamboo sliver laminated lumber after treatment in accordance with the three standards decreased to different levels and the retention ratio of flexural properties was all below 1.0.

The retention ratio of flexural properties treated following ASTM D1037 was greater than those following GB/T 13123 -2003 and GB/T 17657-1999. Because the treatment conditions of ASTM



(a) Side view



(b) View of tension surface

Figure 4. Typical failure mode in the freezing conditions.

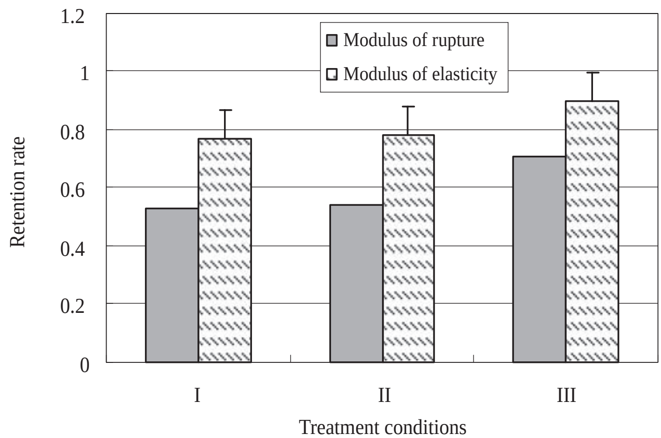



Figure 5. Retention rate of flexual properties of BSLL after alternately hygrothermal treatment.

D1037 cover a freezing process (−12 ± 2°C for 6 h), which enhances the flexural properties to some extent. On the other hand, so far as the bamboo sliver laminated lumber is concerned, the alternatively hygrothermal treatment conditions in GB/T 13123 -2003 and GB/T 17657-1999 are more serious than that in ASTM D1037. At the same time, decrease in MOR of bamboo sliver laminated lumber was more than that in MOE, showing that the load carrying capability was obviously weakened, , with the retention ratio of MOR and MOE being near to 0.6 and 0.8, respectively. Comparison of the retention ratio of flexural properties of bamboo sliver laminated lumber treated in simple hygrothermal conditions with that treated in alternating conditions shows that the former ratio of MOR was all above 0.6 while the latter had two cases with a value below 0.6.

## 4 CONCLUSIONS

As an engineered material, flexural properties of bamboo sliver laminated lumber are significantly affected by the hygrothermal conditions. Retention ratio in simple hygrothermal conditions shows that freezing treatment enhanced the MOR and MOE of bamboo sliver laminated lumber obviously. However, drying, hot water and cold water treatment reduced the MOR and MOE of bamboo sliver laminated to some extent and increasing moisture content increased deformation of the material, as shown in the load-deflection curves.

Alternatively hygrothermal conditions treatment showed that the hygrothermal treatment had more significant effect on the MOR of bamboo sliver laminated lumber, with a retention ratio of MOR below 0.6. The alternatively hygrothermal treatment conditions in GB/T 13123 -2003 and GB/T 17657-1999 are more serious than that in ASTM D1037, for the retention ratio of flexural properties obtained following these two standards was smaller than that following ASTM D1037. When bamboo sliver laminated lumber is exported to abroad, the hygrothermal test results need to take into account the difference between the Chinese standards and the international ones.

## ACKNOWLEDGEMENTS

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## REFERENCES

Liese, W. 1987. Research on Bamboo. Wood Science Technology 21:180–209.

Sh, Q. Zhang, Sh. X. Jiang and Y.Y. Tang. 2002. Industrial Utilization on Bamboo, Technical Report No. 26, International Network for Bamboo and Rattan.

Bai, X. 1996. Experimental and numerical evaluations of structural bamboo-based composite materials. Doctorate dissertation, Clemson, Univ., Clemson, SC.

Li, S. H., S.Y. Fu, B.L. Zhou, Q.Y. Zeng, and X.R. Bao, 1994. Reformed bamboo and reformed bamboo/aluminium composite. J Mater Sci.; 29:5990–6

Lee, A., Bai and A.P. Bangi. 1998. Selected properties of laboratory-made laminated-bamboo lumber, Holzforschung, 5(2):207–210.

Lee A., X. Bai and P.N. Peralla. 1996. Physical and mechanical properties of strandboard made from moso bamboo. Forest Prod. J. 46(9):84–88.

Bai, X. 1996. Experimental and numerical evaluations of structural bamboo-based composite materials. Doctorate dissertation, Clemson Univ., Clemson, SC.

Zhang, J.Y., Q.Y. Zeng, T.X. Yu, and J.K. Kim. 2001. Residual Properties of reformed bamboo/aluminium laminates after hygrothermal aging. Compostie Science and Technology, 61(2001): 1041–1048.

ASTM D1037. 2000. Standard test methods for evaluating properties of wood-based fiber and particle panel materials. American Society for Testing and Materials.

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# Experimental study on flexural behavior of glulam and laminated veneer lumber beams

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ABSTRACT: Poplar is one of the main fast-growing species in China. In this study, the Italian poplar is used in the manufacturing of engineered wood materials, such as glued laminated timber (glulam), laminated veneer lumber (LVL), etc. The overall objective is to take full advantage of the fast-growing species in China and make it applicable to modern timber structures. Firstly, through a series of material mechanical testing, the main physical and mechanical behavior of glulam and LVL were presented. Based on this, experimental study on a total of 31 engineered wood beams was developed and the failure modes and failure mechanism were analyzed in this paper. Then the flexural behaviors, which include load carrying capacity and bending stiffness, were investigated and made a detailed comparison among them. Finally, the influences of lamination combination, load direction, veneer thickness (for LVL members), and beam sizes upon the flexural behaviors of engineered wood beams were discussed. Experimental results have shown that structural behaviors of engineered wood beams were much better than those of sawn beams made from ordinary structural timber. For example, the ultimate load of poplar engineered wood beams exceeds that of sawn Mongolian Scotch pine (MSP) beams by 39.0%~90.0%, while bending stiffness increased by 35.0%~45.0%. When combining LVL with glulam in the beams, they would produce better structural performance. Also the average strain of beam cross-section showed a linear distribution, and the ultimate tensile strain of the beams is 0.006 while the maximum compressive strain of the beams is about 0.009. Moreover, the influences of lamination combination and beam sizes on the beam's flexural behavior are obvious. From this study, it shows that engineered wood materials have a good prospect in building structures of China.

## 1 INTRODUCTION

Most of building structures in China take materials such as steel, cement and clay bricks. This consumes a great deal of mineral and energy resources. And it is very harmful to the environment. Timber structures will not consume the mineral resources. And the trees are benefit to the environment, absorb carbon dioxide and release oxygen during their growth. Also the construction, utilization and removal of timber structure will not lead to the environmental pollution. So timber structure is a kind of green building structure, which has properties of energy and land-saving, ecological environment protection. And it should be encouraged and supported for the government.

In recent years, due to the increasing cost and decreasing availability of large-diameter high quality log resources in the world, engineered wood materials are introduced to the building structures in some developed countries. And engineered wood materials take sawn timber and high performance adhesive as raw materials. And then it is made out through the advanced wood processing technique. After several decades' development, such materials mainly include glued laminated timber (glulam), laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), oriented strand board (OSB), and wood I-joist (Figure 1).

Engineered wood materials keep many good natural performance of sawn timber. Besides of this, they have lower variability in strength, good size stability behaviors, good humidity or fire resistance performance. Also they improve the utilization ratio of timber and are workable, multi-functional, convenient for mass production. What's more, engineered wood materials expand the application field of timber structure. And they have replaced some large-diameter high quality sawn timber, which can protect the environment and reduce the operating cost of economy and society (Fan, 2003; Fan et al. 2004; Liu et al. 2004; Yang et al. 2005).

In Europe and North America, there have many studies on engineered wood materials and they have skilled process and design systems. Its applications include resident buildings, large-span buildings and bridges (Bulleit, 1984; Bulleit et al. 1989; Triantafillou et al. 1992; Milner et al. 1997; Ozarska, 1999; Serrano et al. 2001; Issa et al. 2005). Currently it is called for green building and green building materials and it has more and more demands for timber structures in China. Since there is lack of natural forests resources in China, we can take the home-grown timber and imported timber to manufacture the high performance engineered wood.

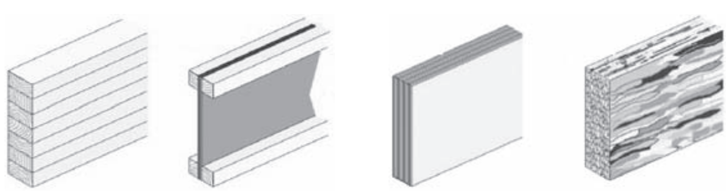
In this paper, the flexural behaviors of glulam and LVL beams made from Italy Poplar are studied through experiments. And glulam and LVL laminates are optimized by combination. Through this study, it can be taken as a reference of manufacture, design and application of this kind of materials.

## 2 EXPERIMENTAL PROGRAM

### 2.1 *Materials*

The sawn poplar timber was sourced from Lianyungang city of Jiangsu province, and sawn Mongolian Scotch pine (MSP) was yielded in northeast China. All but LVL were kiln-dried and the moisture content of wood materials is about 9%~12%. The resin used in glulam and LVL are isocyanate resin and phenol formaldehyde (PF) resin, respectively.

Table 1 shows some tested properties of small clear specimens in which the tested value is mean value of the specimens. Experimental data of the mechanical properties refer to the properties parallel to grain of wood. The tension properties were obtained from the experimental study of small beam specimens, while the compression properties and modulus of elastic (MOE) came from the tests of short columns. The typical stress-strain curves parallel to grain of wood materials are illustrated in Figure 2. In this figure, $m \cdot E_w$ represents the falling slope of the bilinear compression stress-strain curve, which describes the change in stress with strain after the wood has yielded in compression. And $m$ is the ratio of the falling slope to MOE of wood materials.



(a) Glulam (b) I-joist (c) LVL (d) PSL

Figure 1. Specimens of engineered wood materials.

## 2.2 *Specimens design*

There are a total of 31 beam specimens in this study and the specimens design has developed according to the standard of China and America (ASTM D143, 2000; ASTM D198, 2002; GB/T 50329-2002, 2002). The overall objective is as following: (1) To investigate the application prospects of engineered wood materials in China; (2) To study the failure modes and failure mechanism of engineered wood beams; (3) To discuss the flexural behaviors of engineered wood beams and to make a parametric study. Table 2 gives the details of the tested beams and beam section types are shown in Figure 3.

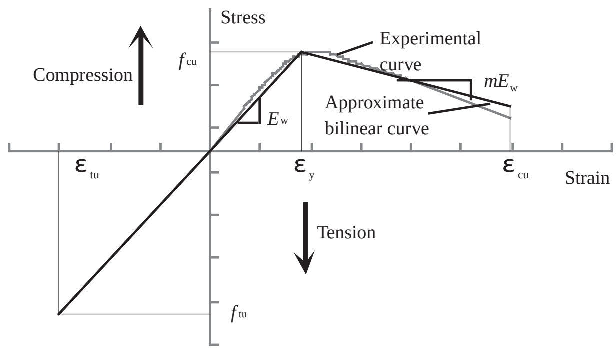



Figure 2. Stress-strain curves parallel to grain of wood materials.

Table 1. Tested properties of wood materials.

| Material type | Laminate/veneer thickness mm | Density y kg/m$^3$ | Moisture content % | Modulus of elastic $E_w$ N/mm$^2$ | Ultimate tensile strain $\varepsilon_{tu}$ % | Yield compressive strain $\varepsilon_y$ % | Ultimate compressive strain $\varepsilon_{cu}$ % | $m$ |
|---|---|---|---|---|---|---|---|---|
| MSP | — | 436 | 10.8 | 10300 | 0.5 | 0.318 | 1.0 | –0.195 |
| Poplar glulam | 25 | 435 | 9.0 | 9700 | 0.6 | 0.349 | 1.2 | –0.0825 |
| Poplar LVL | 2.4 | 580 | 9.2 | 12600 | 0.6 | 0.355 | 1.2 | –0.232 |
| Poplar LVL | 1.9 | 560 | 9.6 | 12600 | 0.6 | 0.359 | 1.2 | –0.194 |
| Poplar LVL | 1.6 | 583 | 9.7 | 13200 | 0.6 | 0.365 | 1.2 | –0.197 |

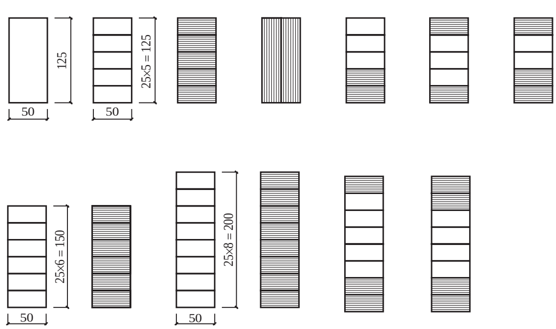



Figure 3. Types of beam section.

Table 2. Details of tested beams.

| Group number | Beam number | Material type | Laminate/ Veneer thickness | Beam sizes |
|---|---|---|---|---|
| 1 | B1, B2, B3 | MSP | — | 50 mm × 125 mm × 2400 mm |
| 2 | B4, B5, B6 | Poplar glulam | 25 mm | |
| 3 | B7, B8, B9 | Poplar LVL | 1.9 mm | |
| 4 | B10, B11 | Poplar LVL | 1.6 mm | |
| 5 | B12, B13 | Poplar LVL | 1.9 mm | |
| 6 | B14, B15 | Poplar LVL | 2.4 mm | |
| 7 | B16, B17, B18 | Glulam-LVL | 25 mm, 1.9 mm① | |
| 8 | B19, B20 | Poplar glulam | 25 mm | 50 mm × 150 mm × 2850 mm |
| 9 | B21, B22, B23 B24 | Poplar LVL | 1.9 mm | |
| 10 | B25, B26, B27 | Poplar glulam | 25 mm | 50 mm × 200 mm × 3800 mm |
| 11 | B28, B29 | Poplar LVL | 1.9 mm | |
| 12 | B30, B31 | Glulam-LVL | 25 mm, 1.9 mm① | |

*****The beam cross-section consist of glulam and LVL, in which the thickness of glulam laminate and LVL veneer are 25 mm and 1.9 mm, respectively.

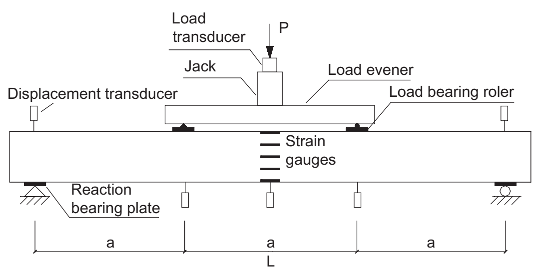



Figure 4. Test set-up.

As shown in Table 2 and Figure 3, Group 4~7 and Group 12 are optimized beams. It has combined glulam with LVL in these beams based upon the mechanical principle and the practical applications. It presented a detailed comparison upon the flexural behaviors between those optimized beams and traditional engineered wood beams in this paper.

According to GB/T 50329-2002 and ASTM D 198, the shear deformation is small enough to be neglected in the total deformation of the beam when the span to depth ratio of the beam is not less than 18. For structural timber members, the bending strength is affected by the beam sizes or beam volume. Thus three types of beam sizes (50 mm × 125 mm × 2400 mm, 50 mm × 150 mm × 2850 mm, 50 mm × 200 mm × 3800 mm) were designed.

## 2.3 *Test procedure*

Tests were executed under four-point bending method (Figure 4). Care was taken to prevent lateral instability. And the applied load was transferred to strain measurement systems through the load transducer. A total of 5 displacement transducers were used at the supports, loading points and mid-span. And it has set strain gages throughout the beam depth. All the measured data were collected simultaneously by the static strain measurement systems.

## 3. EXPERIMENTAL RESULTS

### 3.1 *Failure modes and failure mechanism*

For the tested beams, the materials were in elastic stage at the beginning of the test. And with the increasing of load, the beams showed some plastic behaviors and the flexural stiffness decreased. Also the deflection of the beams was obvious. Then micro-cracks appeared at some defects (knots, grain slope and finger joints, etc.) in the tension area, and low voice sent out at the same time. Finally when the beam collapsed, the beam deflection was quite big. Moreover, once failure began at the outmost timber fiber in the tension area, failure progressed very quickly because of the subsequent longitudinal splitting as the timber failed in tension across the grain. Besides of Beam 4, which failed due to the compression yielding of the timber, failure modes were mostly tension failure of timber and there was less evidence of compression yielding (See Figure 5). Tension failure failed mainly due to the stress concentrations at defects in the tension area.

### 3.2 *Cross-section strain of tested beams*

The experimental results have indicated that strain profiles of beam cross section remain reasonably linear up to ultimate load. It is shown in Figure 6 for a typical strain profile of the engineered wood beam. This means the plane cross-section assumption is valid during the design of this kind of materials.

The ultimate tensile strain of the beams is 0.006 and the ultimate tensile strain will decrease with the increase of beam sizes. In the same time, the maximum compressive strain of the beams is 0.009, while the ultimate compressive strain is about 0.012. So the utilization of compression zone of the beam is insufficient.

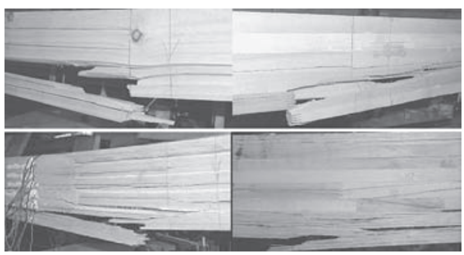


Figure 5. Typical failure modes.

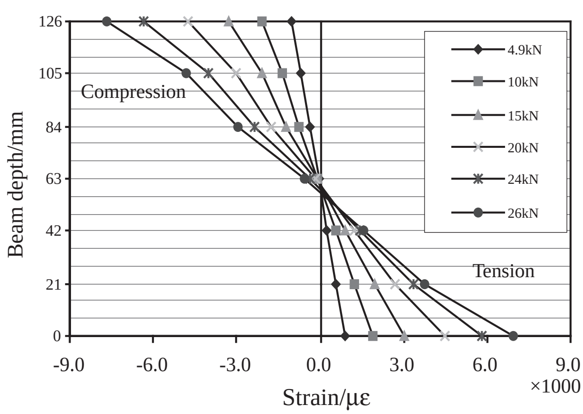



Figure 6. Strain profile at mid-span.

Table 3. Test results.

| Group number | Beam number mm | Beam sizes $P_u$ kN | Ultimate load $EI$ $10^9$ N-mm$^2$ | Bending stiffness |
|---|---|---|---|---|
| 1 | B1-B3 | 50 × 125 × 2400 | 15.6 | 80.35 |
| 2 | B4-B6 | 50 × 125 × 2400 | 21.7 | 80.33 |
| 3 | B7-B9 | 50 × 125 × 2400 | 25.4 | 115.2 |
| 4 | B10,B11 | 50 × 125 × 2400 | 29.6 | 116.5 |
| 5 | B12,B13 | 50 × 125 × 2400 | 27.0 | 114.7 |
| 6 | B14,B15 | 50 × 125 × 2400 | 25.3 | 108.4 |
| 7 | B16 | 50 × 125 × 2400 | 24.6 | 95.78 |
| 7 | B17 | 50 × 125 × 2400 | 24.2 | 108.0 |
| 7 | B18 | 50 × 125 × 2400 | 25.8 | 102.4 |
| 8 | B19,B20 | 50 × 150 × 2850 | 24.8 | 133.2 |
| 9 | B21-B24 | 50 × 150 × 2850 | 29.3 | 182.0 |
| 10 | B25-B27 | 50 × 200 × 3800 | 30.2 | 358.0 |
| 11 | B28,B29 | 50 × 200 × 3800 | 39.4 | 466.3 |
| 12 | B30 | 50 × 200 × 3800 | 43.5 | 433.5 |
| 12 | B31 | 50 × 200 × 3800 | 42.4 | 440.3 |

### 3.3 *Ultimate load behavior*

It is shown in Table 3 the primary test results, in which include the load carrying capacity and bending stiffness. And the tested data is mean value of the groups.

## 4. ANALYSIS OF EXPERIMENTAL RESULTS

### 4.1 *Comparison of flexural behaviors between engineered wood and sawn timber beams*

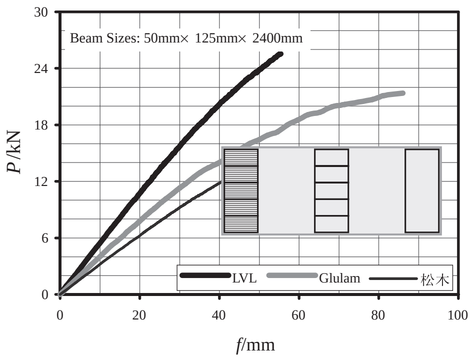
The experimental results have shown that flexural behaviors of poplar glulam and poplar LVL beams are much better than those of sawn timber beams like MSP. For example, the ultimate load of poplar glulam beams exceeds that of MSP beams by 39.0% in this study. In the mean time, the ultimate load of poplar LVL beams exceeds that of MSP beams by 62.6%~90.0%, while bending stiffness increased by 35.0%~45.0%. In addition, engineered wood beam has lower strength variability and, as a result, the allowable strength is higher. Moreover, it also has better ductility for engineered wood beams. What're shown in Figure 7(a) are load-deflection curves of some typical beams.

### 4.2 *Comparison of flexural behaviors among engineered wood beams*

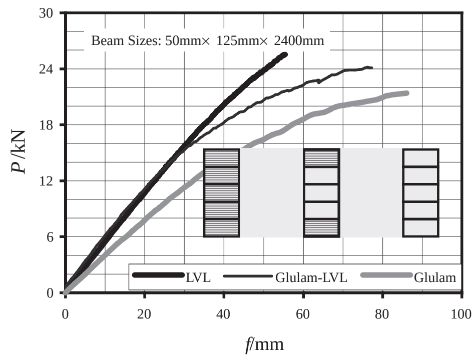
From the experimental results as shown in Table 3, it can be seen that the ultimate load and bending stiffness of LVL beams exceed those of glulam beams by 17.1%~30.5% and 30.3%~43.4%, respectively.

When the outer laminates of glulam beam are replaced by the LVL laminates, the formed composite beams have better structural behaviors as well as good economical efficiency. As an example, the ultimate load and bending stiffness of B16 exceeded those of glulam beams which have the same sizes by 13.7% and 19.3%, respectively. Figure 7(b) and Figure 7(c) show the load-deflection curves of some engineered wood beams. And it is shown in the Figures that ultimate load and bending stiffness will all be improved when LVL laminates are arranged in the tension side of glulam beams. As LVL laminates are placed in the compression side of glulam beams, only bending stiffness can be improved. This is because that the fracture of beams is controlled by the tension behavior of the wood materials.

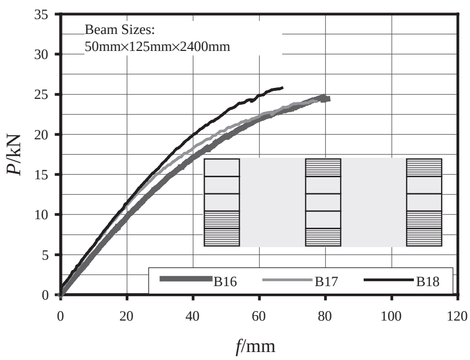
The comparison mentioned above mainly refers to tested beams with sizes of 50 mm × 125 mm × 2400 mm. For beams with sizes of 50 mm × 200 mm × 3800 mm, the advantages are



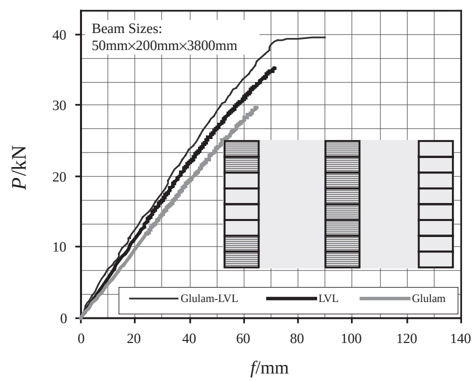

(a) Contrast Curves Between Engineered Wood Engineered and Sawn Timber Beams




(b) Contrast Curves among Wood Beams–1




(c) Contrast Curves among Engineered Wood Beams–2




(d) Contrast Curves among Engineered Wood Beams–3

Figure 7. Comparison of load vs. mid-span displacement curves.

more obvious because of the bigger depth to width ratio. And the ultimate load and bending stiffness of B31 exceeded those of glulam beams which have the same sizes by 40.3% and 22.9%, respectively, as shown in Figure 7(d).

### 4.3 *Analysis of test variables*

#### 4.3.1 *Variation of beam sizes (volume)*

Generally, the bending strength will decrease when the beam sizes or volume increases and it usually use volume factor to express it. For glulam beams in which the applied load is perpendicular to the wide surface of the timber laminate, the volume factor of the bending strength is as following equation (The Editorial Committee of Timber Structure Design Manual, 2005; NDS-1997, 1997).

$$C_v = \left(\frac{V_0}{V}\right)p \tag{1}$$

where,

$C_v$—volume factor

$V$—the volume of reference beam with sizes of 103 mm × 305 mm × 6400 mm

$V_0$—volume of the member (mm$^3$)

$P$—empirically derived coefficients

The bending strength of the glulam beam is the product of the bending strength of reference beam and the volume factor.

Through the analysis of experimental results upon glulam beams with different sizes (Group number 2, 8, and 10) and LVL beams (Group number 3, 9, and 11), the bending strength vs. volume relationship curves are presented in Figure 8.

By the regression analysis upon the curves in Figure 8, empirically derived coefficients $p$ was obtained. And the value of $p$ is 0.10 and 0.154 for poplar glulam and LVL beams, respectively. It must be pointed out that the effectiveness of $p$ value in this study should be verified by further research.

#### 4.3.2 *Variation of veneer thickness in LVL beams*

The veneer thickness of group 4, 5, and 6 is 1.6 mm, 1.9 mm and 2.4 mm, respectively. And the bending strength and bending stiffness of them is shown in Figure. 9. It can be seen from the figure that the bending strength and stiffness of LVL beams will decrease with the increase of veneer thickness.

The conclusion mentioned above is also applicable for glulam beams. It is considered that the defects of beams become more dispersive and the materials are more homogeneous when the laminate/veneer thickness decreases. But the amount of wood processing and glue spreading will increase when the laminate or veneer thickness falls down. Thus the cost of this kind of materials and structural members is higher.

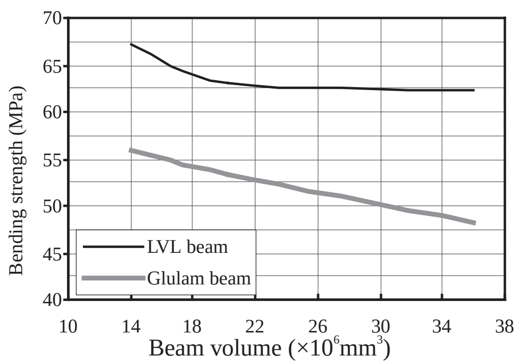
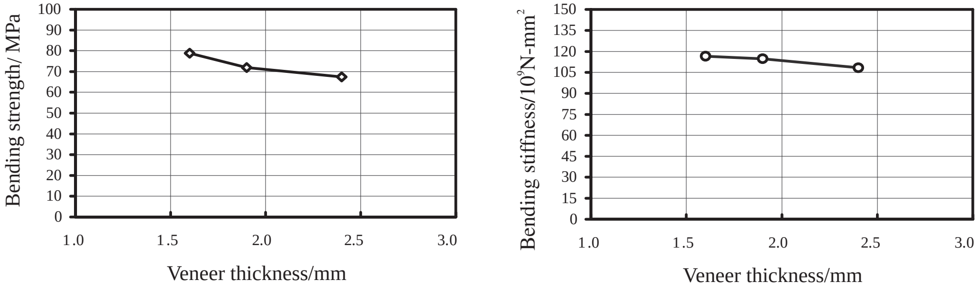



Figure 8. Volume effect on bending strength for engineered wood beams.




(a) Strength vs. Veneer Thickness Relationships

(b) Bending Stiffness vs. Veneer Thickness Relationships

Figure 9. Effect of veneer thickness on flexural behaviors of LVL beams.

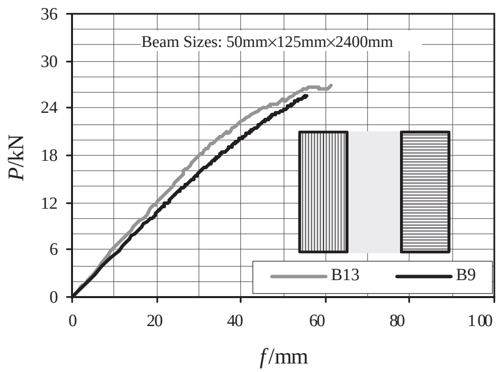



Figure 10. Loads with different directions.

4.3.3 *Variation of load direction*

By the comparison of the experimental results of group 5 and group 3 in Table 3, it indicates that the strength of LVL beams with the applied load is perpendicular to the bond line are slightly lower than that of beams with the applied load is parallel to the bond line. And the bending strength difference is 6.5% between them, while the bending stiffness is almost the same. It has developed a comparison upon the load-deflection curves of them in Figure 10. It is believed that the defects like knots and mechanical joints have uniform distribution along the beam depth when the applied load is parallel to the bond line. As a result, this type of beam has a higher strength.

For LVL member with applied load is parallel to the bond line, it is easy to processing and its cost is lower. At the same time, the appearance is good and it is more applicable in the structural engineering. So this type of LVL member is suggested in the engineering applications.

## 5. CONCLUSIONS

Through the experimental study on 31 engineered wood beams, it is found that the structural behaviors of engineered wood beams made from fast-growing poplar timber are good and it is a type of building material with high quality. Engineered wood materials can make a good utilization of timber, especially timber with small diameter and/or low grade. So they have a good prospect in building structure of China.

According to the experimental results, some conclusions have been drawn as following:

1. The average strain of beam cross-section shows a linear distribution throughout the whole testing. For engineered wood or sawn timber materials, the failure of beams were mainly due to various defects in the tension area of pure bending span. So it should select high quality laminates for outer layers and avoid the finger joints or larger knots at mid-span.
2. The ultimate load of poplar glulam beams exceeds that of MSP beams by 39.0% in this study. In the mean time, the ultimate load of poplar LVL beams exceeds that of MSP beams by 62.6%~90.0%, while bending stiffness increased by 35.0%~45.0%. In addition, engineered wood beam has lower strength variability so as to its allowable strength is higher. The beam displacement was very big when it failed, and it is more applicable to make a camber during the manufacture of glulam or to utilize arch members in the building structures.
3. The ultimate tensile strain of the beams is 0.006 and it will decrease with the increase of beam sizes. In the same time, the maximum compressive strain of the beams is 0.009, while the ultimate compressive strain is about 0.012. So the utilization of compression zone of the beam is insufficient.

4. When glulam and LVL are combined with optimization, the glulam-LVL composite beam has higher cost performance and the two materials gain full utilization. It will have better performance when the depth to width ratio increases for this type of beams.
5. The effect of beam sizes or volume upon bending strength of engineered wood beams is obvious. And the bending strength is lower while the beam volume is larger. For instance, bending strength has changed from 56.0 MPa to 48.3 MPa when beam sizes change from 50 mm × 125 mm × 2400 mm to 50 mm × 200 mm × 3800 mm. Some design parameters are presented by the regression analysis in this study.
6. Bending strength and bending stiffness of LVL beams will decrease with the increase of veneer thickness. For example, bending strength has changed from 79 MPa to 67 MPa as veneer thickness increase from 1.6 mm to 2.4 mm. The conclusion mentioned above is also applicable for glulam beams. It is considered that the defects of beams become more dispersive and the materials are more homogeneous when the veneer thickness decreases. But the cost will become higher when the laminate or veneer thickness falls down.
7. The strength of LVL beams with the applied load is perpendicular to the bond line are slightly lower than that of beams with the applied load is parallel to the bond line. For the latter one, it is easy to processing and its cost is lower. At the same time, the appearance is good and it is more applicable in the structural engineering. So this type of LVL member is also suggested in the engineering applications.


## ACKNOWLEDGEMENTS

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## REFERENCES


ANSI/AF&PA NDS-1997. 1997. National Design Specification for Wood Construction, American Forest and Paper Association and the American Wood Council.

ASTM D143. 2000. Standard Test Methods for Small Clear Specimens of Timber, American Society for Testing and Materials.

ASTM D198. 2002. Standard Test Methods of Static Tests of Lumber in Structural Sizes, American Society for Testing and Materials.

Bulleit, W.M. 1984. Reinforcement of Wood Materials: A Review, *Wood and Fiber Science*, July, pp. 391–397.

Bulleit, W.M., Sandberg, L.B., and Woods, G.J. 1989. Steel Reinforced Glued-Laminated Timber, *Journal of Structural Engineering*, American Society of Civil Engineering, February, pp. 433–444.

Fan, C.M. 2003. Prospects of Timber Structures for Buildings in China, *China Wood Industry*, May, pp. 4–6.

Fan, C.M., and Chen, S.L. 2004. Recent Development of Science and Technology in Timber Structures, *Journal of Harbin Institute of Technology*, June, pp. 812–814.

GB/T 50329-2002. 2002. Standard for Methods Testing of Timber structures, Ministry of Construction of People's Republic of China; and General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Beijing.

Liu, W.Q., and Yang, H.F. 2004. Advanced Glued Laminated Construction and Its Engineering Applications, *8th International Symposium on Structural Engineering for Young Experts (ISSEYE-8)*, Xi'an, China, August, pp. 698–703.

Issa, C.A., and Kmeid, Z. 2005. Advanced Wood Engineering: Glulam Beams, *Construction and Building Materials*, March, pp. 99–106.

Milner, M.W., and Bainbridge, R.J. 1997. New Opportunities for Timber Engineering, *The Structural Engineer*, August, pp. 278–282.

Ozarska, B. 1999. A Review of the Utilization of Hardwoods for LVL, *Wood Science and Technology*, September, pp. 341–351.

Serrano, E., Gustafsson, P.J., and Larsen, H.J. 2001. Modeling of Finger-Joint Failure in Glued-Laminated Timber Beams, *Journal of Structural Engineering*, American Society of Civil Engineering, August, pp. 914–921.

The Editorial Committee of Timber Structure Design Manual. 2005. Timber Structure Design Manual (Third Edition), Beijing.

Triantafillou, T.C., and Deskovic, N. 1992. Prestressed FRP Sheets as External Reinforcement of Wood Members, *Journal of Structural Engineering*, American Society of Civil Engineering, May, pp. 1270–1284.

Yang, H.F., Liu, W.Q., Jiang, D.M., and Dong, G.Q. 2005. Study on Material and Structural Behaviors of Engineered Wood Composite Beams," *Proceedings of the International Symposium on Innovation & Sustainability of Structures in Civil Engineering (ISISS'2005)*, Nanjing, China, November, pp. 2503–2511.

*Modern Bamboo Structures – Xiao et al. (eds)*


# Effects of machine strength grading methods on dimension lumber grades for Chinese fir plantation

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ABSTRACT: From producing to grading there are many factors influencing on final grade distribution of dimension lumber. Grade is one of indices in which wood managers are most interested because lumber price depends on it. Lots of researchers conducted studies on application of ultrasonic wave, longitudinal vibration and transversal vibration methods on predicting the stiffness property of dimension lumber. However, compared with traditional bending method the effects of these three methods on the grade distribution are still a problem. To solve the above, logs of Chinese fir plantation from Fujian provinces of China were felled. These logs will were cut into 470 pieces of dimension lumber of 45 mm by 90 mm and dried to a targeting moisture content of 12%. Then each piece was graded respectively by ultrasonic wave, longitudinal vibration, transversal vibration and bending methods according to the suggested machine grading design value table. Different grading methods have obvious effects on characteristic values, grade distribution and yield of dimension lumber. The transversal vibration method seems to be more precise grading method though it produces the low value of Chinese fir. C3 should be greater than $I_c$, following by C2, $II_c$, $III_c$ and C1 for visual grades and machine strength grades for Chinese fir lumber. MSR lumber from Chinese fir plantation may offer a higher value alternative to the production of visually graded lumber.

## 1 INTRODUCTION

Facing future development of timber structures in China, Chinese fir (*Cunninghamia lanceolata*) wood from plantation forestry will be one of most potential lumber source because it is one of the major and commercially available plantation species with large scale area, great stock volume and high growth maturity degree (Zhou, 2006). From the investigation by Wu (1955, 1984) and the statistical information from State Forestry Administration (SFA, 2005), the main distribution areas and stock volumes of Chinese fir plantation were determined, four major regions being Anhui province, Sichun province, Hunan province and Fujian province.

In recent years, interests on the application study on dimension lumber in China are increasing (Wang *et al*, 2005; Ren *et al*, 2006; Zhou *et al*, 2007). Unlike in North American, as there is currently no commercial production from Chinese fir plantation in China, the sampling plan focused on collecting representative logs from regional plantation stands, rather than lumber from sawmills. For our past preliminary in-grade lumber test program, four regions were all selected as the representative to collect sample trees based on topography, climate and growth pattern (Ren *et al*, 2006). The investigation shows that Chinese fir trees of the diameter of breast height (DBH) 20–35 mm are usually more than 26 years old and in the mature age phase. In order to efficiently utilize Chinese fir wood and keep a sustainable development for Chinese fir plantation source trees of the diameter range was suggested to be selected for commercial production of dimension lumber.

The grade of dimension lumber is one of indices in which wood managers are most interested because lumber price is depended on it. There are many factors influencing the grade yield, covering from felling to grading. The age-based choice of trees in felling is very important related to the diameter of logs. Juvenile and mature wood have a big difference not only in wood properties

(Luo, 1995) but also in strength reducing characteristics. Defects of skip and wane origin from cutting. Many visual grading studies stayed on maximum strength reducing defects (Wilson *et al*, 1934; Kunesh *et al*, 1972; Samson M., 1993; Ormarsson S., 1999). Beside strength reducing characteristics such as knots, knot holes, burls, abnormal grain distortion or decay, effects of machine grading methods such as ultrasonic wave, longitudinal vibration and bending, should be also considered on setting the grade of dimension lumber. Transversal vibration, as a potential method, was studied on the feasibility of predicting the stiffness property of dimension lumber (Zhou *et al*, 2007). In this paper, the sampling procedures used for preliminary in-grade studies to produce the test sample, and grading results of 45 by 90 mm dimension lumber of the plantation Chinese fir for four methods of ultrasonic wave, longitudinal vibration, transversal vibration and static bending are presented and discussed.

## 2 SAMPLING PREPARATION

### 2.1 *Sampling procedure*

A total of 220 standing trees of the plantation Chinese fir with diameter at breast height ranging from 250 to 320 mm were collected from Sanming in Fujian province for the preliminary in-grade lumber testing program. Tress from the DBH range may produce logs with less juvenile wood, higher density wood, and greater mechanical properties. The number of trees was roughly in proportion to the stock volumes in the region.

### 2.2 *Sampling preparation and visual grading*

Lumber was sawn from the logs following a pattern typically used in China to maximize the volume of recovered sawn timbers. The lumber was then kiln-dried to an average moisture content of 12% and planed to the final dimension of 45 by 90 by 3700 mm. All pieces were graded by a grader in trained to apply the visual grading rules stipulated in GB50005-2003 (MOC, 2003). Pieces were assigned either the grades $I_c$, $II_c$ or $III_c$. As the grading rules in GB50005 were developed based on the North America grading rules and have the equivalent grades as shown in Table 1, visual grades of all the lumber was confirmed by a certified grader from North America.

Before machine grading, all samples were conditioned at ambient conditions to a targeted moisture content of 12%.

## 3 MACHINE STRENGTH GRADING METHODS

### 3.1 *Machine strength grades*

A grading method for Chinese fir wood from plantation forest was suggested (Zhou *et al*, 2007). The data source of the table below was three main production areas of Chinese fir plantation wood

Table 1. Equivalent grades in GB50005 and North America.

| Visual grades in GB50005 | Visual grades in North America |
|---|---|
| $I_c$ | Select Structural |
| $II_c$ | No. 1 |
| $III_c$ | No. 2 |
| $IV_c$ | No. 3 |
| $V_c$ | Stud |
| $VI_c$ | Construction |
| $VII_c$ | Standard |

in China. Three major regions containing Huangshan in Anhui province, Hongya in Sichun province and Huaihua in Hunan province, were selected as the representative to collect sample trees, based on topography, climate and growth pattern. For each production area, the sampling method was to ensure that the test material is representative of the total population. By analyzing strength cumulative probability of dimension lumber, the machine strength grades were given (Table 2). The result has been included in the standard draft for Machine strength graded lumber in China.

### 3.2 *Machine strength grading methods*

To study the difference of machine grading methods, four methods of Ultrasonic wave, longitudinal vibration, transversal vibration and static bending are selected, as shown in Figures 1 to 4. Among them some are potential and some are used for machine grading methods. The same group of samples was machine-graded respectively by ultrasonic wave, longitudinal vibration, transversal vibration and static bending. Pieces were tested such that maximum strength-reducing characteristics were randomly located. To study difference among these methods, the dynamic test results were directly used for grading lumber without the transformation to static data.

As shown in Figure 1, ultrasonic wave method is that when the longitudinal ultrasonic wave transmits thought a piece of lumber the wave velocity would be influenced by lumber species and lumber density. Modulus of elasticity can be determined by Equation 1.

$$E_u = C^2\rho \tag{1}$$

Where $C$ is wave velocity (m/s) and $\rho$ is lumber density (g/cm$^3$).

The transmission mode of longitudinal vibration method shown in Figure 2 is similar to ultrasonic wave method.The difference is that longitudinal vibration method needs an impact force on an end surface. The fundamental frequency has a relationship with modulus of elasticity (Formula 2).

$$E_1 = 4L^2f^2\rho \tag{2}$$

Where $L$ is lumber length (m), $f$ is fundamental frequency (Hz) and $\rho$ is lumber density (g/cm$^3$).

Table 2. Machine strength grades for dimension lumber from Chinese fir plantation.

| Grade characteristic value | C1 | C2 | C3 |
|---|---|---|---|
| Mean modulus of elasticity (MPa) | 8800 | 10000 | 12000 |
| 5th percentile modulus of elasticity (MPa) | 7216 | 8200 | 9840 |
| Modulus of rupture (MPa) | 20.38 | 28.57 | 30.05 |

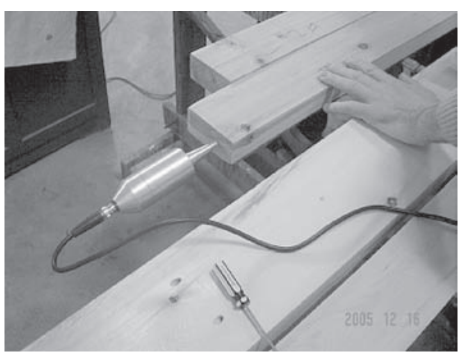


Figure 1. Ultrasonic wave method.

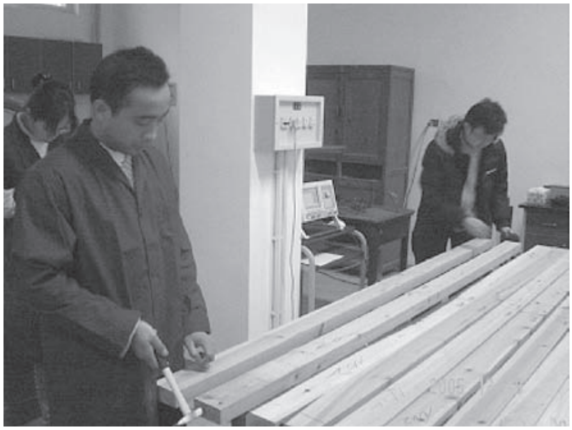

Figure 2. Longitudinal vibration method.

Figure 3. Free-free transversal vibration method.

Transversal vibration method is based on the transversal vibration theory of free-free beam. As shown in Figure 3, when a free-free beam is suffered to an impact vertical to beam length, a transversal wave would happen. The fundamental frequency depends on the lumber size, density and etc. Modulus of elasticity of the beam can be determined by Formula 3.

$$E_t = 48\pi^2 L^4 f^2 \rho/(4.73^4 h^2) \tag{3}$$

Where $L$ is lumber length (m), $f$ is fundamental frequency (Hz), $\rho$ is lumber density (g/cm$^3$) and $h$ is lumber thickness (m).

Due to no grading machine in China a bending test machine was used, as shown in Figure 4. Span length was 1.62 m to achieve a span-to-depth ratio of 18:1. Each piece was loaded edge-wise under third-point loading at a 50 mm/min rate of deflection and loading proceeded until ultimate failure. The time to failure averaged approximately 1 minute. Modulus of elasticity of the beam can be determined by Formula 4. In the paper static bending is used for a control method.

$$E_t = 23PL^3/(108bh^3d^2) \tag{4}$$

Where $P$ is lumber length (m), $L$ is lumber span (m), $b$ is lumber width, $h$ is lumber thickness (m) and $d$ is deflection (m).

All test results were not adjusted to the data at specific moisture content because there is currently no reliable adjust formula developed from structural lumber of Chinese domestic species. Further work involved the effect of moisture content on lumber strength properties will be carried out for Chinese species.

## 4 RESULTS AND DISCUSSION

The results of visual grading are shown in Table 3. As Table 3 demonstrates, $I_c$ is the largest in piece number and volume, accounting for near to half of the whole pieces. $III_c$ is more about 43% than $II_c$. Lower grades have about 27% of all pieces.

In the visually grading program it was found that the former three visual grades are mainly determined more by knot and wane, while the last two grades may also depend on check, split and decay besides knot and wane. In order to get better assessment results for three grading methods, only three visual grades remained in the study. The mechanical properties, by visual grade, of dimension lumber tested are summarized in Table 4. Usually the higher is the grade the larger the strength. However $III_c$'s MOE is higher than any one of other two grades such that is also seen in some literatures (Robert GE *et al*, 2000; Ren *et al*, 2006). The reasons needs further study.


Figure 4. Edge-wise static bending method.

Table 3. Lumber yield for visual grades.

| Visual grades | Piece number | Volume ($m^3$) |
|---|---|---|
| $I_c$ | 312 | 4.675 |
| $II_c$ | 57 | 0.854 |
| $III_c$ | 101 | 1.513 |
| $IV_c$ | 109 | 1.633 |
| $V_c$ | 61 | 0.914 |
| Total | 640 | 9.589 |

All test results for each grading methods were listed in Table 5. The ultrasonic wave method got a largest difference in minimum and maximum MOE, and characteristic values of MOE were also heightened 14.6%.

Figure 5 shows the cumulative probability of MOE for dimension lumber from Chinese fir plantation. Besides the 5th percentile MOE, these three methods are also lower than the ultrasonic method in 50th and 95th percentile MOEs.

Table 4. Mechanical properties for three visual grades.

| Visual grades | No. | Mean MOE | 5th percentile MOE | Mean MOR | 5th percentile MOR |
|---|---|---|---|---|---|
| $I_c$ | 312 | 10.43 | 7.90 | 48.77 | 29.79 |
| $II_c$ | 57 | 9.92 | 7.46 | 43.42 | 25.83 |
| $III_c$ | 101 | 10.66 | 8.21 | 46.82 | 28.56 |

Table 5. Stiffness properties for each machine grading method.

| Methods | Sample size | Minimum MOE (GPa) | Maximum MOE (GPa) | Mean MOE (GPa) | 5th percentile MOE (GPa) | Standard Deviation |
|---|---|---|---|---|---|---|
| Ultrasonic wave method | 470 | 4.32 | 24.55 | 11.94 | 8.99 | 2.12 |
| Longitudinal vibration method | 470 | 6.73 | 18.98 | 10.51 | 7.81 | 1.78 |
| Transversal vibration method | 470 | 6.10 | 17.47 | 10.01 | 7.68 | 1.64 |
| Edge-wise bending method | 470 | 4.98 | 15.72 | 10.42 | 7.85 | 1.63 |

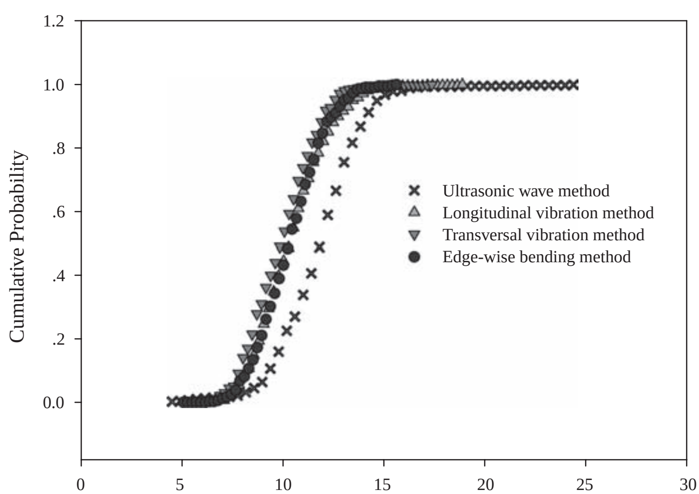


Figure 5. Cumulative distribution of MOE for each machine grading method.

According to the suggested machine grading design value table (table 2), the mechanical properties, by machine grading, of dimension lumber tested are summarized in Table 6. Both C3 and C1 grades should not be assigned according to the actual values for the ultrasonic wave method, while the C3 grade should not be assigned for the longitudinal vibration method. Transversal vibration method shows a good performance in reflecting the strength property whether or not high and low grades.

Figure 6 shows that grade yield for each grading method. Except these three grades, all pieces left were grouped to R grade. Transversal vibration method causes a largest percentage in C2 or R grades. For ultrasonic wave method, 90% of all pieces are assigned to C3, more 233 pieces than that for the bending method. Some pieces, which should actually be low grade, were assigned to higher grade. It indicates that the ultrasonic wave method may cause the reduction in practical use safety.

Table 6. Actual stiffness properties for each machine grading method.

| | C3 | | C2 | | C1 | |
|---|---|---|---|---|---|---|
| Methods | Mean MOE (GPa) | 5th percentile MOE (GPa) | Mean MOE (GPa) | 5th percentile MOE (GPa) | Mean MOE (GPa) | 5th percentile MOE (GPa) |
| Ultrasonic wave method | 12.30 (10.66) | 9.84 (8.36) | 0 | 0 | 8.80 (8.08) | 7.70 (6.84) |
| Longitudinal vibration method | 12.00 (11.17) | 10.55 (9.06) | 10.00 (10.39) | 9.54 (8.60) | 8.80 (9.43) | 7.81 (7.67) |
| Transversal vibration method | 12.00 (12.13) | 11.12 (10.76) | 10.00 (10.49) | 9.04 (9.04) | 8.80 (9.38) | 8.68 (8.50) |
| Edge-wise bending method | 12.00 | 10.90 | 10.00 | 9.26 | 8.80 | 8.32 |

* the data in the bracket is corresponding static test results.

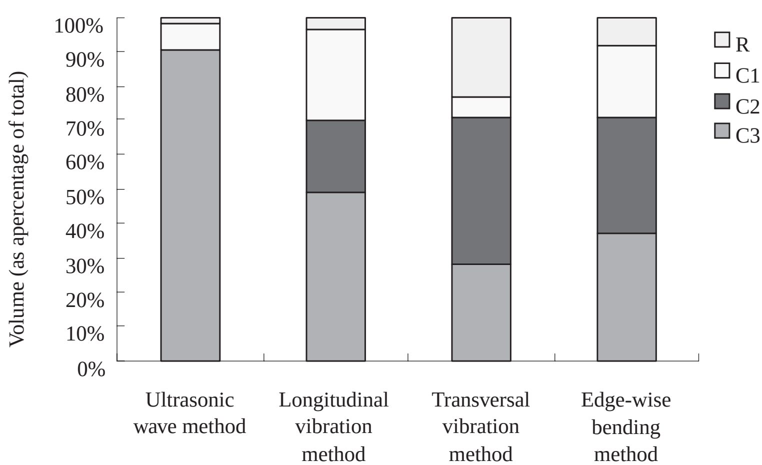


Figure 6. Yield comparisons between machine grading methods.

Table 7 gives the visual grade yield for each machine strength grade. Except ultrasonic wave method each machine strength grade for other three machine grading methods includes three visual grades, the $I_c$ grade accounting for more 60 percent.

According to tables 2 and 4 the sequence in the design strength should be C3, $I_c$, C2, $II_c$, $III_c$, and C1 for Chinese fir lumber, although the characteristic strength value of the $III_c$ grade is higher than that of C2 grade. ALS (American Lumber Standards) rules stipulate that after removing MSR boards there shall be no visual grades produced that have a design bending strength greater than the design bending strength of lowest MSR category produced. In this study three machine strength grades were used. Therefore the rejected lumber can only be assigned to visual grades below $III_c$. Because only former three high visual grades were involved in this study the price of R grade should be referred in accordance with $IV_c$ grade.

After the lumber was sorted into visual and MSR grades, the economic value was determined for each grading method. The value comparisons of visual grades versus machine strength grades and other three methods versus the bending method should be forecasted based on approximate current lumber market prices. Currently the Chinese market price of No 1 or No 2 grade lumber imported from North American is about 2500 RMB/$m^3$. Combining with market prices of log and lumber of Chinese fir the future possible market price for each grade of Chinese fir lumber in China is forecasted (Table 8).

Based on Tables 4, 7 and 8 the values for different grading methods were calculated as shown in Table 9. The value for the transversal vibration method is the lowest with a decrease being 340 RMB/$m^3$ relative to the bending method, while the value for the Ultrasonic wave method is the highest, an increase being 71.08 RMB/$m^3$ relative to the bending method. There was an 188.87 RMB/$m^3$ increase in the value of Chinese fir when the bending machine grading was added to the value of Chinese fir lumber compared with the visual grading method.

Till now there is no production of visually graded lumber and MSR lumber in China. With the fast development of wood structures the demand for dimension lumber is increasing. The first thing for manufactures is to invest in the equipment necessary for MSR grading. As we known, allowable MOE values are based on static tests of lumber tested on edge. Therefore, regardless of any grading method based on dynamical test methods, for example ultrasonic wave method,

Table 7. Piece yield for visual grades for each machine strength grade.

| Machine strength grade | C3 | | | C2 | | | C1 | | | R | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Visual Grade | $I_c$ | $II_c$ | $III_c$ | $I_c$ | $II_c$ | $III_c$ | $I_c$ | $II_c$ | $III_c$ | $I_c$ | $II_c$ | $III_c$ |
| Ultrasonic wave method | 279 | 48 | 97 | 0 | 0 | 0 | 27 | 8 | 4 | 6 | 1 | 0 |
| Longitudinal vibration method | 148 | 20 | 62 | 70 | 10 | 17 | 81 | 24 | 20 | 13 | 3 | 2 |
| Transversal vibration method | 96 | 10 | 27 | 125 | 23 | 51 | 17 | 6 | 7 | 74 | 18 | 16 |
| Edge-wise bending method | 130 | 17 | 44 | 111 | 21 | 40 | 43 | 9 | 11 | 28 | 10 | 6 |

Table 8. Future possible market price for each grade in China.

| Grade | C3 | $I_c$ | C2 | $II_c$ | $III_c$ | C1 | $IV_c$ |
|---|---|---|---|---|---|---|---|
| Price (RMB/$m^3$) | 3000 | 2800 | 2600 | 2500 | 2300 | 2200 | 1800 |

Table 9. Value change for different grading methods.

| Grading methods | Value (RMB) |
|---|---|
| Ultrasonic wave method | 20535.46 |
| Longitudinal vibration method | 18860.10 |
| Transversal vibration method | 17634.37 |
| Edge-wise bending method | 20034.91 |
| Visual grading method | 18704.89 |

longitudinal vibration method and transversal vibration method, some equations are needed to estimate static MOE from the dynamic MOE. It is also suggested that the mechanical properties of lumber from its logs must be determined before some species will be used for making dimension lumber.

## 5 CONCLUSIONS

Different grading methods have obvious effects on characteristic values, grade distribution and yield of dimension lumber. Among ultrasonic wave method, longitudinal vibration method and transversal vibration method, the transversal vibration method seems to be more precise grading method though it produces the low value of Chinese fir. In determining design strength for Chinese fir lumber, C3 should be higher than $I_c$ following by C2, $II_c$, $III_c$, and C1. MSR lumber from Chinese fir plantation may offer a higher value alternative to the production of visually.

## ACKNOWLEDGEMENT

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## REFERENCES

Wu C.L. 1955. Distribution of *Cunninghamia lanceolata*. *Journal of Grography*. Vol. 21, No. 3, pp. 273–285.

Chinese State Forestry Administration (SFA). 2005. Report of Chinese forestry resources. Chinese Forestry Press, Beijing.

Zhou H.B. 2006. Studies on Design Methods for Sound Insulation of wood structure walls and vibration performance of wood structure floors. Ph.D dissertation. Chinese Cademy of forestry, Beijing.

Wang Y.W., Long W.G. and Yang X.B. 2005. A research on machine grading rule of dimension lumber. Sichuan Building Science, Vol. 31, No. 6, pp. 3–7.

Zhou H.B., Ren H.Q., Jiang J.H., et al. 2007. Study on machine grading for dimension lumber from Chinese fir plantation. Symposium of 11th Wood Science Branch of Society of China Forestry Society. June 1–4. Kunming, Yunnan province, China.

Ren H.Q., Yin Y.F., Ni C., et al. 2006. In-grade Lumber Testing of Chinese fir plantation. 9th World Conference on Timber Engineering. August 6–10. Portland, OR, USA.

Luo X.Q., Guan, N. 1995. Differences between mechanical properties of juvenile and mature woods of China-fir from natural stand and plantation. *World Forestry Research*. Vol. 8. Spl. pp. 172–180.

Wilson T.R.C. 1943. Guide to the grading of structural timbers and the determination of working stresses. Miscellaneous Publication No. 185, United States Department of Agriculture, USA.

Kunesh R.H., Johnson J.W. 1972. Effect of single knots on tensile strength of 2 by 8 Douglas-fir dimension lumber. *Forest Products Journal*. Vol. 22, No. 1, pp. 32–37.

Samson M. 1993. Modeling of knots in logs. Wood Science and Technology, Vol. 27, No. 6, pp. 429–437.

Ormarsson S., Dahlblom O. and Perterson H. 1999. Influence of spiral grain on stiffness grading of structure timber. Pacific Timber Engineering Conference. March 14–18. Rotorua, New Zealand.

Zhou H.B., Ren H.Q., and Yin Y.F. 2007. Evaluating static elastic properties of wood structure building dimension lumber using transverse vibration. *Journal of Building Material*. Vol. 10, No. 3, pp. 271–275.

Chinese Ministry of Construction (MOC). 2003. GB50005–2003 - Code for design of timber structures. Chinese Architecture and Building Press, Beijing, China.

Robert G.E., Thomas M.G., David W.G., et al. 2000. Mechanical grading of lumber sawn from small-diameter lodgepole pine, ponderosa pine, and grand fir tress from Northern Idaho. *Forest Products Journal*. Vol. 50, No. 7/8, pp. 59–65.

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# The research of joint composed by laminated bamboo lumber

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ABSTRACT: The bearing capacity and failure form of the joint composed by laminated bamboo lumber and steel bolt are researched by static loading experiment. The result shows that the laminated bamboo lumber joint display high strength, rigidity and excellent deformability. The main board and bolts of joint fail at the same time, it indicates that the laminated bamboo structure laminate can ensure the effective transmission of shear and show reliable load resistance integrality.

## 1 INTRODUCTION

In wood structures, the property of joint connections, which play a very important role in the whole strength and rigidity, is crucial to the global stability of a structure. Whether connections can transfer loads to the foundation within a comparatively long time or a disaster is directly associated with wood structures' safety, reliability and durability.

In this research, bamboo laminated lumber joint is used in the crucial link of wood structures-the joint connection. By analyzing the ability of bearing compression and property of deformation of bolted joint, structural mechanical property is estimated. Bolted joints, with the merits (Heine, 2001) of being convenient in connecting construction, transferring stress equally, having strong bearing capability, good fatigue resistance and reliability under cyclic loading, is widely used in wood structures as a kind of structural connections. Under the assumption of the elasto-plastic deformation of side boards and bolts in connection through yield model, the yield strength of members are well forecasted and disagreement brought by repeated estimating the point of proportional limit is reduced to a large extent. Further research on the ability of shear transferring at joints of bamboo laminated lumber in pole and beam and roof truss will provide studies and datum which can accelerate the use of bamboo laminated lumber in construction.

## 2 FACTURE OF SPECIMEN AND TESTING METHOD

### 2.1 *Place where specimen was made and its method*

Material and joint of bamboo laminated lumber is produced by Zhejiang Xinchang Bamboo & Timber Co., Ltd, while specimen is made at Wood Industry Research Institute of Chinese Academy of Forestry.

The method with which specimen were made was under the instruction of "Standard for methods testing of timber structures (GB/T50329-2002)". As shown in Figure 1, six specimens were made and dimension of their side board and main board was 65 × 140 × 480 mm, while there were 6 bolts in two-row kind and 2 bolts in single-row kind (material of bolt is Q235, tensile strength is 380 ~ 470 MPa). Main board and side board of which specimen consisted were compression-parallel-to-grain. Pressure bearing face of the end should be perpendicular to axis, and when laminated together main board and side board should be drilled through at once at the speed of 100 mm/min. Orbicular steel bolt with diameter of 12 mm is selected, whose two ends protrude side boards for 20 mm respectively. One of the fastening condition of bolts was fastened and the other totally loose, having no prestressing.

### 2.2 *Place where test was conducted and its method*

The place where test was conducted is National Construction Engineering Testing Center, China academy of building Research, the ultimate load of universal test machine used is 500 kN.

Loading method is as follows: first, load to 0.3 F (F is the specimen's theoretic bearing strength), and keep the load for 30 seconds, then unload to 0.1 F, and keep the load for 30 seconds, then load one grade of load (0.1 F) every 30 seconds until it gets 0.7 F, slow down the speed and keep loading until the specimen is destroyed.

## 3 THE RESULT OF THE TEST AND THEORETICAL ANALYSIS

### 3.1 *Method for finding the bearing strength of joint composed by bamboo laminated lumber*

The strength of bolted connection and mechanical properties such as yield and ultimate load is well understood through load-displacement curve and character of elasto-plastic deformation of connection. However, the bearing capacity of wood structure have always been quite difficult to figure out (Mclain and Tangjitham, 1983). As is shown in Figure 1, it is difficulty to find which point is the design bearing capacity in the load-displacement curve. In 1932, Trayer did a lot of tests and with this understanding he put the concept proportional limit into bearing capacity of wood structures, he considered that when the connection displaced under stress, if the displacement didn't change with load of a certain value, then the point was considered as proportional limit point (Trayer, 1932). For many years, the theory of proportional limit have been the foundation of American wood structure design, but this method is still the source of confusion and disagreement.

In this research, Chinese <Standard for methods testing of timber structures (GB/T50329-2002)> was used in the calculation method of strength reduction factor of joint composed by

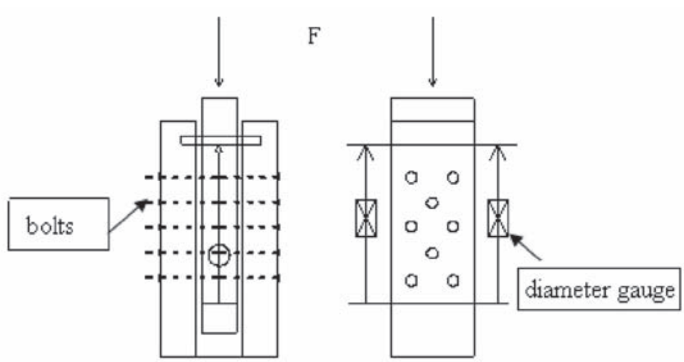



Figure 1. Diagrammatic sketch of specimen.

laminated bamboo lumber. And the academic calculation equation for strength of single bolt is as follows (when steel bolt reach the yield point, calculate use the two equations and select the smaller one):

$$F = 2 \times \left[0.3 \times d^2 \sqrt{\eta f_c f_y \times 1.7} + 0.09a^2 \eta f_c \sqrt{\eta f_c /(1.7 f_y)}\right] \tag{1}$$

$$F = 2 \times \left[0.443 \times d^2 \sqrt{\eta f_c f_y \times 1.7}\right] \tag{2}$$

Where, $d$ is the diameter of steel bolt (mm); $a$ is the thickness of side board (mm); $f_c$ is the compression strength parallel to grain of standard small clear specimen ($N/m^2$); $f_y$ is the yield point of steel used by steel bolt; η is the reduction factor of compression of wood, when $d \geq 14$ mm, $\eta = 0.8$, when $d \leq 14$ mm, $\eta = 0.85$; $F$ is the estimated strength of the connection when steel reach its yield point (N).

In 1949, Johansen built yield limit model that was perfected (Mclain and Thangjtham, 1983; Soltis et al., 1986), so the yield strength of connection can be found with a certain precision. And it is considered that the bearing capacity strength is yield point strength, then the yield point can be got by excursion of 5%. Yield point is defined as the point of intersection of the load-displacement curve and the parallel line of linear part of the curve. And the excursion distance between the parallel line and the linear part line is 5% of the bolt diameter (Wilkinson, 1991). Under the assumption of elasto-plastic deformation of side board and bolt of connection, the yield strength of the member is well forecasted through this model, and the method reduced the disagreement brought by repeating finding the proportional limit point to a great extent, building safe design on a reasonable foundation. At present, many standard still use the 5% excursion as the design bearing capacity of connection in wood structure (Fig. 2). The bearing capacity is defined as the destroy of connection or the deformation displacement reaches 0.6 in or more, and consider the boundary value as the largest bearing capacity (ASTM, 2001). The Chinese standard for methods testing of timber structures (GB/T50329-2002) makes the relative displacement of 10 mm and more (ASTM, 1999; 2001) the limit of connection bearing capacity. According to these academic research methods for the bearing capacity of wood structure connection and design value mentioned above, research on bearing capacity of bamboo laminated lumber shows that load-displacement curve has obvious primary condition of linear section and later condition of plasticity section, and that after the yield point the deformation of connections obviously accelerates and shows a typical character of elasto-plastic deformation. If following the standard of

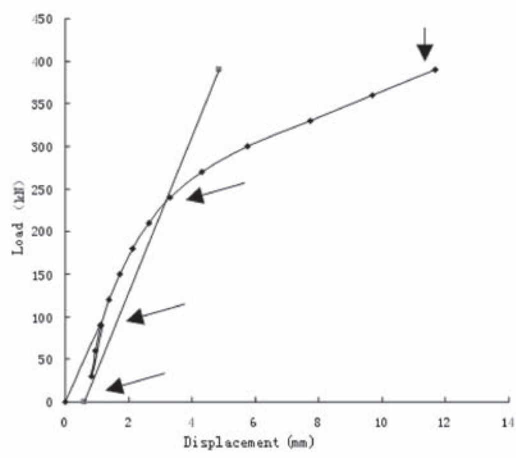



Figure 2. Load-displacement curve of bamboo laminate joint.

American NDS and calculate with 5% deformation, bamboo laminated lumber's standard design bearing capacity is 240 kN. The method is reasonable since that the point of intersection of the 5% excursion line and load-displacement curve is approximately the proportional limit point. And the largest bearing capacity got from the Chinese standard for methods testing of timber structures (GB/T50329-2002) is 380 kN.

Associated with the requirement of design bearing capacity in truss in wood structure of wood structure project department of INBAR, this research used the Chinese code for design of timber structures, selected the bamboo laminated lumber whose design bearing capacity was 380 kN to substitute the deal timber of Yunnan province with dimension of $65 \times 140 \times 480$ mm, whose design bearing capacity is 80 kN. So it is obvious that the connection of bamboo structure is stronger than that of timber structure, and at the same dimension level, the bamboo laminated truss can totally satisfy the requirement of factual project.

### 3.2 *Research on theoretic calculation and reduction factor of bearing capacity of multi-bolt joint composed by laminated bamboo lumber*

The rigidity and strength of bolted connection don't vary directly with the number of bolts (ASTM, 1999; 2001), as single bolts in multi-bolted connection don't equally bear the load, which will induce some bolts' larger load than others and stress concentration, and this eventually result in reduction factor (Doyle, and Scholten, 1963; Isumov, 1967), which reflect the property of the integrity in bearing load.

According to the research on calculation method for reduction factor of joint composed by laminated bamboo lumber, bearing capacity of single bolt in connection is 50 kN, so the theoretical bearing capacity connection with 8 bolts should be 400 kN, while the value of that connection got in test is 380 kN, so the reduction factor can be got from the following equation:

$$p = n \times p_{single} \times C_g \tag{3}$$

Where $p$ is strength of connection; $n$ is the number of bolt; $P_{single}$ is strength of single bolt connection; $C_g$ is the reduction factor.

According to equation (3), the reduction factor is 95%, from which the excellent whole bearing character of bamboo multi-bolted joint is shown.

Bamboo multi-bolted connection's good integrity in bearing load can also be approved by figure 3, from which we can see the connections act almost the same under either the fastening condition or the totally loose condition.

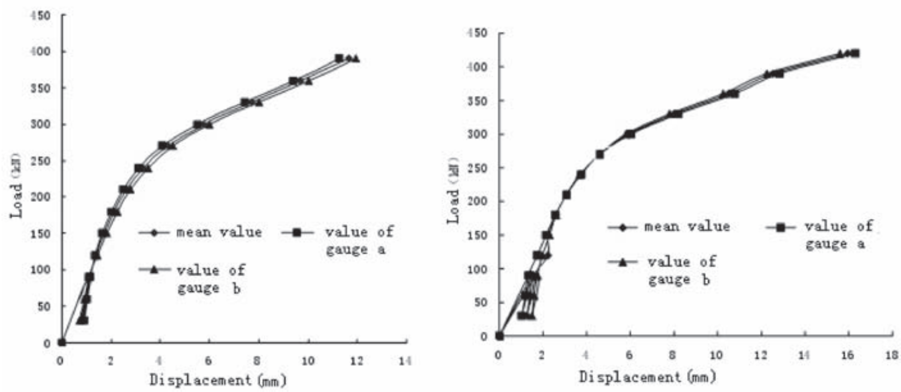


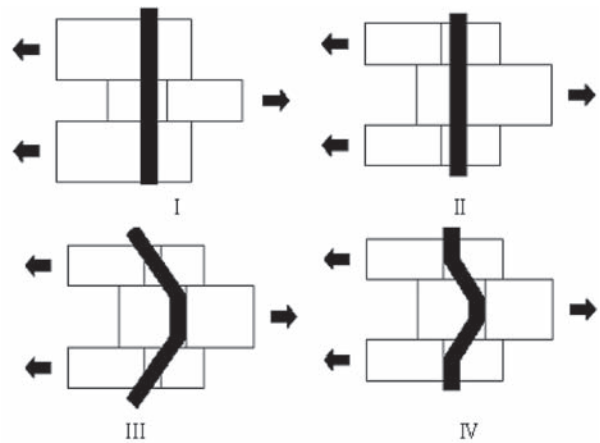

Figure 3. Load-displacement curves.

### 3.3 *Failure form of shear joint*

The strength of shear connection is the result of coordinating between the material mechanical property of side boards and that of bolts. According AFPA 2007 standard, four models were built with consideration of time relationship of the fracture of side boards and bolts under load (Fig. 4).

Mode I when the connection reaches its ultimate strength, side boards and bolts are undamaged while main board reaches its ultimate strength and yield, so the model is controlled by the strength of main board.

Mode II when the connection reaches its ultimate strength, main board and bolts are undamaged while side boards reaches their ultimate strength and yield, so the model is controlled by the strength of side board.




I crushing in main member; II crushing in side member; III rotation of fastener; IV crushing in side and main members & rotation of fastener.

Figure 4. Failure forms.

(a) the failure form of main board hole; (b) the flexural failure of bolt.

Figure 5. Failure detail of joint.

Mode III when the connection reaches its ultimate strength, main board and side boards are undamaged while bolts reaches their ultimate strength and yield, so the model is controlled by the strength of bolts.

Mode IV when the connection reaches its ultimate strength, main board, side boards and bolts are damaged at the same time, so the model is controlled together by the strength of main board, side boards and bolts.

Mode IV the most perfect failure form, in which main board, side boards and bolts all reaches the ultimate condition, making full use of materials and getting the goal of effective use of materials (Salenikovich, et al., 1996; Dolan and Madsen, 1992; Dolan, et al., 1996). According to the theory mentioned above, this research studied the failure condition of the main board, side boards and bolts of connection. Figure 5 shows the disconnected main board and side boards of connection. From Figure 5 we can see the grooves in the inner side of side board and the main board acted the same, while the shear bolts of connection rotate to the same extent. From the mode mentioned above, conclusion can be drawn that joint composed by laminated bamboo lumber is a typical ideal failure form who can fully make use of mechanical strength of materials.

### 3.4 *Research on ductility of bamboo laminated lumber*

Ductility is an important data in evaluating the mechanical property of building materials, and it refers to the deforming capability of materials, members and structures with no obvious reduction in bearing capacity in nonlinear condition under load or other indirect effect. In wood structure buildings, the ductility of connection is crucial to the stability of the structure (Falk and Moody, 1989). Especially in disasters such as earthquake, typhoon, good ductility of a structure will act as a buffer to the disasters, preventing disaster from taking place at once and enhancing the safety of the structures. Also, connections of structures with good ductility have the ability of consuming energy and will consume the energy of earthquake.

There are many ways to show the ductility of members, here the frequent method is analyzing load-displacement curve to study the connection, and the area under the curve reflects the ductility, the larger the better.

Bamboo in itself consists of structure with good ductility, and so is the members made from it. Even if compared with wood lumber with good ductility, bamboo laminated lumber shows better. Just as figure 4 shows, when it reaches yield point, bamboo's load-displacement curve still ascends obviously and the connection's bearing capacity rise with it, whereas wood connection shows quick decrease and its ductility is not better than bamboo (Guy, 2001). This substantive characteristics is consistent with its exterior phenomena. Figure 5 shows that the ultimate strength of bamboo connections is determined by large distortion in main boards and side boards instead of their damage, whereas research by Guy T. Anderson showed that wood connections reached their ultimate strength because of their damage, which is a conform of good plasticity of bamboo.

## 4 CONCLUSIONS AND SUGGESTIONS

1. Research on the load-displacement curve of joint composed by laminated bamboo lumber shows that American NDS design standard is good and appropriate in finding its design bearing capacity.
2. Research on the reduction factor of joint composed by laminated bamboo lumber indicates its value is 95%, which reflect bamboo connections' good integrity in bearing load.
3. Research on the yield mode of joint composed by laminated bamboo lumber shows they have excellent yield model: Mode IV in ASTM (1997)—the most perfect yield mode.
4. The comparison between the ductility of bamboo and wood connections indicates that joint composed by laminated bamboo lumber is good at ductility because of bamboo's excellent

plasticity; compared with the academic value of connections made from deal timber of Yunnan province, bamboo connections' bearing capacity is about four times of it.

5. Pseudo-dynamic loading device is suggested in after research, so the power-wasting earthquake resistance property of bamboo connection can be studied quantitatively.

## REFERENCES


Heine, C.P. 2001. Simulated Response of Degrading Hysteretic Joints with Slack Behavior. Ph.D. Dissertation. Virginia Polytechnic Institute and State University. Blacksburg, VA.

Mclain, T.E. & Tangjitham, S. 1983. "Bolted Wood Joint Yield Model." Journal of Structural Division, ASCE, 109 (8), 1820–1835.

Trayer, G.W. 1932. "The Bearing Strength of Wood Under Bolts." Technical Bulletin No. 332. USDA, Washington DC.

Zahn, J. 1991. "Design Equation for Multiple Fastener Wood Connections." Journal of Structural Engineering, ASCE, 117 (11): 3477–3486.

Soltis, L.A. et al. 1986. "Bearing Strength of Bolted Timber Joints." Journal of Structural Engineering, ASCE, 112 (9): 2141–2154.

Soltis, L.A. & Wilkinson, T.L. 1987. "Bolted-Connection Design." USDA Forest Service General Technical Report FPL-GTR-54. Forest Products Laboratory. Madison, WI.

Mohammad, M., Quenneville, J.H.P. & Smith, I. 1998. "Influence of Cyclic Loads on Strength and Stiffness of Bolted Timber Connections." Proceedings of the 5th World Conference on Timber Engineering. Vol. 1: 375–382.

Wilkinson, T. 1991. "Dowel Bearing Strength." USDA Forest Service Research Paper FPL-RP-505. Forest Products Laboratory. Madison, WI.

Annual Book of ASTM Standards v4.10, 2001. "Standard Test Method for Determining Bending Yield Moment of Nails." American Society of Testing and Materials Standard F 1575-95. ASTM, Philadelphia, PA.

Annual Book of ASTM Standards v4.10, 2001. "Standard Test Method for Evaluating Dowel-Bearing Strength for Wood and Wood-Based Products." American Society of Testing and Materials Standard D 5764-97a. ASTM, Philadelphia, PA.

ASTM, 1999. "Standard Test Method for Cyclic Properties of Connections Assembled with Mechanical Fasteners." American Society of Testing and Materials Standard E06.13. 7th Draft Standard. ASTM, Philadelphia, P.A.

Chinese Standard, Testing Method for Timber Structures (GB/T50329-2002), Ministry of Construction, China.

Cramer, C.O. 1968. "Load Distribution in Multiple-bolt Tension Joints." Journal of Structural Division, ASCE, 94 (STS): 1101–1117.

Doyle, D. & Scholten, J.A. 1963. "Performance of Bolted Joints in Douglas-fir." USDA Forest Service Research Paper FPL-2. Forest Products Laboratory. Madison, WI.

Isumov, N. 1967. "Load Distribution in Multiple Shear-plate Joints in Timber." Publication No. 1203. Canada Department of Forestry. Ottawa, Canada.

Salenikovich, A.J., Loferski, J.R. & Zink, A.G. 1996. "Understanding the Performance of Timber Connections Made With Multiple Bolts." Wood Design Focus, 7 (4): 19–26.

Dolan, J.D. & Madsen, B. 1992. Monotonic and cyclic nail connection tests. Canadian Journal of Civil Engineering. Ottawa, Canada. 19 (1): 97–104.

Dolan, J.D., Gutshall, S.T. & McLain, T.E. 1996a. Monotonic and cyclic tests to determine short-term load duration performance of nail and bolt connections. Research Report No. TE-1994-001. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Falk, R.H. & Moody, R.C. 1989. Wood diaphragms: Performance requirements and analytical modelling. In Structural Design, Analysis and Testing, A.H-S. August edition, American Society of Civil Engineering Journal, New York, N.Y., pp. 101–111.

Guy T. Anderson. Experimental investigation of group action factor for bolted wood connections Virginia polytechnic institute and state university 2001 thesis.

*Structural applications of bamboo*

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# Application of bamboo connector to timber structure—Introduction of construction and dismantlement of Japanese government pavilion Nagakute in Expo 2005 Aichi, Japan

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ABSTRACT: The 2005 World Exposition was held with the main theme "Nature's Wisdom" in Aichi Prefecture, Japan. NAGAKUTE NIPPON-KAN was constructed using eco-friendly technology. The timber connecting system using bamboo connector developed by authors is adopted to the structural timber connection in this pavilion. Energy consumption was reduced by the bamboo cover cage as sunscreen, bamboo grass green wall and bamboo roof tiles as insulation member. After the EXPO 2005 ended, the timber members obtained from the dismantled building were was sold by Internet auction to reuse.

## 1 INTRODUCTION

The 2005 World Exposition was held from 25 March until 25 September 2005 (total of 185 days) in Nagoya Eastern Hills (Nagakute Town, Toyota City and Seto City). Total visitors were 22,049,544 persons. The main theme of this EXPO was "Nature's Wisdom". In the EXPO2005, Japanese government exhibited two pavilions in the site of SETO and NAGAKUTE. "Japan pavilion NAGAKUTE" is one of them (see Photo 1). This building was designed as a building, which is suitable to the concept of the environmental protection. It was constructed using as much eco-friendly technology as possible. We introduce the new timber material, timber engineering technology and eco-friendly technologies adopted in Japan pavilion NAGAKUTE in this paper.

## 2 OUTLINE OF JAPAN PAVILION NAGAKUTE

This pavilion is large-scale timber structure with over 6,000 $m^2$ floor area and is covered by bamboo cage. The size of the bamboo cage is 90 meters by 70 meters and 19 meters high. The bamboo cage reduced the quantity of solar energy striking and the thermal load. The durability test of bamboo for this cage is carried out by authors. From this test result, smoked bamboo is adopted as the bamboo cage material. The cross section is shown in Figure 1. The bamboo cage is shown in Figure 2.

Photo 1. Whole view of JAPAN Pavilion NAGAKUTE.

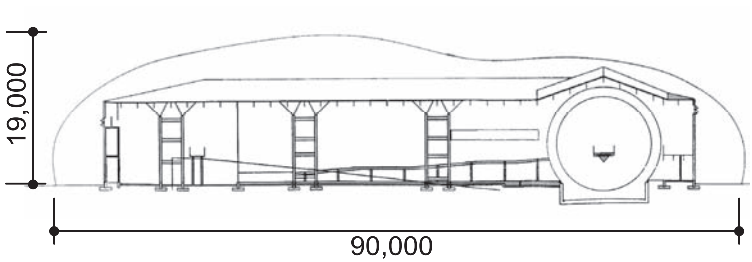


Figure 1. Cross section (Unit in mm).

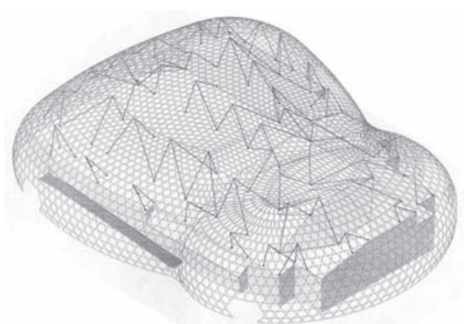

Figure 2. Bamboo cage.

## 3 STRUCTURE

### 3.1 *Bamboo connector*

The connecting method by bamboo connector adopted in the pavilion is based on the connecting method using metal connector and adhesives [1]. The bamboo connector was developed by the authors (see Photo 2). The connecting mechanism is shown in Figure 3. In this system, a bamboo connector is embedded at joint with adhesive (see Photo 3). Total number of the bamboo connectors in this pavilion is over 60,000 pieces. Bamboo connector realizes the connection can be cut off by saw. After the EXPO, bamboo connector is not required to be separated from dismantled parts from this pavilion for recycling.

### 3.2 *Tension strength of laminated bamboo*

The bamboo laminated lumber which is the material of a bamboo laminated connector is tested to research the tension strength. The list of specimens is shown in Table 1. The shape and size of each specimen is shown in Figure 4. The tension strength as test results is shown in Figure 5. The strength of specimen with 4 lamimae is slightly higher than that of specimen with 7 lamimae. The strength of specimens with 4 laminae and urea resin and the specimens with 7 laminae and polyurethane resin are slightly higher than that of other specimens.

Photo 2. Bamboo connector (T-type).

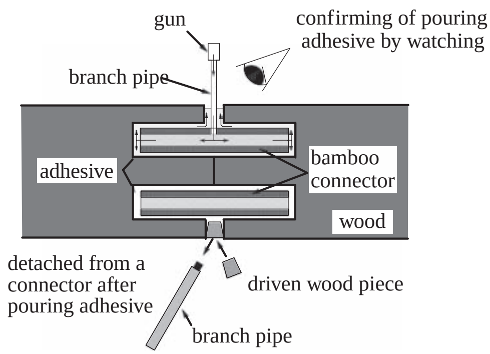


Figure 3. Mechanism of joint using T-type connector.

Photo 3. Beam-column connection.

Table 1. List of specimens.

| Specimen name | Number of laminae | Adhesive | Number of specimen |
|---|---|---|---|
| BL4-API | 4 | Polyisocyanate | 4 |
| BL4-PUR | | Polyurethane resin | |
| BL4-YUR | | Urea resin | |
| BL7-API | 7 | Polyisocyanate | |
| BL7-PUR | | Polyurethane resin | |
| BL7-YUR | | Urea resin | |

3.3 *Tension strength of splice joint using bamboo connector*

The list of specimens is shown in Table 2. In all specimens, SUGI (Japanese cedar) with the size of 105 × 105 × 950 mm is used. The range of Young's modulus of the SUGI lumbers is from 6.77 to 7.36 GPa. The range of moisture content is from 8.5% to 26.5%. The number of specimens for each series is 6. The total number of specimen is 36.

The shape and size of specimens are shown in Figure 6. The arrangement for tension tests parallel to the grain is shown in Figure 7. Three specimens of each series were loaded by monotonous loading, other three specimens of each series were loaded by repeated loading. The gap between the batted faces of timbers at splice was measured by 4 displacement transducers around the splice

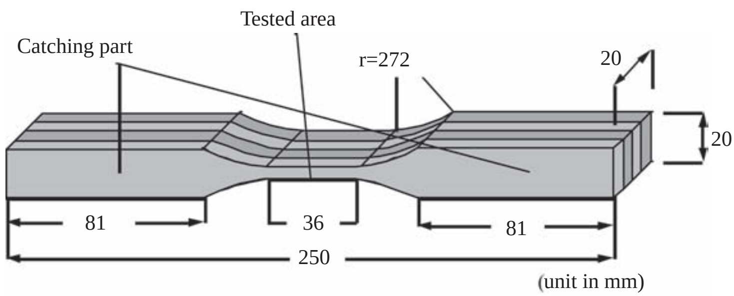


Figure 4. Shape and size of specimens.

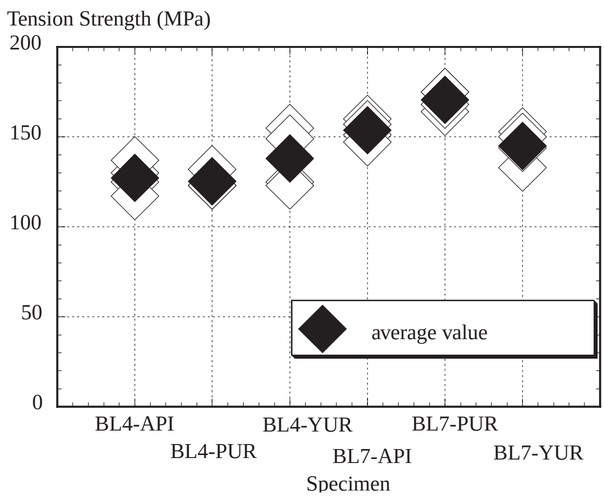


Figure 5. Tension strength of laminated bamboo.

Table 2. List of specimens.

| Specimen name | Number of laminae | Adhesive | Number of specimen |
|---|---|---|---|
| L4-API | 4 | Polyisocyanate | 3 specimens for monotoously loading |
| L4-PUR | | Polyurethane resin | |
| L4-YUR | | Urea resin | |
| L7-API | 7 | Polyisocyanate | 3 specimens for repeated loading |
| L7-PUR | | Polyurethane resin | |
| L7-YUR | | Urea resin | |

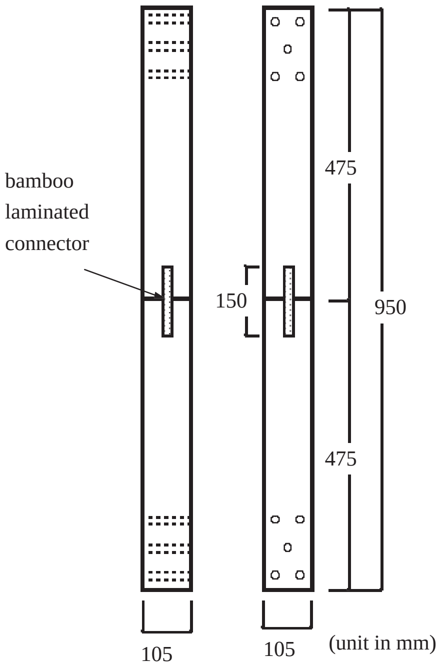


Figure 6. Shape and size of specimens.

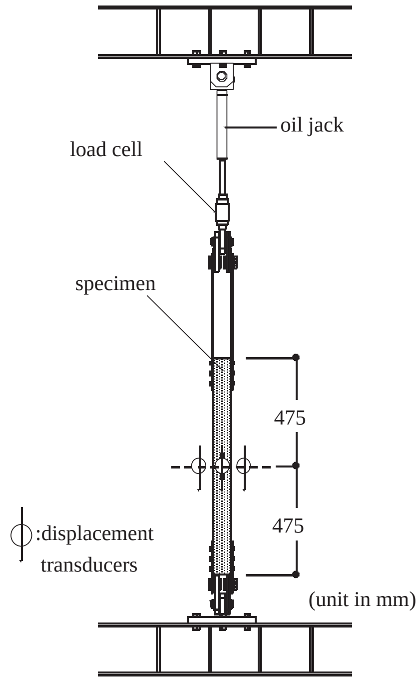


Figure 7. Test set-up.

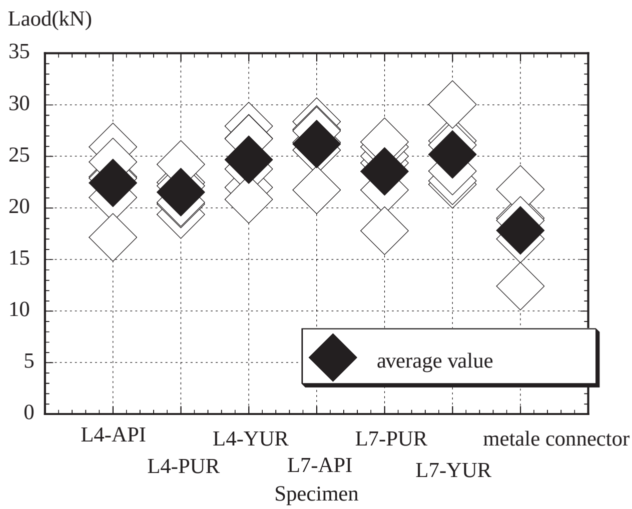


Figure 8. Tension strength of splice joint using bamboo connector.

during test. In this test, polyurethane bond was used as adhesive for filling up around the connector. The urethane sheet was inserted to prevent filling of adhesive at batted face.

The maximum load of all specimens is shown in Figure 8. The value for the specimen with metal connector is shown in this figure. The size and shape of the metal connector developed by authors is same as that of the bamboo laminated connector used in this test. The curing time for the joint with metal connector is same as that of the specimen with bamboo laminated connector. The maximum load of the specimens with the bamboo laminated connector was higher than that of the specimens with metal connector. The bonding effect between the bamboo and adhesive is higher than that between the metal and adhesive, 7 laminae system in the bamboo connector has slightly higher strength than that of 4 laminae system. The reason for this phenomenon is that the outer skin of bamboo with higher strength is contained largely in the bamboo laminated connector with 7 laminae. On the other hand, there is no difference between the strength of specimens with various kinds of adhesives used for laminating.

### 3.4 *Other eco-friendly constructions*

The other eco-friendly constructions were used in the pavilion, for example, bundled column made of small diameter log from forest thinning. This pavilion was composed of boxed beam [2] and the bundled column (see Photo 4, 5). The main hall under construction is shown in Photo 6. The bamboo connectors are used at the beam-column connections, boxed beam, bundled column and bamboo structure mentioned as follows.

## 4 BAMBOO STRUCTURE

Many bamboos were used in this pavilion. For example, entrance passage constructed by round bamboo (see Photo 7). Connection of round bamboo in the entrance passage is adopted to new bamboo connecting system developed by authors (see Photo 8).

The assembly process of the round bamboo connecting system is shown in Figure 9. This connecting system was used at bamboo connection. In this study, urethane adhesive is used in all connections.

Photo 4. Bundled column.

Photo 5. Bundled column.

Photo 6. Main hall on construction.

Photo 7. Passage of round bamboo.

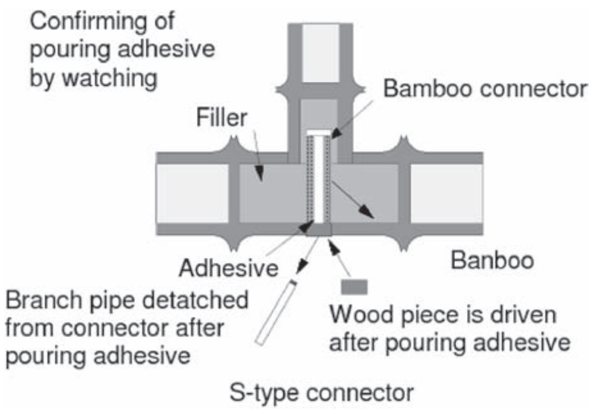


Figure 9. Mechanism of round bamboo connection using S-type connector eco-friendly technologies.

Photo 8. Connection of passage made of round bamboo.

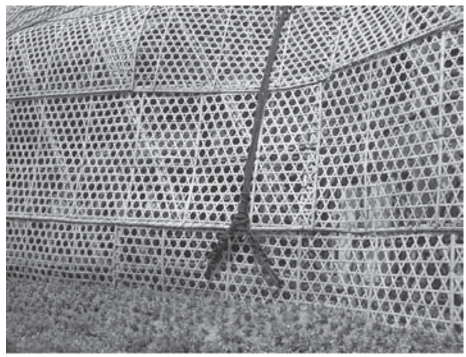

Photo 9. Bamboo cage.

Photo 10. Bio plastic Insulation wall.

Photo 11. Insulation made from bamboo fiber.

Furthermore, a lot of new timber technology and material are used in the pavilion. Bamboo cage is taken in traditional technology of bamboo craft (see Photo 9). Bio plastic insulation wall has an effect on saving fossil fuel and reducing global warming gas as shown in Photo 10. Photo 11 shows insulation made from bamboo fiber. This insulation is effective material to recycling and biomass. Bamboo grass green wall is adopted in this pavilion (see Photo 12). Photo 13 shows the roof tile made of round bamboo. Plywood downpipe is shown in Photo 14.

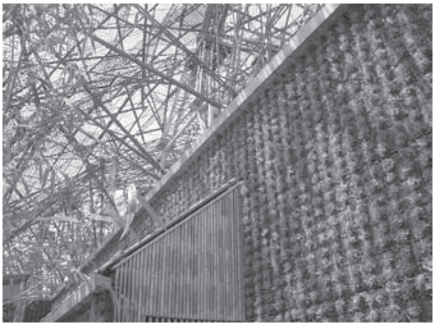

Photo 12. Bamboo grass green wall.

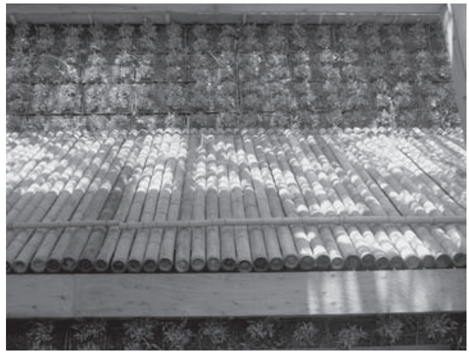

Photo 13. Bamboo roof tile.

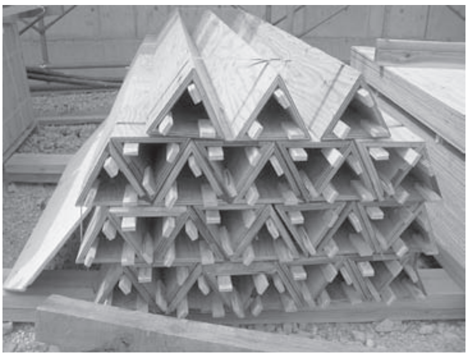

Photo 14. Plywood downpipe.

Photo 15. Dismantling works.


Photo 16. IC tug.

Photo 17. Dismantled columns delivered to Oita University.

## 5 AFTER THE EXPO2005

After the EXPO2005 ended, the pavilion was dismantled as shown in Photo 15. Dismantled timber is sold to reuse by Internet auction. Timber materials are controlled by IC tug (see Photo 16). Oita University was bought five dismantled columns to reuse the five columns (see Photo 17).

## 6 CONCLUDING REMARKS

This pavilion attracted a great deal of considerable attention as the eco-friendly building. The entire building is a trial construction using new technologies and materials for the earth environmental protection.

## REFERENCES

Inoue M. et al. 2003. Development of New Connecting System for Timber Joint Using Adhesive and Bamboo Laminated Connector, *Proceedings of the IAWPS2003*, Vol. 1, Daejeon, Korea, Apr., 2003, pp. 736–740.

Inoue M. et al. 1999. Structural Behaviour of Box Beam Jointed by New Connecting System, *Proceedings of Pacific Timber Engineering Conference* '99, Vol. 3, Rotorua, New Zealand, Mar., 1999, pp. 123–130.

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# Small bamboo structure made by architecture students at the University of Kitakyushu, Japan

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ABSTRACT: Since 2002, a design program has been elaborated for the second year students of the Faculty of Environmental Engineering at the University of Kitakyushu in Japan. The aim of the design program is trying to find new concepts, and ways of using bamboo material, bamboo construction methods and last but not least making small spatial bamboo structures. A total of more than 300 students; every year 9 groups of about 5 to 6 students in one group, made already 54 bamboo objects. The objects are planned and made during the months April and June, and exhibited for the period of one year. For the first four years of this program, there was no specific decided theme; the students could freely choose their own theme and make spatial structures, some groups made art related objects; some groups made structures close to architectural expressions. For the year 2006, the theme of the program has been evolved from making "bamboo objects" to making "bamboo cubes". The size of the bamboo cube must not exceed 140 cm. In the first two years of this program, "Moso bamboo" or "Phyllostachys edulis" was used. Since 2004, "Madake bamboo" or "Phyllostachys bambusoides" had been used. The reason why we changed the material from Moso bamboo to Madake bamboo is because the objects are small scaled, and Madake bamboo is easier to work with, especially to split and bend the bamboo. The Moso bamboo is a bit more difficult to handle with, especially to bend it for small scaled structures. Besides of the bamboo material, only rope could be used for the construction. In this report, the aim of the bamboo design program, the design, construction method, and construction process of the 54 objects are explained. Based on this study, further elaboration of the design program will be suggested.

## 1 INTRODUCTION

In 2001, the faculty of environmental engineering at the University of Kitakyushu started. There are 4 departments at the new faculty; 1) department of chemical processes and environments, 2) department of mechanical systems and environmental engineering, 3) department of information and media sciences, 4) department of environmental space design. The aim of the new faculty was to develop an environmental education program. From 2008, a new department will be adding to the existing 4 ones, and some departments will change their naming. The five departments will be; 1) department of chemical and environmental engineering, 2) department of mechanical systems engineering, 3) department of information and media engineering, 4) department of architecture, 5) department of life and environment engineering. The bamboo objects are made by students of the department of environmental space design, students at this department are studying architecture (from 2008, department of architecture).

The bamboo objects are made by second year students, in the first semester of the second year. The lecture in which the objects are made is called workshop 1. There are 4 different themes or projects in this lecture; and one of the themes is making a bamboo object. The bamboo object must be made in a very short time; there are only 4 to 5 lectures, spread over 4 to 5 weeks. One lecture last 180 minutes. Because there is no time enough to finish the objects during the lectures, students are working also after the classes.

## 2 AIM OF MAKING THE BAMBOO OBJECTS

There are several aims for making the bamboo objects, and the main purposes are as noted below:

- All the students are belonging to the department of architecture; in the education program it is very difficult to let students participate in the whole process from planning a building until realizing a building. For that reason, making in a short time a construction, or object in bamboo, it can be possible to have an idea of this whole process. The students are
  1. thinking about the concept and design of their object.
  2. they need to collect all the material to make the object; in this case using bamboo.
  3. they need to cut the bamboo in the forest, and prepare the bamboo so that it can be used as building material. They need to prefabricate all the elements of their object; and assemble them together.
  4. one year later, they need to dismantle again the object and bring the used bamboo to a place in the campus where the bamboos will be returned to nature in the form of soil. The process of becoming again soil will take a longer time, in most cases several years.
- Another aim is to bring the students of architecture aware of using besides stone and concrete material, local and natural building material in the design of their buildings. Unfortunately, in the designs made after this workshop, only some students do really apply more local building materials.
- Making students aware of the problems bamboo forests are facing is another aim. The objects are exhibited during one year. Every year, new objects are replacing the old ones; so there is always an exhibition of bamboo objects. Not only the students of architecture, but also students of other departments as well as the teaching and administrative staff, and visitors of the university will become aware of the problems the bamboo forests are facing at.

## 3 PROCESS OF MAKING THE BAMBOO OBJECTS

The bamboo objects are made in 4 to 5 weeks and exhibited during one year. The process is as below.

- In the first lecture, the students are explained about the problems of the bamboo forest, and about the possibility and methods of using bamboo as building material. There is also a short explanation of the way they need to cut, carry and prepare the bamboo material. Following, the students are divided in 9 groups of about 5 to 6 students. Every year, there are about 50 to 55 second year students; they are divided in 9 groups because there are only 9 courtyards which can be used as exhibition space in the university building. Then, the first week they need to think about what they will make, and about the amount and size of bamboo they need to realize their design.

Picture 1. Cutting bamboos.

- In the second lecture, all students go to a bamboo forest near the university where they cut the bamboo. They cut the bamboos to a certain length and also cut the branches and leaves if they didn't plan to use them in their object. Up to know, bamboo leafs were seldom used in the objects.
- The following 2 or 3 lectures (depending of the lectures last 4 or 5 times), the bamboo objects are made based on the designs which have been thought during the first week. However, during the prefabrication process, many designs are going to be changed. The main reason for that is because most of the students do not really are familiar with bamboo material and are not able to imagine what can be made out of it. Especially the construction methods for their objects are mostly not well investigated in advance. For the construction method it is preferred that they find methods in which the bamboo's specific characters are exploit as much as possible; most students relay still too much on the fact they may use ropes.
- All the bamboo objects are exhibited for one year. During this one year the students will see how their objects undergo changes. There is first of all the change in color. If the objects could dry well, then the objects' color will change little by little; but if they couldn't dry well and rain has come soon after the objects are finished, then the objects become very fast dark colored and in some cases start to rot soon after finishing their works. This is because the bamboo is not treated during the workshop period.

## 4 BAMBOO FORESTS WHERE THE BAMBOO MATERIAL IS TAKING FROM

Figure 1 of the next page, shows the area map of the Kitakyushu Science and Research Park and its surroundings. The University of Kitakyushu is the white building which is situated in the northeast of the forest with number 4 on the map. The bamboo used for the objects is taking from bamboo forests near the university. In the forests, several kinds of bamboo are growing, but only Moso bamboo (Phyllostachys edulis) and Madake bamboo (Phyllostachys bambusoides) had been used up to now. In the first year (2002), the bamboo was taken from the forest place number 1 on

Picture 2. Preparing the parts for the bamboo objects.

Picture 3. The bamboo objects are assembled in the courtyards.

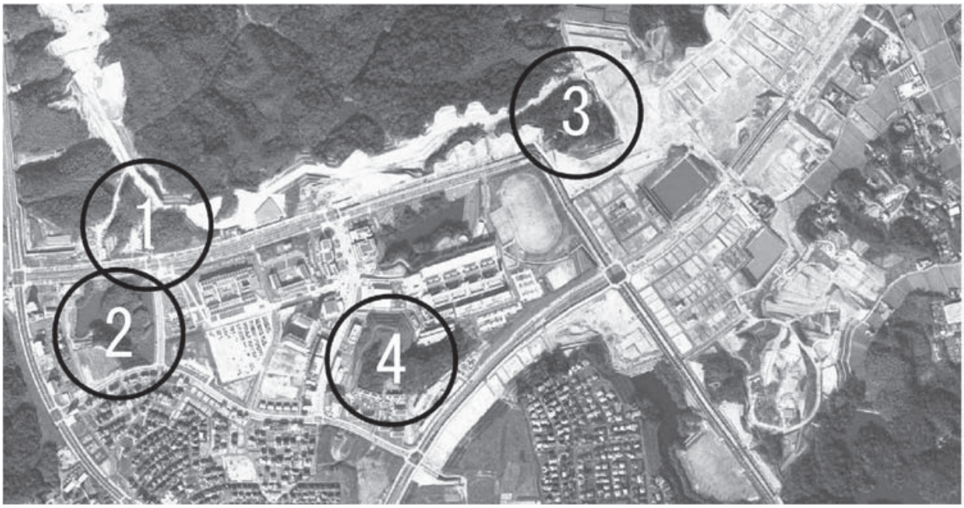



Figure 1. Bamboo forest in the Kitakyushu Science and Research Park (Aerial photograph reference: Google Map).

the figure, in the second year (2003); the bamboo was taken from place number 2. In both places (1 = 2002, 2 = 2003); Moso bamboo was growing. In the meantime, the bamboo forest of place number 1 has disappeared due to the development of a land readjustment project. Place number 2 is the Hibikino South Park, a neighborhood park of about 4 ha large. The forest and bamboo forest in this park have been partly maintained by the NPO Kitakyushu Biotope Network Group.

Because the Moso bamboo is heavy, and also rather difficult to cut, split and bend, especially for small objects, and in our case where there is not enough time, we decided in 2004 to change the kind of bamboo and use the Madake bamboo (Phyllostachys bambusoides) instead of the Moso bamboo. Madake bamboo is found in the forests of numbers 3 and 4. The forest of number 3 is the Yatsurugi Shrine, a small shrine surrounded by a small forest; in this forest both Moso and Madake are growing. The forest number 4 is a small forest which is located behind the foreign students' house of the university. In this forest only Moso is growing. Because every year a large amount of bamboos is cut, it is feared that all the bamboo will disappear in these forests, so we decided in 2007 to take bamboo from another forest more in the north of the Kitakyushu Science and Research Park. Also this kind of bamboo was Madake.

## 5 THE BAMBOO OBJECTS

The next two pages are showing all the bamboo objects. Table 1 shows all the bamboo objects made in 2002, 2003 and 2004; table 2 shows the objects made in 2005, 2006 and 2007. For the years 2002, 2003, 2004 and 2005 the theme was completely free. Students could make whatever they wanted to make. Since 2003 there was only a limitation in height because some of the objects made in 2002 and 2003 were unstable and there was a fear that the windows of the courtyard could get broken. The limitation in height was 140 cm. Some groups did neglect the height limitation but they took in consideration the danger of the windows. In 2004, because we changed from Moso to Madake and because there was a limitation in height, most of the bamboo objects became small-scaled and most of the groups used split bamboo.

Year after year, the objects became more sensitive in terms of their artistic expression because the objects are exhibited during the period of one year. The second year students are making the objects, but the first years students are unintended confronted with the objects for one year. And

Table 1. Bamboo objects 2002–2004.

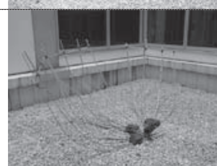
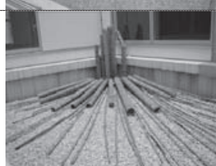
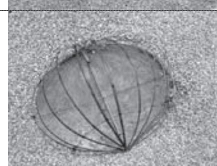
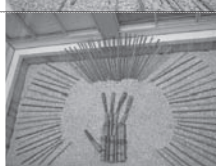
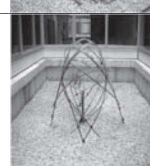
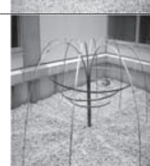
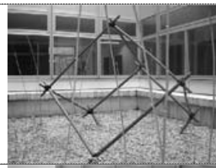
| | 2002 | 2003 | 2004 |
|---|---|---|---|
| Group 1 |  |  |  |
| Group 2 |  |  |  |
| Group 3 |  |  |  |
| Group 4 |  |  |  |
| Group 5 |  |  |  |
| Group 6 |  |  |  |
| Group 7 |  |  |  |
| Group 8 |  |  |  |
| Group 9 |  |  |  |

Table 2. Bamboo objects 2005–2007.

| | 2005 | 2006 | 2007 |
|---|---|---|---|
| Group 1 |  |  |  |
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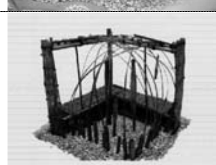
| Group 6 |  |  |  |
| Group 7 |  |  |  |
| Group 8 |  |  |  |
| Group 9 |  |  |  |

one year later, when they start to make their objects they reflect some things they have learned from the former exhibited objects.

Group 7 of 2005 made an object of something looking like a cube. This object, and the above made explanation about the improvement in artistic expression, was the reason why we decided in 2006 to start with making the bamboo cube. The size of the cube was 140 cm × 140 cm × 140 cm. Because all groups made cubes; there was homogeneity among the objects. On the other hand, it was very difficult for all groups to finish their cube in such a very short time of 4 to 5 weeks. For that reason in 2007 we asked the students to make an object which was sized less than 140 cm × 140 cm × 140 cm. Some groups kept the idea of the cube, but some did not, so that there was again diversity among the objects.

## 6 CONCLUSION AND REFLECTIONS

Since 2002, during a period of 6 years long, already 54 small-scaled bamboo objects have been made by over 300 students. In the beginning we did not know very well what it could become but after 6 years we can make some conclusions and reflections.

First of all, bamboo as a natural local material has become again a material that starts to show interest by many people. There are all the students who made the bamboo objects, and also all the students at the other departments who looked at the exhibited objects for 6 years, there is the academic and administrative staff, as well as the visitors at the university, but also people living in and around the Kitakyushu Science and Research Park. Together with the bamboo activities explained in another report, many activities have been published in local journals and magazines. Without doubt it can be said that the problems bamboo forests are facing have been made more open to the general public.

Conclusions concerning the bamboo forest and adjacent forests; 6 year long bamboo thinning has been undertaken. Several hectares of bamboo forest have become little by little maintained. Not only in the area around the Kitakyushu Science and Research Park, but also more distant places start to become maintained. If the making of bamboo objects could become a yearly tradition, then we may expect that more hectares of bamboo forest could be target for preservation. This could result in a complete control of the expanding bamboo forest.

On the other hand unfortunately, techniques related to construction methods with bamboo material have not been developed well in these 6 years. Until now the emphasis was mainly put on the bamboo forest problem, and only on finding ways for the use of bamboo. Only the process of cutting bamboo, and carrying the bamboo out of the forest has been solved. Of course in the beginning phase this was an important factor but as a reflection, in future activities we should shift towards the more technical aspects. Especially, techniques specific to bamboo material must be developed. One way to do so could be by choosing every year the same theme, for example by making not only artistic objects but by making bamboo cubes with emphasis on the assemblage of the parts. Techniques and construction methods, joints etc. should be more investigated. Most students are relaying too much to the fact they can use ropes. The use of rope does not make them thinking or trying to find new solutions of assemblages techniques.

*Modern Bamboo Structures – Xiao et al. (eds)*


# Development of prefabricated bamboo mobile house

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ABSTRACT: This paper introduces a new type of prefabricated house using laminated bamboo sheets and structural elements. The authors adopted a modular design concept to make keep the fabrication cost-effective and easy for construction. The structural design was based on a procedure modified from the design guidelines for lightweight wood frame structures. Connection details similar to those used in conventional lightweight wood frame structures can be used in the bamboo house.

## 1 INTRODUCTION

Most prefabricated lightweight house or mobile structures are made of steel and timber. As we know, metallurgical industry always costs much energy and it is not environment. Although, timber is a kind of environmental material, it is limited in China and the Chinese Government restricts the logging in order to protect the shrinking forests. In order to fully take the advantage of the tremendous resource of bamboo forests in the Hunan Province of China, the Institute of Bamboo, Timber and Composite Structures (IBTCS) at the Hunan University is conducting a comprehensive research program on developing environment friendly bamboo buildings and bridges.

This paper focuses on the research intended to develop a new type of prefabricated temporary or mobile houses using bamboo. The technology was invented primarily by the third author.

## 2 GENERAL DESIGN

As shown in Figure 1, the house is single story with an L-shape plan. The prefabricated bamboo building had a foot square area of approximately 60 $m^2$, and was built for temporary housing the asphalt materials laboratory. Part of the building is covered with single slope roof whereas the other part of the building is covered with unequal double slope roof. The planar dimension of the building was chosen based on a modular length of 1220 mm (4 ft.). The foundation of the prefabricated bamboo house is reinforced concrete slab on manually impacted ground surface. The construction of this foundation is simple and convenient. The foundation slab has a better load capacity and the thickness of the foundation should be more than 300 mm so that it can be water proof.

## 3 DESIGN AND MANUFACTURE OF BAMBOO MEMBERS

### 3.1 *Material properties*

The main basic material used in manufacturing the prefabricated bamboo house was bamboo veneer sheets with a typical nominal dimension of $l \times b \times t = 2440$ mm $\times$ 1220 mm $\times$ 28 mm. The

Figure 1. Picture of construction.

Table 1. Material properties

| Density | Elastic modulus | Compression resisting strain | Tension resisting strain | Moment resisting strain |
|---|---|---|---|---|
| 880 kg/m$^3$ | 6000 MPa | 23.11 MPa | 18.15 MPa | 31.8 MPa |

material properties of the laminated bamboo are summarized in Table 1 based on extensive tests conducted at the IBTCS.

### 3.2 *Bamboo column*

Two types of laminated bamboo columns were conceived and used in building the temporary laboratory. The open shape can be either C, I, H or T shapes, and the H shape illustrated in Figure 2 was used as the main form for the columns in this project. The flange and web elements of a column can be either glued or bolted together. Figure 3 shows the bolted detail of an H shape column. The hollow laminated bamboo columns are illustrated in Figure 4, and they were used in other project of IBTCS (Zhou et al. 2007). Depending on the design requirements, the elements of a section can be added up to provide sufficient geometric properties.

### 3.3 *Bamboo beam*

Laminated bamboo beams or girders, named as GluBam, were developed by the IBTCS, using a procedure including finger jointing and cold pressing the bamboo veneers sheets. Figure 5 shows an example of such laminated bamboo beam. The laminated bamboo beams were mainly used as the top and the bottom chords for the prefabricated bamboo house.

### 3.4 *Bamboo truss*

Truss was used to carry the roof loads for the bamboo house. Figure 6 shows an example for a double slope symmetric triangular truss. One layer bamboo veneer plates and bolts were used as connectors. The web chord was made of a single layer bamboo veneer strip (28 mm thickness).

### 3.5 *Wall, floor and roof*

The composite panel is used as wall, floor or roof. The frame of the panel is made of Chinese Fir, when the panel is used as wall, the wall panel is made of bamboo plywood and the wall is filled with glass wool as thermal insulation material. Steel mesh is nailed on the wall panel, and then cement mortar is brushed as the outside surface layer. The detailed applications of the wall is shown in Figure 7.

### 3.6 *Connections*

The most important characteristic of the prefabricated mobile bamboo house is that all the major members of the prefabricated bamboo can be dismantled, so we use bolts and steel fasteners to connect the members. The connections involved the use of primarily nails, bolts, connecting plates and steel connectors such as angles and channels.

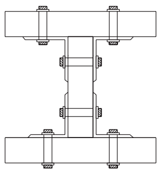


Figure 2. H-shape column.

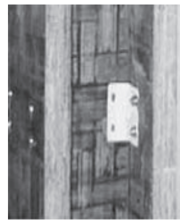


Figure 3. Details of element connector.

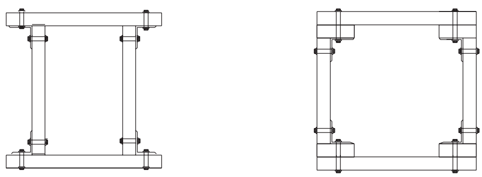


Figure 4. Examples of hollow sections.

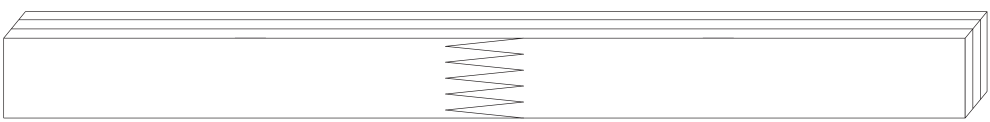


Figure 5. New glulam—glubam [Xiao et al. 2007].

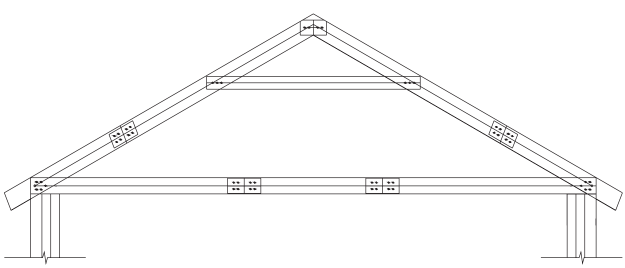
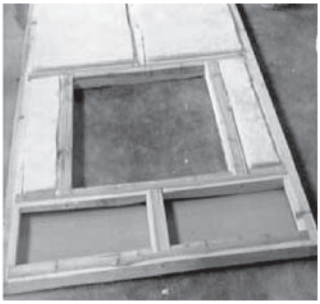
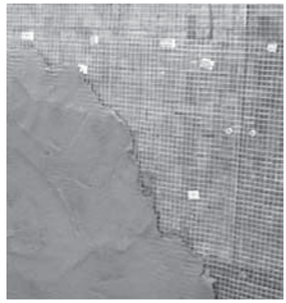


Figure 6. Bamboo truss.



(a)



(b)

Figure 7. Composite wall.

(a)

(b)

Figure 8. Connection details for column (a) bottom end and (b) top end.

## 4 STRUCTURE ANALYSIS AND CALCULATION

The load resisting system of this house is frame system with wall panels and connections are assumed to be pinned. The analysis and design are mainly based on the design guidelines of the Chinese lightwood frame design code (GB50005), with necessary modifications and the adoption of the mechanical properties of the laminated bamboo.

## 5 CONCLUSIONS

A new type of prefabricated building system using laminated bamboo was proposed and studied in this project along with the actual construction of a temporary building. The general advantages of the new prefabricated building system can be summarized as,

1. A convenient and speedy construction can be achieved by adopting a modular design concept.
2. The main structural members can be reused using the connection details proposed.
3. The bamboo building system is essentially an environment friendly construction.
4. The laminated bamboo structural elements developed in this project have high strength/weight and stiffness/weight ratios, suitable for a variety of applications.
5. The proposed new system is quite cost-effective with the cost per unit area being very competitive compared with existing systems using other types of materials.

## ACKNOWLEDGEMENT

The research described in this paper was sponsored by the Institute of Bamboo, Timber and Composite Structures (IBTCS) of the Hunan University, under the support of the Program for Changjiang Scholars and Innovative Research Team Project by the Ministry of Education of China (Project No. IRT0619). The construction of the 10 m long modern bamboo roadway bridge was funded by the Agriculture Development Office, Leiyang, Hunan Province, under the direction of Mr. Zhou, Bingya. The authors warmly and heartily thank all the sponsors and collaborators.

## REFERENCES

GB50005. 2003. Code for design of timber structure. Ministry of construction of China. 2003.

GB50017. 2003. Code for design of steel structure (GB50017-2003). Ministry of construction of China.

Xiao, Y. and Anderson, J.C. Design of steel structures. First Edition. 2007. The Higher Education Press. Beijing.

Janssen, J.A. 2000. Designing and Building with Bamboo. INBAR Technical Report No 20.

Xiao, Y.; Shan, B.; Chen, G.; Zhou, Q.; and She, L.Y. 2007. Development of A New Type of Glulam—GluBam, Proceedings of the International Conference on Modern Bamboo Structures. ICBS-2007. Changsha. China. Oct. 28–30.

Zhou, Q.; Shan, B.; and Xiao, Y. 2007. Design and Construction of a Modern Bamboo Pedestrian Bridge. Proceedings of the International Conference on Modern Bamboo Structures. ICBS-2007. Changsha. China. Oct. 28–30.

*Modern Bamboo Structures – Xiao et al. (eds)*


# Design and construction of a two-story modern bamboo house

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ABSTRACT: The research group led by Prof. Xiao at the Hunan University and the University of Southern California had been working on developing various new types of structure elements using bamboo materials. One of the mile-stone projects is to design and build a modern residential house using these new products. The demonstration house has a foot square area of about 140 $m^2$, and total building floor area of about 230 $m^2$. The design attempts are to construct this modern bamboo house essentially following the design requirements set in design codes such as the Uniform Building Codes for lightweight wood frame buildings in North America. This paper presents the details of the design and some special considerations for construction.

## 1 INSTRUCTIONS

Lightweight wood frame structures are widely used in residential housing development in North America. The main structural feature is to rely on uniformly spaced studs and sheets to withstand all kinds of in-plane and out-plane forces system. The so-called "platform construction" enables the staged construction due to the separation of walls and floors. The floor constructed in previous stage serves as a platform for the erection of the walls, upper floor structures, with minimum requirement of heavy equipment.

The authors at the Institute of Modern Bamboo, Timber and Composite Structures (IBTCS) of the Hunan University directed by Prof. Xiao have developed several new technologies using bamboo in modern construction.

This paper reports the mile-stone project of building a modern bamboo residential house, which integrates all the newly invented bamboo technologies and products.

## 2 DESIGN FEATURES

The bamboo building has a foot square area of approximately 140 $m^2$, the total building floor area is about 260 $m^2$. The first story includes a main living room with fireplace, guest dining area, kitchen, family dinning room, family room, guest room and two bathrooms. The floor of the first story is elevated for 600 mm to provide natural ventilation under the floor. A two-car garage is built on grade and attached to the main building with entrance to the family room. A staircase connects the living room to the second story, which includes a master bedroom with bathroom, two family rooms with a shared bathroom, and in-house balcony overlooking the main living room on first story. Figure 1 shows the architectural appearance of the modern bamboo residential house.

## 3 DESIGN FEATURES

The modern bamboo building was designed and constructed using similar details as wood frame structure. The height of the two stories was 2.8 ~ 3.2 m. The building adopts the platform construction. The lateral load resisting system on each floor relies on the walls made of laminated bamboo stud of about 40 mm by 84 mm in section and 10 mm thick veneer sheets. The floor diaphragm was made of glubam beams (Xiao et al. 2007) supported on the walls and 1220 mm by 2440 mm bamboo veneers nailed on top of the floor beams. The roof system was designed and built by pre-assembled bamboo trusses with a spacing of 610 mm. Braces were used to provide stability perpendicular to the truss plane.

The bamboo house was designed following the similar design procedures for wood frame buildings. Due to the fact that the laminated bamboo typically has higher strength and stiffness, the house was designed with conservative assumptions.

## 4 MATERIAL AND STRUCTURAL ELEMENTS

The main basic material used in manufacturing the structural elements was bamboo veneers with a dimension of 2,440 mm long, 1,220 mm thick and 28 mm thick. The veneers were further made into various laminated structural elements using the glubam technology developed by Xiao et al. (2007). The authors are currently conducting several tests for quantifying the structural behavior of various laminated bamboo elements. Figure 2 shows the test setup of the bamboo roof truss. The shear wall tests are scheduled to perform in near future.

Figure 1. Perspective drawing of modern bamboo house built by IBTCS.

Figure 2. Laminated bamboo truss test at IBTCS.

## 5 CONSTRUCTION PROCESS

### 5.1 *Foundation*

A raised floor system was designed to elevate the living space off the ground, isolating it from moisture and pests. Figure 3 shows several procedures of foundation construction. Clearance between the bottom of the joists and the ground is 600 mm. The bamboo house site partially occupied the existing spread concrete mat of a previous masonry building, thus concrete mat was extended to cover the entire foot plan. Perimeter cripple walls were made by concrete filled hollow concrete masonry blocks on concrete strip foundation. Concrete blocks were also used to built pedestals to provide supports of joists within the perimeter of the house. Sill plates were anchored on top of the cripple walls and concrete block pedestals using 12 mm diameter bolts spaced less than 800 mm and embedded 200 mm deep in the concrete infill. Asphalt sheets were used as moisture insulation between the sill plates and the footing. The exteriors of the cripple walls were coated with asphalt also.

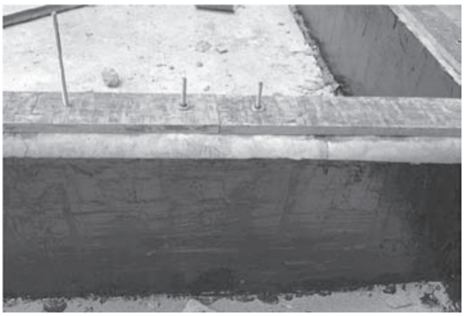
The elevated space under the first story floor was ventilated by providing openings on the cripple walls, which satisfied the typical requirements of 0.067 $m^2$ for every 14 $m^2$ of plan area (1 square foot per 150 square feet).

### 5.2 *Bamboo framing wall*

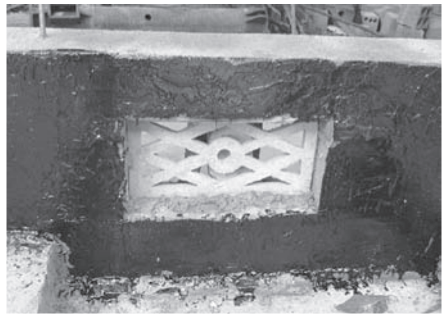
The wall framing are consisted of laminated bamboo studs, top plates, bottom plates and headers. Figure 4 illustrates the installation of stud walls. Studs in exterior walls of this two-story building had a cross section of about 40 mm by 84 mm, roughly equal to the size of $2 \times 4$ lumber used in the North American market. The stud spacing was 406 mm in exterior walls of the first floor, whereas 610 mm in the second floor. The walls are filled with heat-insulation wools. The bottom plates and top plates of wall framing usually act as a fire-stopping. The walls were sheathed with

(a) Excavation foundation

(b) Concrete filled masonary block footings



(c) Sill plates



(d) Ventilation opening on cripple wall

Figure 3. Construction of foundation.

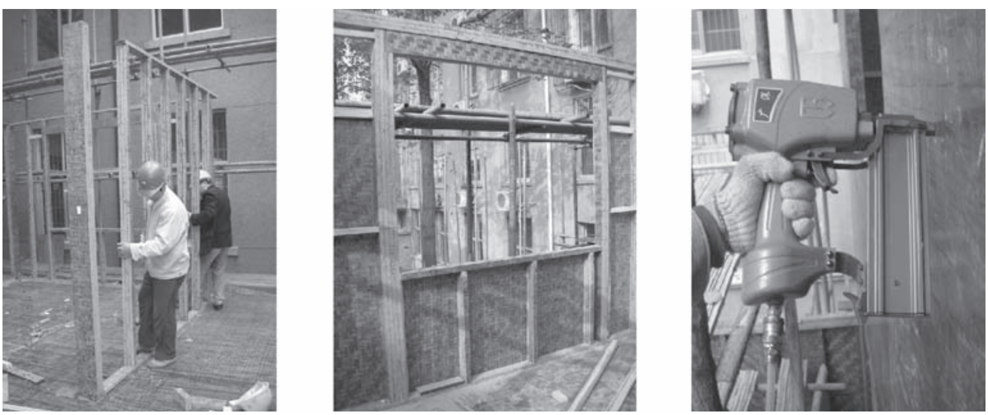
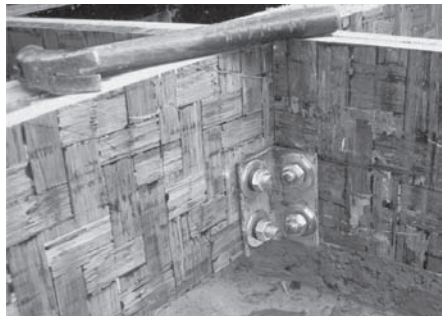


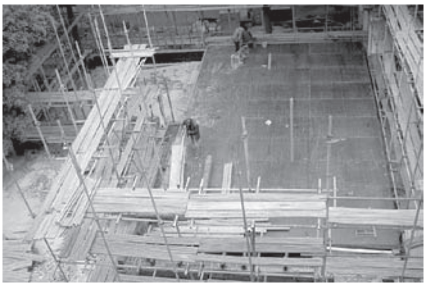
Figure 4. Installation of laminated bamboo walls.

bamboo veneer panels that were attached vertically to the wall frame. The panels were connected to the wall frame studs and top and bottom plates using nails spaced 150 mm on center along the panel edges and 300 mm along the intermediate studs. The exterior cladding included waterproof underlayment, wire mesh and stucco mortar cladding surface. The gypsum panels were attached to framing with screws spaced 305 mm on center along the panel edges and intermediate studs to form the interior sheathing of walls.

(a) First floor joists



(a) Connection detail for joists



(c) First floor sheathing

(d) Second floor joists and sheathing

Figure 5. Construction of floor systems.

### 5.3 *Floor system*

The floor system included glubam joists and the veneer sheathing on top of the joists. The primary joist was 84 mm wide by 185 mm deep and the secondary joist was 56 mm wide by 185 mm deep. The primary joists were supported on foundation blocks or walls whereas the secondary joints were supported on the primary joists using steel angle brackets. The bamboo veneer sheathing panels where affixed on top of the joists using nails or screws at a spacing of about 150 mm along the panels edges and 300 mm along the intermediate joists.

### 5.4 *Roof system*

The laminated bamboo roof trusses were prefabricated at the facility in the nearby laboratory. The prefabricated trusses were then carried on the platform on top of the ceiling of the second story. The roof trusses were erected and installed on the load-bearing walls of the second story. Wood blocks were used to maintain the spacing of 610 mm between the trusses. After making sure each truss was vertical, lateral braces were set in place to keep the stability in the direction perpendicular to the truss plane. The bamboo veneers sheets of 2,440 long by 1,220 wide (or 8 ft. by 4 ft.) were than nailed on the slopes of the trusses, with the longer dimension perpendicular to the truss rafters. The bamboo panel sheets were staggered to avoid continuous seams in the short direction. Two layers of waterproof underlayment were affixed on the surface of the bamboo veneer sheathing. Glazed clay tiles were last installed using two nails for each tile. The roof for the garage used slightly different system. The spacing of the trusses was 1,220 mm and purlins were used to interconnect the truss rafters and to provide the underneath supports for the roof sheathing.

(a) Moving prefabricated truss to site

(b) Erection of prefabricated truss

(c) Alignment of roof trusses

(d) Installation of roof sheathing

(e) Affixing waterproof underlayment

(f) Installation of concrete tiles

Figure 6. Roof construction process.

## 6 CONCLUSION

Using the newly invented laminated bamboo structural elements, a two-story, 260 $m^2$ floor area modern bamboo house was designed and constructed. The project demonstrated that the modern bamboo building can be constructed using many similar procedures and details as the wood frame structures.


## ACKNOWLEDGEMENTS

The research described in this paper was conducted at the Institute of Bamboo, Timber and Composite Structures (IBTCS) of the Hunan University, under the support from the Program

Figure 7. Completion of main structure of bamboo house as of December 2007.

for Changjiang Scholars and Innovative Research Team Project by the Ministry of Education of China (Project No. IRT0619).

## REFERENCES

GB50005. 2003. Code for design of timber structure. Ministry of construction of China. 2003.

Xiao, Y.; Shan, B.; Chen, G.; Zhou, Q.; and She, L.Y. 2007. Development of A New Type of Glulam—GluBam, Proceedings of the International Conference on Modern Bamboo Structures. ICBS-2007. Changsha. China. Oct. 28–30.

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# Prefabricated low cost housing using bamboo reinforcement and appropriate technology

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ABSTRACT: The objective of this research is to give an alternative house construction technology, which exploiting bamboo potential as replacement for steel reinforcement. Basically, this research is an explorative research in design and implementation on the building material, prefabricated building components, casting equipment and method, and assembling process. The result of this research is a prototype of prefabricated building, which use prefabricated components with steel reinforcement for structural element and bamboo reinforcement for architectural element such as partition wall panel, formwork panel and doo r-window frame.

## 1 INTRODUCTION

### 1.1 *Background*

Housing need is one of the most elementary human needs. The need of the houses for the refugee of the tsunami disaster in Aceh in five year ahead reached up to 78.000 units. Not to mention the earthquake that occurred Yogyakarta and Central Java that demolished and devastated 569.825 houses. Apart from that, other various kind of disaster that recently attacked Indonesia has increase the amount of housing needs that is necessary as the action of emergency response.

In additional to emerge of the needs of housing as the effect of natural disaster, the increase needs of housing also emerge as the increase of population and urbanization. Affordability is the main requirement of house provisions for low income society to achieve. On keeping the price of the house down, there is a tendency of the builders to curtail the building quality, so that a large scale squandering happened.

One of the efforts to reach the affordability is by taking advantages of local building material and using appropriate technology. Bamboo is available in almost all Indonesian regions but less of exploitation. Meanwhile, bamboo is one of the most sustainable materials on earth.

### 1.2 *Purpose*

The research of 'Prefabricated Low Cost Housing Using Bamboo Reinforcement and Appropriate Technology' is aiming to give an inexpensive alternative building system by using simple technology and using the potential of bamboo as concrete reinforcement for architectural element. By the use of the appropriate technology, the prefabrication process and the erection of the components are expected can be done by labors intensive.

## 2 BUILDING PROTOTYPE

### 2.1 *Concepts*

The main concept of this prefabricated house prototype is exploiting the use of bamboo in a real manner as prefabricated concrete reinforcement for the architectural (non-structural)

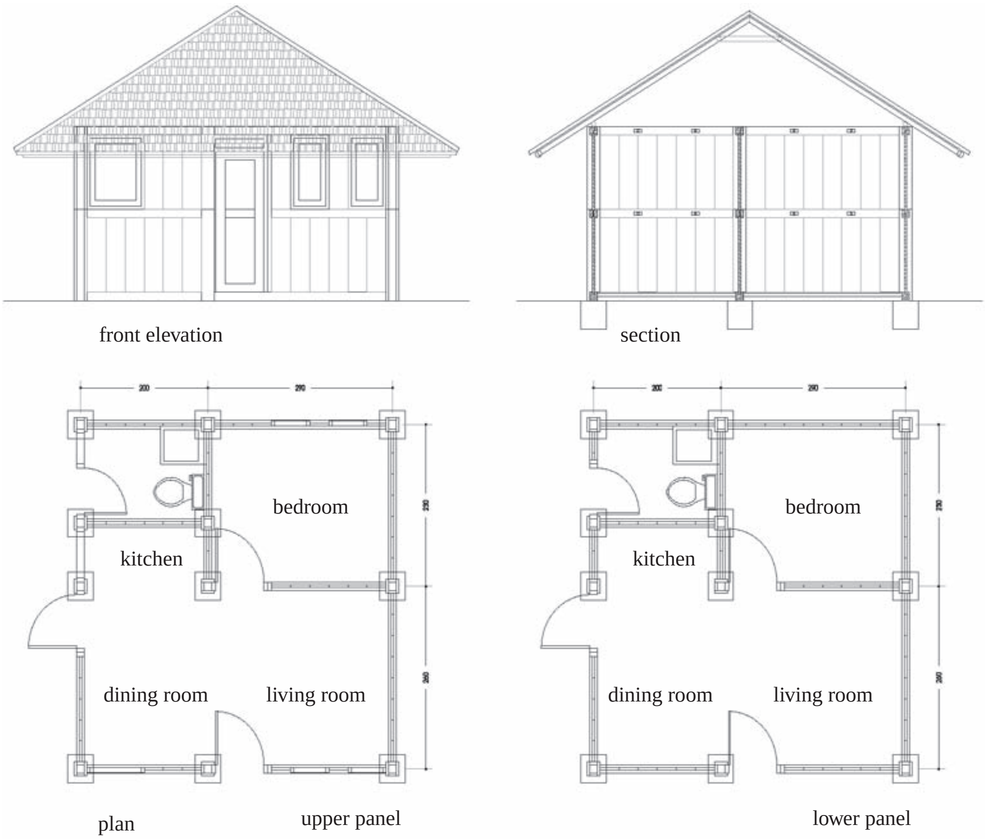


Figure 1. The design of the prototype.

components, while the structural component still use concrete with steel reinforcement to make sure the strength of structure in a long period of time. Beside that, the most important concept in this housing design is to divide the wall in two parts, lower and upper parts. This division is aiming to lessen the weight of the prefabricated partition wall component and also in accordance to the window frame placement onto the upper part of the wall.

### 2.2 *Design*

The building prototype is designed for approximate 25 m$^2$ or exactly 4,9 $\times$ 4,9 m$^2$ in appropriate with the wall module planning as shown in Figure 1. The module of prefabricated panel which have a significant role in determining structure module is the width of the wall panel (30 cm) and the width of formwork panel (20 cm).

### 2.3 *Prefabricated component*

As shown in Figure2–7, prefabricated components which are required in this system are:

- Bamboo reinforced concrete partition wall panel, 4 $\times$ 30 $\times$ 110 (cm)
- Bamboo reinforced formwork panel
- Bamboo reinforced door-window frame
- Steel reinforced concrete tie beam

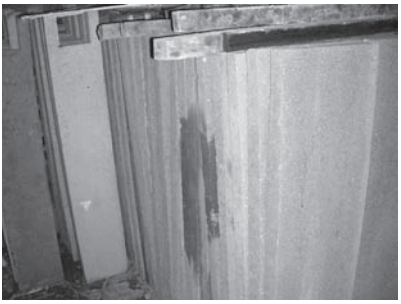

Figure 2. Bamboo RC partition wall and formwork.

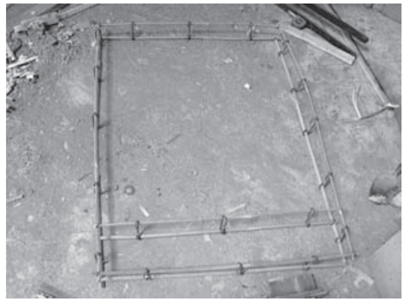

Figure 3. Bamboo reinforcement for window frame.

Figure 4. Bamboo RC window frame.

Figure 5. Bamboo RC door frame.

Figure 6. Steel RC tie beam.

Figure 7. Steel RC middle and top beam.

- Steel reinforced concrete middle beam
- Steel reinforced concrete top beam

### 2.4 *Prefabricated partition wall panel*

The volume of this prefabricated partition wall panel is the biggest in this building prototype. It reached 1.25 m3 or 42% of the total concrete volume for wall construction that attained 2.98 $m^3$. This $4 \times 30 \times 110$ cm prefabricated panel size is used as the main element of either building envelope or partition wall. The average weight of this component is 28 kg. The weight of this partition wall panel becomes more important for the ease of erection and transportation.

In order to save the cost, this panel is made of concrete with bamboo reinforcement. Considering that the use of this component is just for architectural purpose as wall partition, bamboo can be used to give the tension strength of the panel especially during the phase of erection and transportation. When it is all been erected, this panel gets lot of pressure force.

At the beginning, this partition wall panels were cast in wet mixture. This system has a constraint on a low productivity level and wider working space. A set of casting equipment can only be used no more than twice a day. To increase the productivity of casting process of partition wall panel, the panels were cast in dry mixture by using metal casting equipment (see Figure 8). Within this casting method, the productivity increased to 11 panels a day in average by one unskilled worker. Beside that, this system can save the space.

The other advantage of using this dry casting system is the condition of low water content in concrete made the bamboo to absorb less water so the expansion and shrinkage of the bamboo reinforcement, as shown in Figure 9, can be reduced.

The constraints faced on this dry mix casting system are:

- The position of the casting process and the panel after casting was unstable, so that the process of detaching the moulding has to be done very carefully.
- Dry mix casting produce the panel in a coarse surface and sometimes gave unneatly edge.

### 2.5 *Prefabricated concrete tie beam*

The purpose of prefabricated reinforcement concrete tie beam is to transfer the weight of the wall and other components above into the foundation. The overall measure of this U-shape tie beam is $12 \times 12$ cm$^2$ with $4 \times 2$ cm$^2$ opening as the base of the partition wall panel. The weight of this component is 32 kg per meter. Amongst this prototype, the longest tie beam is 278 cm, 90 kg in weight and still be able to be lifted by 2 workers. This is the heaviest component in this prototype.

As structural component, this prefabricated component is made out of steel reinforced concrete in wet casting system. Therefore, the length of the formwork or molding is made according to the longest dimension (278 cm) and can be adjusted. The productivity of casting this component is only 1–2 components per day and it can be done in parallel with other components.

### 2.6 *Prefabricated reinforced concrete middle and top beam*

Middle and top beam is the beam that is separated in two pieces, in order to make the erection processes easy to do. The dimension of the beam is around $6 \times 12$ cm$^2$. Those pair of beams are then united into $12 \times 12$ cm$^2$ beams by using nut and bolt and cast in situ for the top beam.

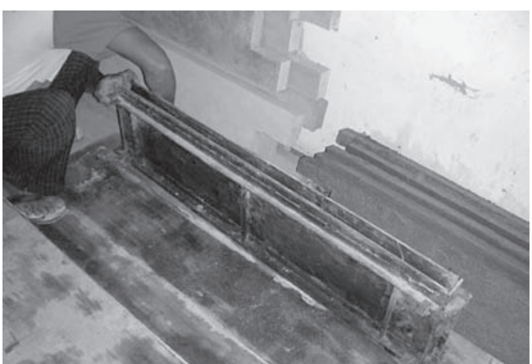

Figure 8. Steel moulding equipment for dry casting.

Figure 9. Bamboo splits for reinforcement.

## 2.7 *Prefabricated formwork panel*

Prefabricated formwork panel is an architectural element to make the erection process goes quickly and easy. This U and H-shape components are made of bamboo reinforced concrete.

The Erection of Prefabricated Components

The final phase of the construction is the erection process, assembled the components together into a building. Before that, all the building components were brought to the site from the workshop. One of the key successes of construction with prefabricated system is the weight of the components that will affect the way of transportation and erection (see Figure 10).

The construction phase on the site is started with the foundation works that used square pad foundation out of reinforced concrete and completed with retaining brick as supporter to prefabricated concrete tie beam, as shown in Figure 11. After the foundation work was completed, prefabricated tie beams were placed on site with some adjustment on the connection of steel reinforcement (see Figure 12. and Figure 13).

After all the tie beams assembled, column reinforcements prepared before, have to be erected too, followed with the set of formwork panels, partition wall panels and middle beam.

After all the lower parts of the wall as well as door frame assembled, the next phase is pouring in situ concrete into the formwork panel as in situ column up to middle beam. The assembling of the upper parts of the wall can only be done after in situ column in the lower part dry enough and the whole system quite rigid.

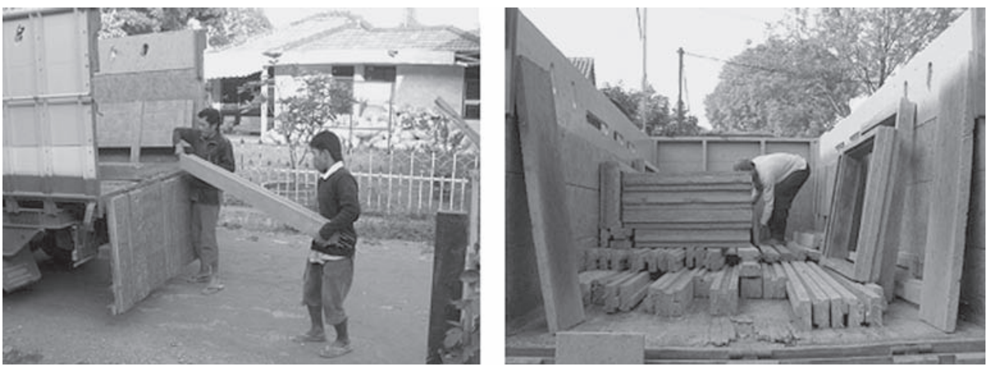

Figure 10. Transportation of the prefabricated components.

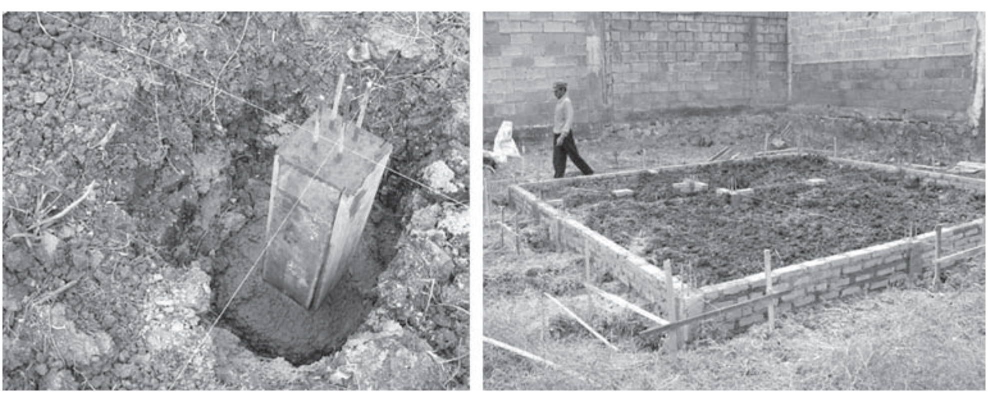

Figure 11. Foundation.

Figure 12. The assembling of prefabricated tie beam.

Figure 13. The adjustment of steel reinforcement of tie beam.

Figure 14. The assembling of prefabricated partition wall panel in accordance with middle beam.

Figure 15. The assembling of prefabricated door frame.

Figure 16. The assembling of upper component.

Figure 17. The completion of all prefabricated component assembling.

In the phase of erection in the upper parts as shown in Figure 16 and Figure 17, the integration with electricity system has to be well coordinated, especially for the cable tray, electric switches and electric sockets.

After pouring concrete for column and ring balk in the upper parts at once, the roof construction can be started. Basically, the roof construction on this system is separated from the prefabricated wall construction, so the choice of structure, shape and material would be unimpeded. The prefabricated house prototype itself is covered with the bamboo roof frame and covered by ceramic roof tile. Bamboo is selected as roof frame material in order to socialize the wide range of bamboo uses. Bamboo is also the cheapest choice compared to other roofing material.

Roof frame system is made by fabrication on site as shown in Figure 18. The roof frame is separated in four triangle frame and then united in the top of the building (see Figure 19). This prototype was designed with a wide overhang to protect the wall from the rain water.

The result of this research was a prototype of prefabricated building as shown in Figure 20. The finishing of this building can be done in many ways. Wall and column finishing can be done by plastering or directly paint in coarse painting with acrylic paint or lime paint. Lime covering is an ancient technology that is no longer used by the people. It is natural and cheap and could cover the crack or fissure in the joins or the components.

Figure 18. The prefabrication of roof frame on site.

Figure 19. The completion of roof frame assembling.

Figure 20. The prototype of prefabricated house.

## 3 CONCLUSION

The performance of bamboo as concrete reinforcement in this system is excellent. There are no cracks so far because of the shrinkage of bamboo within concrete. Bamboo gives the prefabricated panel tension strength against crack during erection and transportation.

Prefabricated house prototype, which is using bamboo reinforcement for architectural component, apparently enable it to be used as an alternative of a mass house construction with self-help housing system, because within the casting technology and its erection is relatively easy to do.

## ACKNOWLEDGEMENT

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## BIBLIOGRAPHY

Dunkelberg, K. 1985. Bambus-Bamboo, Institut fur Leichte Flachentragwerke.

Frick, H. 2004. Ilmu Konstruksi Bangunan Bambu, Penerbit Kanisius.

Gutierrez, J.A. Structural Adequacy of Traditional Bamboo Housing in Latin America, Technical Report, INBAR.

Hidalgo, O. 2003. Bamboo: The Gift of Gods, D'Vinni LTDA.

Idris, A.A.; Firmanti, D.A. 1994. Penelitian Bambu untuk Bahan Bangunan, Puslitbangkim.

Janssen, J.J.A. 1995. Building with Bamboo, Intermediate Technology Publication Limited, London.

Sutanto, H. 1989. Pemakaian Bambu sebagai Tulangan Beton, Fakultas Teknik Jurusan Sipil, UKI Jakarta.

Waliyudin, Pangajab, Perilaku Mekanik Bambu. 1994. Department of Civil Engineering, Gajah Mada University.

Wibowo, A. 1994. Kekuatan Sambungan Bambu dengan Baut dan Beton Pengisi, Department of Civil Engineering, Gajah Mada University.

Widyowijatnoko, A. 1999. Kajian Konstruksi Bambu Plaster dan Konsep Pengembangannya, Department of Architecture ITB.

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# Design and construction of a modern bamboo pedestrian bridge

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ABSTRACT: This paper reports the design, construction, testing of the world's first modern bamboo pedestrian bridge. Comparing with the steel structure, the price of the bamboo over-bridge can economize almost 50%. In the meantime, adopting bamboo beam, called as glubam®, the bridge has much lighter superstructure and is easier to construct compared with conventional steel or concrete. The authors adopted a modular design concept, enabling the efficiency of construction. Column and girder elements were manufactured using laminated bamboo veneer sheets, and were joined using steel nails, bolts, plates and angle connectors. Three full-size girders were tested to verify the behavior of the main structural girders with different design configurations and were proved to be satisfactory. The bridge is functioning well for more than one year after it was opened to usage.

## 1 INTRODUCTION

In modern cities and along modern highways, pedestrian bridges are increasingly been constructed. Existing pedestrian bridges, such as such as the No. 1 bridge at the Longtan Guoshu Park in Guangzhou, the Xianyou Seoul Bridge, the world's longest Missouri River pedestrian overpass, etc., are all built with conventional steel and concrete. Metallurgical and cement industries are always high-energy consumption, high-pollution industries, and do not meet the requirements of sustainable development. It is gradually being recognized as a way to achieve sustainable development to use natural, environment-friendly, renewable, organic materials to reduce or to replace at least partially the conventional steel and cement in construction industry.

At present, most widely used natural and organic material is wood. In the North America, Europe and many industrialized counties, wood structures occupy a significant portion of bridge and building construction.

Many years of over logging and expansion of agriculture cultivation in last century has had devastated effects on the forests in China. Domestic wood resource becomes very limited. However, the increasing need of continuous construction boom has turned China into the larges word importing country in the world. Recognized by the seriousness of the problem, China has adopted policies of preserving forests and retrieving agriculture land for forest recover. Such policies should have beneficial impacts in future, whereas developing other natural and organic materials replacing wood might be a viable choice to solve the urgent need.

China is one of the world's richest countries with bamboo resource and has had a certain degree of industrial development of bamboo products. However, the existing bamboo products in the civil engineering market are low value-added products, such as forms for concrete casting, scaffoldings and flooring materials etc., have not yet penetrated into the mainstream market for load carrying materials. To use bamboo as a basic material in modern bridges and building structures, to a certain extent to replace the conventional structural materials, can provide more value added bamboo products and significantly raise the level of bamboo processing industry, consequently, improving the economical development.

Hunan province is one of the few major bamboo-growing areas in China. Collaborating with local industry and government, the Institute of Modern Bamboo, Timber and Composite (IBTCS) at Hunan University is conducting a comprehensive research program, intended to develop modern bamboo structures for buildings and bridges. This paper reports the authors' efforts in developing modern bamboo pedestrian bridges.

## 2 PROJECT OVERVIEW

Hunan University campus bamboo pedestrian bridge had a width of 1.5 m and a span of 5 m span, with two stairways. The bridge location is close to the Environment and HVAC laboratory on the west side of Lu-shan South Road. According to the field surveying, there two pedestrian traffic flows near the HVAC laboratory, one is the aisle along the sidewalk of the Lu-shan south road and the other is the road in front of the laboratory building. There is an elevation difference of 2.26 m between the sidewalk and yard of the laboratory. The function of the pedestrian bridge was to provide the directly connect the two pedestrian traffic to the sidewalk without any disturbance. Figure 1 and Figure 2 show the plan view and the elevation view of the bridge, respectively.

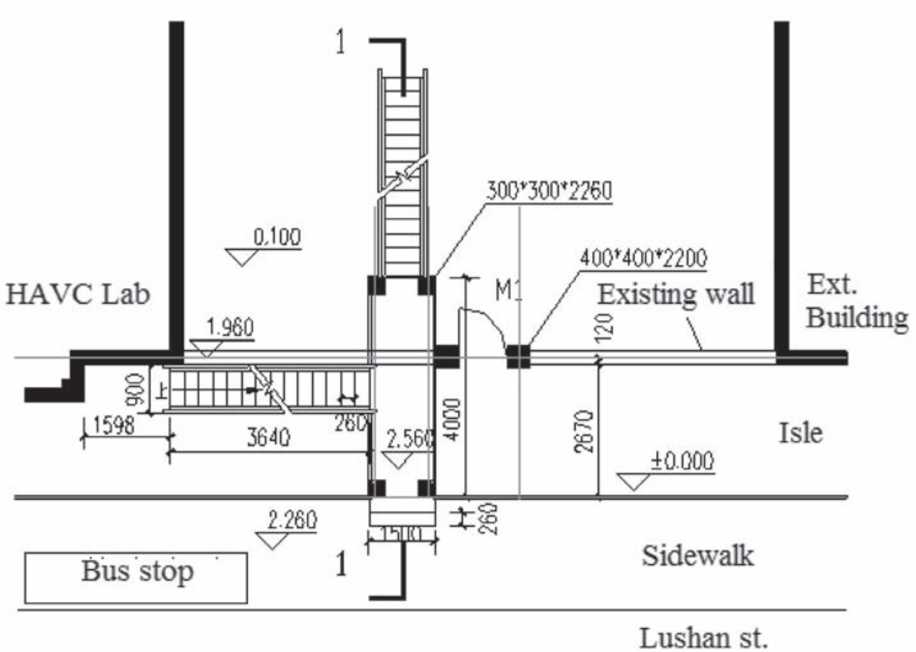


Figure 1. Plan view of bridge site.

## 3 CONSTRUCTION OVERVIEW

The traffic capacity of the modern bamboo pedestrian bridge was determined according to the "Guidelines for Construction of Urban Pedestrian Overpass and Tunnel" (CJJ65-93, 2003), with the reduction coefficient of 0.75. Clear height under the bridge had to be more than 2.3 m to allow pedestrian traffic. The design traffic live load for the bridge and the stairways was 5 kPa, and the allowable defection needed to be under L/600, here L is the bridge length between the two simple supports. The average annual rainfall in the region is 1500 ml, with a relative humidity of 85%. In order to avoid direct contact of the rainwater with the superstructure, waterproof sheets were provided on top of the laminated bamboo veneer deck sheets before laying the 80 mm thick bamboo strips reinforced precast concrete panels. The top finish was made with slight bulging in the middle to scatter water using approximately 20 mm thick cement mortar and gravels.

The main load-carrying components of the bamboo bridge were laminated bamboo girders, made from 28 mm thick bamboo veneer sheets, using a processing method and manufacturing equipment invented by the authors (Xiao et al. 2007). The columns were assembled with a H-shape hollow section, as can be seen in Figure 3. The columns were erected to stand on the concrete pedestals with fixtures made of steel angles and bolts shown in Figure 4.

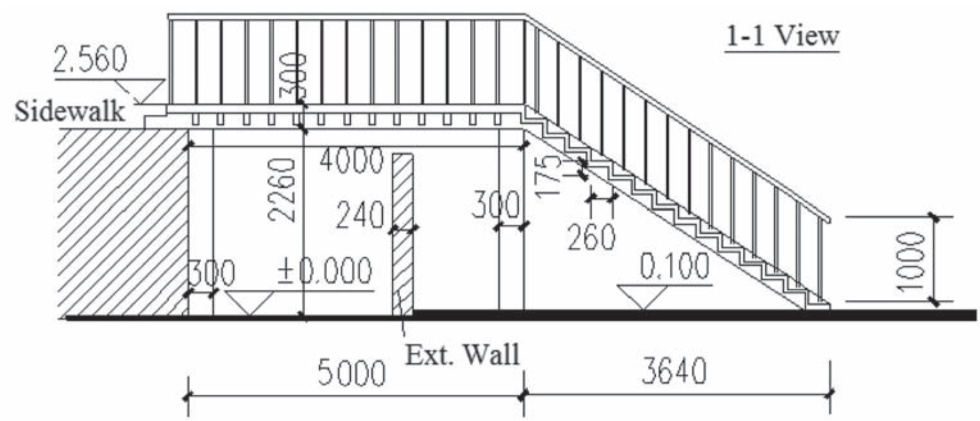


Figure 2. Elevation view.

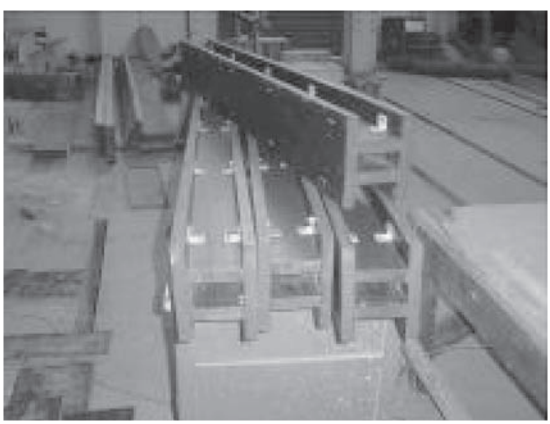

Figure 3. H-type hollow column.

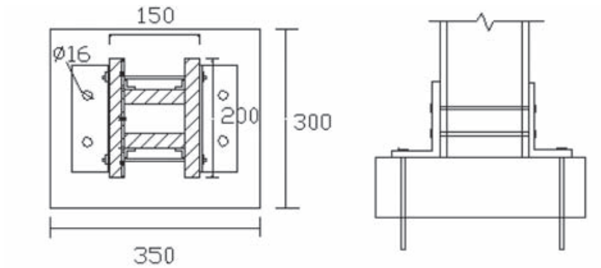


Figure 4. Foundation and column connections.

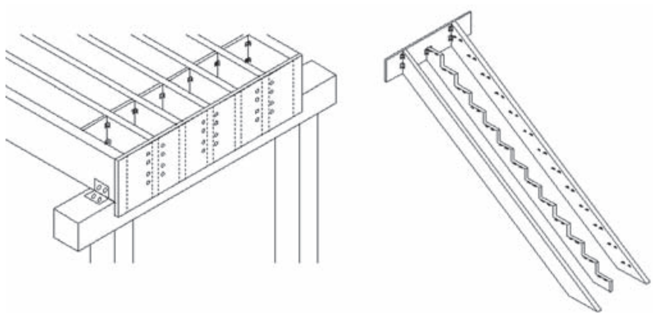

Figure 5. Details of main staircase.

The main structure of the bridge was designed and constructed based on a modular design concept. Crossbeams were built on top of the columns at the two ends of the bridge. The superstructure made of six 300 mm × 90 mm laminated bamboo girders (GluBam®) were supported on the cross beams. The girders were transversely tied together using clapboards. The connections between the elements were made using steel angles, connection plates tightened with threaded rods.

For the construction of the main staircase, the upper end of the two main inclined beams were supported to the seal plate of the six girders using threaded bolts and connecting steel plates. Figure 5 schematically shows the staircase. The side staircase was supported on a frame made with two columns and a crossbeam.

One end of the bridge was tied to the retaining wall of the elevated sidewalk, therefore the leaning action due to the horizontal component of the support force of the main staircase can be transferred to the retaining wall through the girders. The side staircase and its supporting frame were made to form a self-balanced triangular frame to avoid the transverse force to the girders.

All of the major structural elements were manufactured at the laboratory and then the components were assembled at the site. The project was completed by three technical staffs in less than one month. Figure 6 shows the completed bridge.

## 4 TESTING OF LAMINATED BAMBOO GIRDERS

### 4.1 *Specimen detains*

The model BEAM-1 was 56 mm thick, laminated by two sheets. The beam was made 5 m long by joining three shorter segments using bolted steel plates. The dimension of BEAM-2 and BEAM-3 were similar and the 84 mm thick girders were made by laminating three sheets with staggered

Figure 6. Modern bamboo pedestrian bridge constructed by the authors.

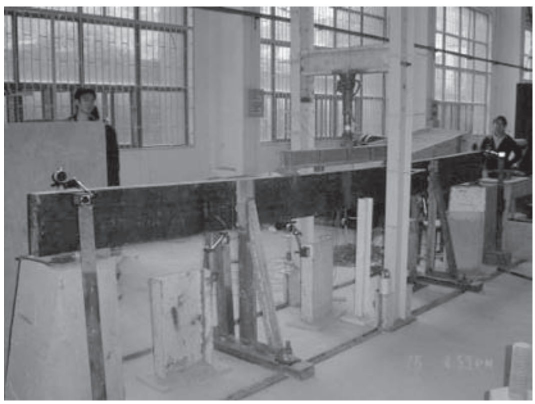

Figure 7. Full-scale bamboo girder beam test.

Table 1. Testing matrix of full-scale GluBam specimens.

| Specimen | Depth (mm) | Thickness (mm) | Processing methods |
|---|---|---|---|
| BEAM-1 | 300 | 56 | Two-layer veneers, three segments connected by steel plates |
| BEAM-2 | 300 | 84 | Three-layer veneers with staggering joints |
| BEAM-3 | 300 | 84 | Three-layer veneers with staggering joints, bottom strengthened by CFRP sheets |

joints. The soffit of Beam-3 was reinforced with CFRP layer for potential increase in stiffness and strength. The girder beam was tested as a simply supported beam with four-point loading. A manually controlled hydraulic jack was used to apply the quasi-static load to a spread beam which transmitted two concentric loads spaced at 1,300 mm to the test specimen. Lateral supports using steel frames and ball-bearing were provided to the sides of the beam specimen to prevent premature lateral instability. Dial Indicators were used to measure deflections along the beam. The test setup is shown in Figure 7.

### 4.2 *Test observations*

Figure 8 shows the final failure conditions of the three full-scale girder beams. Due to the use of bearing type connections between the bamboo girder segments and the steel connecting plates, visible deformation can be seen at the joints after the loading was applied to Beam-1. The steel plates yielded first followed by the bearing buckling near the holes at the joints. The beam had a residual displacement even after the removal of the load. The test girder BEAM-2 behaved well in initial loading until some cracks became visible when the load exceeded 10 kN. The cracks widened when the load reached 15 kN following further increase of the mid-span deflection. The compression side of the beam bulged out corresponding to the maximum load of 17.5 kN, indicating the failing. During the testing of BEAM-3, little change can be seen until the detection of a cracking sound corresponding to a load of 25 kN. At the maximum load of about 32.5 kN, the compression side of the beam near mid-span suddenly crippled and the loading was then terminated.

### 4.3 *Discussion of test results*

Figure 9 shows the load and mid-span deflection relationships for the three model bamboo beams. The joint plates of BEAM-1 model yielded and buckled prematurely, and the bamboo beam did

(a) (b) (c)

Figure 8. Failure patterns for bamboo girder specimens: (a) Beam-1; (b) Beam-2; and (c) Beam-3.

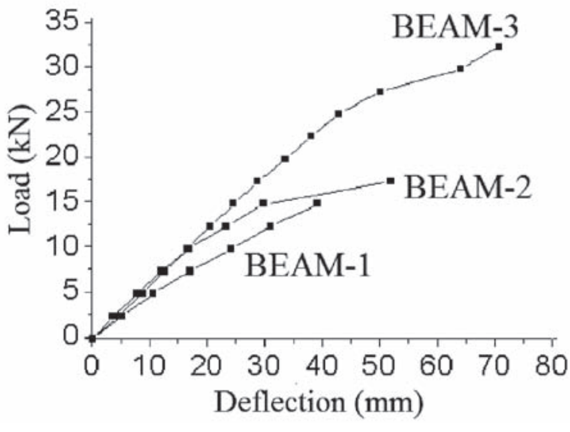


Figure 9. Load and mid-span deflection relationships.

not develop its capacity. Therefore, further increase of the connecting plate thickness should result in increasing the load carrying capacity of the bamboo beam. Although this design was not been adopted in the pedestrian bridge construction, it is still a viable method to limit the damage to the connecting plates. BEAM-2 model at the early loading behaved linearly due to the use of three-sheets lamination. Due to the weakening at each joint, the effective thickness can only be counted as two layers of lamination. BEAM-3 model performed in a linear fashion up to a load of 25 kN. The load carrying capacity was almost double of that of BEAM-2, indicating the enhancing effects using CFRP. Both BEAM-2 and BEAM-3 failed in a brittle manner.

Based on structural mechanics theory and the modules obtained from material tests, the behavior of the laminated bamboo girders can be analysed. The analysis indicated an initial stiffness of 0.355 kN/mm BEAM-1 and an initial stiffness of 0.532 kN/mm for BEAM-2 and BEAM-3, respectively. The measured results for initial stiffness was higher than the prediction, indicating that the analysis conservative.

Despite the fact that the CFRP can enhance the behavior of the bamboo beam, the final design of the girders for the pedestrian bridge adopted the details as BEAM-2.

## 5 CONCLUSIONS

The authors used the recently invented laminated bamboo and successfully constructed a modern bamboo pedestrian bridge, which might be the world's first bamboo bridge of its kind. The pedestrian adopted modular design to make the constructed simple. Tests were performed on three laminated bamboo model beams to verify the design of the girders for the bridge. The laminated beams performed reasonably well and had adequate strength and stiffness. After the completion for more than a year, the modern bamboo bridge is shown to function well. The proposed bamboo bridge provides the a new option for construction of pedestrian crossings over streets and highways.


## ACKNOWLEDGEMENT

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## REFERENCES


CJJ69-95 (2003), Guidelines for Urban Pedestrian Overpass or Underground Tunnel Construction, Ministry of Construction, China.

JTG D62 (2004), Design Guidelines for Reinforced and Prestressed Concrete Highway Bridges (in Chinese). People's Transportation Press. 2004.

Xiao, Y.; Shan, B.; Chen, G.; Zhou, Q.; and She, L.Y. (2007), Development of A New Type of Glulam—GluBam, Proceedings of the International Conference on Modern Bamboo Structures. ICBS-2007. Changsha. China. Oct. 28–30.

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# Construction of world first truck-safe modern bamboo bridge

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ABSTRACT: The Institute of Modern Bamboo, Timber and Composite Structures (IBTCS) is conducting a comprehensive research program, with the goal to develop modern bamboo structures for buildings and bridges. This paper reports the design, construction, testing of the world's first truck-safe modern bamboo road bridge. The authors developed laminated bamboo girders and verified their 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 FRP 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. The field tests were carried out using an over loaded two-axel truck with a total weight of 8.6 ton which exceeded the given design truckload of 8.0 ton. The bridge performed satisfactorily with the mid-span deflection corresponding to the critical service loading condition much smaller than the code required limit.

## 1 INTRODUCTION

Modern bamboo structures should be developed based on the theory of modern mechanics, materials science, structural design and testing. Structures thus developed with bamboo as the main structural material can improve the level of value-added bamboo usage, contributing to the realization of sustainable construction industry. This paper presents the research, design and testing of the world's first modern bamboo bridge to carry traffic truckloads along with a brief report of the authors' efforts in developing modern bamboo structures.

## 2 LAMINATED BAMBOO GIRDER

The main load-carrying components of the bamboo bridge were laminated bamboo girders, made from 28 mm thick bamboo veneer sheets, using a processing method invented by the authors [Xiao et al. 2007]. The newly developed bamboo product is named as glubam, in comparison with the existing timber product glulam. The process involves finger-jointing the sheets and cold pressing, etc. Figure 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.

Figure 1. Laminated bamboo girder.

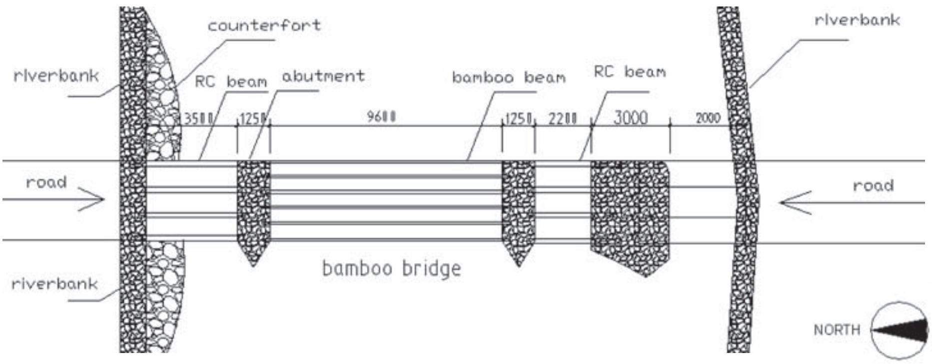



Figure 2. Layout of overall bridge.

## 3 TRUCKLOAD BRIDGE

### 3.1 *Design considerations*

After the successful completion of the first modern bamboo pedestrian bridge in 2006 [Zhou et al. 2007], the authors were given the opportunity to design and construct a truck loaded 10 m long bridge in the Village of Daozi, Leiyang, Hunan Province. 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 1.5 m wide old stone bridge at the site not capable of carrying truck transportation, nor safe for pedestrians in 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 utilizing the existing stone piers. As shown in Figure 2, the new bridge had a total length of 22.8 m consisting of four simple spans. The center 10 m long span was designed and constructed using the laminated bamboo girders and the remaining shorter spans were constructed using reinforced concrete beams and slabs.

The design truckload was two-axel 8 ton truck. Based on analysis, nine 600 mm deep by 100 mm wide laminated bamboo girders were used to carry the 10 m long span. As shown in Figure 3, 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 authors designed the bridge assuming a 16-ton truckload applied at the mid-span of the bridge. The final design was based on controlling the mid-span deflection to be below the limiting value of 1/600 of the span length, per the Chinese bridge design code [JTG D62 2004]. Also for simplicity and safety, the CFRP layers were neglected in the design. If considering the test results of the laminated bamboo girders and neglecting shear lag effect, the bridge could carry an ultimate load of more than 80 ton applied at its mid-span.

### 3.2 *Construction of modern bamboo bridge*

The bamboo bridge under construction is shown in Figure 4. 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 piers to reduce the effects 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.

Previous research by the authors showed that avoiding the direct exposure of the laminated bamboo girders to rainwater is the key to ensure the durability. 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 slits between the precast concrete panels were sealed by waterproof sealant. Steel railings were installed at last to provide safety for pedestrians.

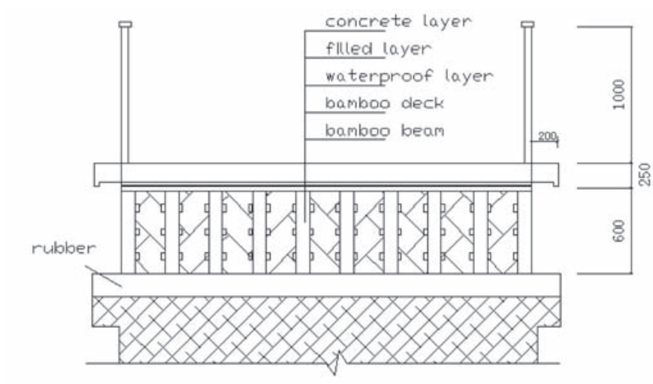


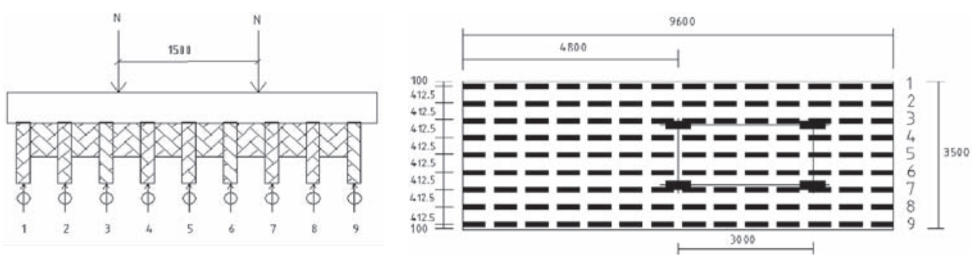

Figure 3. Section sketch of bamboo bridge.

Figure 4. Construction stages: (a) installation of bamboo girders; (b) installation of water proof materials.

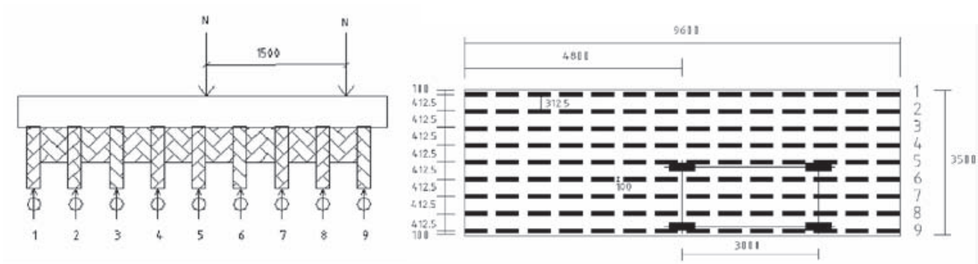
### 3.3 *Field loading test on bamboo bridge*

In order to understand the actual behavior of the world's first truck-safe modern bamboo bridge, field tests were carried out on the main span modern bamboo bridge, thirty days after the completion of the overall bridge, as shown in Figure 5. The loading was carried out using a truck loaded with stones, which represented the possible overload 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 ton, with the measured weight for the front wheels was approximately 1.6 ton, whereas about 7.0 ton for the rear wheels. Based on influence line analysis, the critical load was at the condition where the rear axle wheels are positioned close to the mid-span. As shown in Figure 6, dial gauges were installed under each of the nine girders at the mid-span for measuring their deflections. Two types of loading cases shown in Figure 6 were carried out.

Figure 5. Truck loading test of Leiyang bridge.




(a)




(b)

Figure 6. Loading and instrumentation conditions: (a) loading Case-1 for centerline loading; (b) loading Case-2 for eccentric loading.

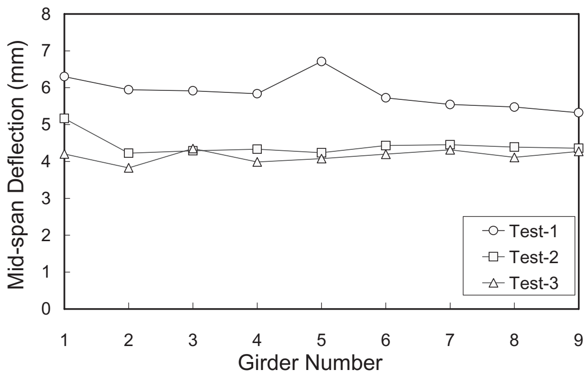



Figure 7. Mid-span deflection of bamboo girders corresponding to 8.6 ton truckload Case-1.

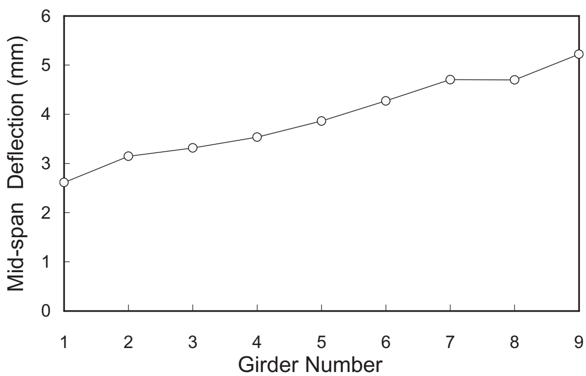



Figure 8. Mid-span deflection of bamboo girders corresponding to 8.6 ton truckload Case-2.

Figure 7 shows three test results of mid-span deflections measured for the nine girders in critical loading Case-1. All the mid-span 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 [JTG D62 2004]. Critical deflections were also below this limit value when the truck was positioned away from the bridge centerline and close to one edge, as shown in Figure 8.

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 is currently monitored regularly to obtain its long-term performance and to assure the safety of the operation.

## CONCLUSIONS

Using the large size laminated bamboo girders, named as GluBams®, developed by Xiao et al. the world's first truck-safe modern bamboo roadway bridge was designed and built, based on the theory of mechanics, design and experiment. Field truck loading tests indicated that the bridge performed extremely well with significant safety margin.

The authors 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.

ACKNOWLEDGEMENT

The research described in this paper was sponsored by the Institute of Bamboo, Timber and Composite Structures (IBTCS) of the Hunan University, under the support of the Program for Changjiang Scholars and Innovative Research Team Project by the Ministry of Education of China (Project No. IRT0619). The construction of the 10 m long modern bamboo roadway bridge was funded by the Agriculture Development Office, Leiyang, Hunan Province, under the direction of Mr. Zhou, Bingya. The authors warmly and heartily thank all the sponsors and collaborators.

## REFERENCES

Zhou, Q.; Shan, B.; and Xiao, Y. (2007), Design and Construction of a Modern Bamboo Pedestrian Bridge. Proceedings of the International Conference on Modern Bamboo Structures. ICBS-2007. Changsha. China. Oct. 28–30.

Xiao, Y.; Shan, B.; Chen, G.; Zhou, Q.; and She, L.Y. (2007), Development of A New Type of Glulam – GluBam, Proceedings of the International Conference on Modern Bamboo Structures. ICBS-2007. Changsha. China. Oct. 28–30.

JTG D62 (2004), Design Guidelines for Reinforced and Prestressed Concrete Highway Bridges (in Chinese). People's Transportation Press. 2004.

*Composites of bamboo and other materials*

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# Experimental verification of bamboo-concrete composite bow beam with ferro-cement bond

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ABSTRACT: Sudhakar has developed various structural components using bamboo concrete composites (bamcrete) and demonstrated them in building houses as is presented in a companion paper. This paper presents the initial experimental verification of one of the structural arch forms proposed by Sudhakar using bamboo as a structural element. In this case, two bamboo arches vertically separated are connected using Ferro-Cement Band ties to generate a Bow Beam Arch as a load bearing member. This paper presents the manufacturing details of the bow beam arch and the initial experimental results.

## 1 INTRODUCTION

### 1.1 *Problem area*

Various researchers have tried using Bamboo as a replacement of steel as in case of reinforced concrete members. However, this has not achieved much popularity. Extensive literature survey and history of development of different bamcrete structures is presented in a companion paper.

Utilization of thin bamboo (Dendrocalamus Strictus) as a structural element, especially as a beam element is an engineering challenge. Bamboo in general is a hollow structure. Hidalgo mentions that bending the bamboo is a problem as it gets crushed as one tries to bend it. He proposes a unique method of bending the bamboo when it grows. However, Dendrocalamus Strictus has a thick wall with very small hollowness. It is a widely available species in India. Because it is thin (less than 5 cm in diameter at the base), it is a neglected species for structural applications. However, it has been found that it is a species that can be bent in the form of arches which has the potential of being used as a load bearing structural member. More over it also has good compressive stress. Here bamboo has a different role compared to the case where bamboo is used as a replacement of steel in RC members. In this paper we present the construction method of the bow beam with ferro-cement bands and the results of the initial experimentation.

Figure 1 shows the picture of a load bearing application of the Bow Beam Arch of 7.3 m span in Haritha by Dr. Sudhakar, built in 2005. He also experimentally tested the structure as shown in Figure 2 in October 2005. It has a span of 3.3 m. It was loaded with one ton of uniformly distributed load. This is still taking this load. Though deflection measurements can not be trusted, this structure under open sky, as shown in the figure has with stood the load till date. No cracks have been noticed.

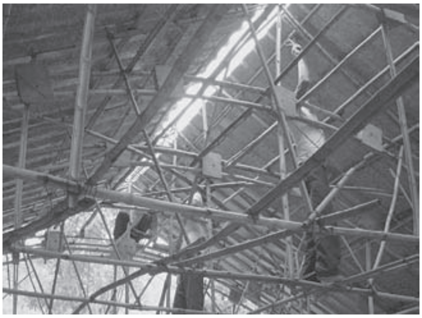

Figure 1. Bow Beam Arches built in 2005.

Figure 2. At Harita since October 2004.

Figure 3. Cross-section of bamboo at different height.


Figure 4. Work bench for bending bamboo.

### 1.2 *Sample preparation*

This section presents the details of the specimen that was made using the bending table constructed at IIT Delhi and was used as a demonstration in a workshop conducted by us to various artisans, architects and other interested members.

Figure 3 shows the thick walled bamboo samples from different heights for compressive stress experiment of the Dendrocalamus Strictus. Because of this thick wall, we are able to bend the bamboo.

A bamboo concrete composite arch is made using three bamboo culms—two are used as arch element and one as a tie element. In order to prepare the arch, the workbench as shown in the Figure 4 is used. Here, as per the crown height and the length of arch to be prepared, the guides are positioned which guide the bamboo culm to take the shape of an arch. One bamboo culm is taken and its base is fixed on the workbench at one end. Now the upper portion of bamboo culm is bent gently along the guides fixed on the workbench. Second bamboo culm is taken and fixed on the opposite end so that the two bamboos have opposite orientations. These two bamboo culms are temporarily separated with the required amount of spacing using wooden wedges. Now, the number of bands to be provided is decided on the basis of the amount of load to be applied on the arch. Here we have provided seven bands. One band is at the crown and one band each at the two landings of the arch. The remaining four are placed in regular intervals. The arch can be tied by either a steel wire or a RC beam as shown in Figure 2 or by a bamboo (Figure 4).

Figure 5 shows the construction details of the shear connector. The connections are made using the mild steel rod of 6 mm diameter. At the position of the bands the bamboo is drilled along the diameter at a spacing of 15 cm between two drilled holes. It is ensured that the holes drilled in one

Figure 5. Connection details.

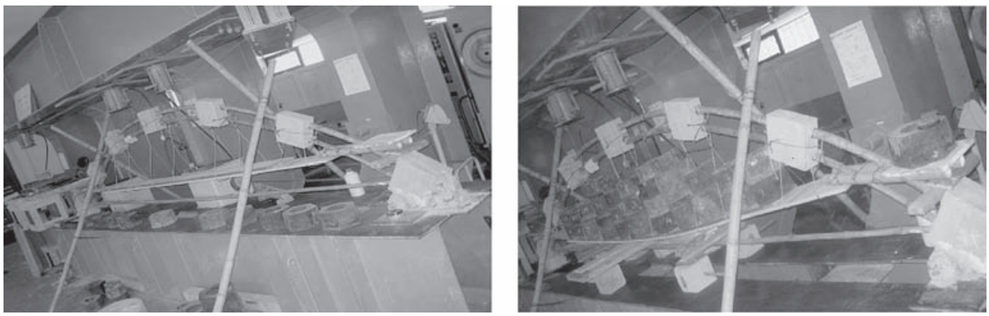

Figure 6. Bamboo-concrete composite arch with 880 kg of nearly distributed load.

bamboo are in line with the others in the second parallel bamboo. The two parallel sides of the steel rod, bent into U shape, are made to pass through the two bamboos and the extended portions are bent to close the rectangular stirrup with a proper overlap on the fourth side.

Further, the connection so made is painted with a rich cement paste Tapecrete P151, a polymer cementitious product It is water resistant. This is done in order to prevent the absorption of water by the bamboo from the concrete when it is allowed to set. This also ensures a better grip between the concrete and bamboo. The band region is then wrapped with chicken mesh. This ensures uniform bonding between the concrete and the bamboo skeleton. The formwork is prepared by ensuring the requisite amount of cover for the concrete.

Proper compaction while concreting is ensured in the band region that includes the chicken mesh. The concrete is allowed to set. After 24 hours the form work is removed and the concrete surface is painted with water proofing compound such that there is no evaporation and no further wet curing is needed.

### 1.3 *Sample testing*

The arch is loaded by static loading. The ends of the arch are fixed using bricks on a steel plat form. Two wooden planks are suspended from the arch with steel ropes. The weights are distributed along the plank as shown in the figure below. Static loads are placed on the plank. Loading of the structure is done using weights of 50 kg, 20 kg and 10 kg. The loading is in a nearly uniformly distributed manner. Two pairs of bamboo are used to hold the arch in a vertical plane as shown in the Figure 6. Deflection of the arch is measured using a dial gauge fixed at the bottom of the crown of the arch. The experimental results are presented in tabular/graphical form as shown in Table 1, and Figure 7 & 8. The structural details are given in Table 2.

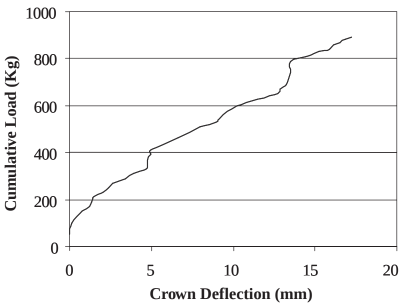


Figure 7. Load deflection while loading.

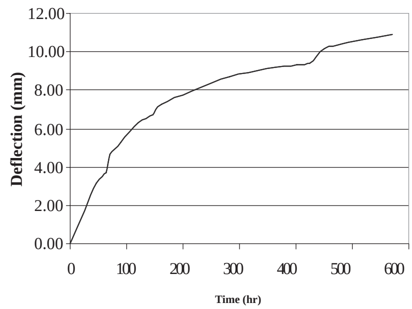


Figure 8. Deflection due to creep.

Table 1. History of loading and deflection.

| Sr. No. | Position of Load | | | Weight (kg) | Cumulative load (kg) | Deflection (mm) |
|---|---|---|---|---|---|---|
| | | | | 0 | 0 | |
| 1 | | C | | 50 | 50 | 0 |
| 2 | L | | | 50 | 100 | 0.15 |
| 3 | | | R | 50 | 150 | 0.74 |
| 4 | L | | | 20 | 170 | 1.2 |
| 5 | | | R | 20 | 190 | 1.33 |
| 6 | L | | | 20 | 210 | 1.45 |
| 7 | | | R | 20 | 230 | 2.05 |
| 8 | L | | | 20 | 250 | 2.39 |
| 9 | | | R | 20 | 270 | 2.64 |
| 10 | L | | | 20 | 290 | 3.39 |
| 11 | | | R | 20 | 310 | 3.93 |
| 12 | | C | | 20 | 330 | 4.7 |
| 13 | L | | | 20 | 350 | 4.73 |
| 14 | | | R | 20 | 370 | 4.73 |
| 15 | L | | | 20 | 390 | 4.97 |
| 16 | | | R | 20 | 410 | 4.97 |
| 17 | L | | | 50 | 460 | 6.63 |
| 18 | | | R | 50 | 510 | 7.97 |
| 19 | L | | | 20 | 530 | 8.97 |
| 20 | | | R | 20 | 550 | 9.23 |
| 21 | L | | | 50 | 600 | 10.25 |
| 22 | | | R | 50 | 650 | 12.74 |
| 23 | L | | | 20 | 670 | 12.85 |
| 24 | | | R | 20 | 690 | 13.25 |
| 25 | L | | | 50 | 740 | 13.53 |
| 26 | | | R | 50 | 790 | 13.53 |
| 27 | L | | | 20 | 810 | 14.63 |
| 28 | | | R | 20 | 830 | 15.25 |
| 29 | L | | | 10 | 840 | 15.9 |
| 30 | | | R | 20 | 860 | 16.17 |
| 31 | L | | | 10 | 870 | 16.53 |
| 32 | | | R | 10 | 880 | 16.87 |
| 33 | | C | | 10 | 890 | 17.26 |

L: Left; C: Centre; R: Right.

Table 2 Structural details.

| Sr. No. | Details | Notations | Value |
|---|---|---|---|
| 1 | Length of arch | $L$ | 4700 mm |
| 2 | Crown Height | $H$ | 845 mm |
| 3 | Outer Diameter of bamboo culm of upper bow | $D1$ | 36 mm |
| 4 | Inner Diameter of bamboo culm of upper bow | $d1$ | 7.5 mm |
| 5 | Outer Diameter of bamboo culm of lower bow | $D2$ | 33 mm |
| 6 | Inner Diameter of bamboo culm of lower bow | $d2$ | 7.5 mm |
| 7 | Clear spacing between two bamboo bows | $S$ | 75 mm |
| 8 | Angle of Inclination of the arch at the landing | $\theta$ | 0.53 radian |
| 9 | Area of cross section of the first bamboo | $A_1$ | 1018 mm$^2$ |
| 10 | Area of cross section of the second bamboo | $A_2$ | 855 mm$^2$ |

Figure 9. Bow arches (2 No.) before ferro-cementing, carrying human load of about 1 ton in a workshop.

Loading on the arch is done up to 880 kg of nearly distributed load. The normal reaction at any one of the two supports is thus 4300 N. The tensile load and stress generated in the bamboo culm used as a tie element can be determined as 7400 N and 12.4 N/mm$^2$ respectively. The above tensile load is less than the 10000 N that the ferro-cement band tie could with stand and the tensile stress is insignificant compared to the reported tensile strength of the bamboo. A significant long term deflection was observed that seemed to have stabilized after some time. It can be concluded that even though the beam could take a good load, its creep related properties need to be studied.

## 2 CONCLUSIONS

Experimental study was carried out to the study the properties of Bamcrete Bow beam. The following conclusions can be made:

a. Dendrocalamus Strictus has excellent bending properties and has great potential to be used as a load-carrying member.
b. The shear key using Ferro-cement band is very effective in providing the rigidity.
c. It was seen that the Bamboo-concrete composite arch of 4.7 m span loaded with the above loading of 880 kg, deflected by further 17 mm initially and then by a further 17 mm in the subsequent 2 months time due to creep, making the total deflection of 34 mm (Fig. 9). The creep data needs to be investigated further.

## ACKNOWLEDGEMENTS

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## REFERENCES


Sudhakar, P. et al. 2007. Conceptual Development of Bamboo Concrete Composite Structures in a typical tribal belt, India. *International Conference of Modern Bamboo Structures, Changsha, October 2007,* China.

Hidalgo, Oscar & Lopez. *Bamboo - The Gift of Gods*. ISBN 958-33-4298-X.

Sudhakar, P. 1995. *Haritha Villu*. Haritha Ecological Institute, Paloncha, Khammam district, A.P., India. (in Telugu).

Brink, F.E. & Rush, P.J. 1966. *Bamboo Reinforced Concrete Construction*. US Naval Civil Engineering Laboratory, California, USA.

Iyer, S. 2002. *Guidelines for Building Bamboo-Reinforced Masonry in Earthquake-Prone Area in India*. University of Southern California, USA.

Sudhakar, P. 2006. *Engineering evaluation of Bamboo Bow Beams as Load Bearing Structures*. Project Completion Report NMBA, TIFAC, DST, Govt. of India, India.

Limaye, V.D. 1952. *Strength of Bamboo (Dendrocalamus strictus.)* Indian Forester.

Naik, N.K. *Mechanical and Physico-Chemical Properties of Bamboo by Aerospace Engineering Department*. Mumbai, India: Indian Institute of Technology, Bombay.

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# Experimental verification of bamboo-concrete composite column with ferro-cement bond

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ABSTRACT: This paper presents the initial experimental verification of one of the structural forms—column—using four thin bamboos of dendrocalamus strictus, for taking the axial load with Ferro-Cement Bands as ties. In a test structure the column is 1.4 m high and has the ferro-cement band ties at the top, middle and bottom. The uniaxial compression testing is done in a UTM machine to study its behavior. The maximum load carried and the mode of failure is reported. This is potentially a cost effective design of a bamboo column, which can be mass produced with minimal resources requiring only marginally skilled labour. We suggest the name 'BAMCRETE' for such bamboo concrete composites.

## 1 INTRODUCTION

### 1.1 *Problem area*

Bamboo of dendrocalamus strictus has a good compressive strength and our initial experiments reconfirm it. However, being thin with less than 5 cm of outer diameter at the base, these are not popularly used for columns. On the other hand, it is widely available in most parts of India and grows even in marginal lands. This rapidly renewable resource has a huge potential of several tens of millions of tons per year. It is therefore an engineering challenge to harness the good compressive strength of this species of thin bamboo for structural applications. It would be good if a structure built out of such an environment friendly material offers a cost effective solution. Use of the bamboo in large scale structural engineering applications can promote the bamboo plantations even in marginal lands which effectively perform eco-healing. The possibility of carbon trading can substantially improve its economics.

Even with larger diameter bamboos, structural elements are made with joints between different bamboos that require specially finished spacers of wood or bamboo and drilling to close tolerances. This requires a high degree of skills resulting in high costs. Alternately, engineered bamboo wood is used which is essentially a three dimensional solid made out of slats of bamboo. It destroys the wonderful 'nature engineered' tubular structure of bamboo besides being expensive on account of the adhesives and substantial processing used.

Ferro-cement band as a rigid cost effective tie has been developed by Sudhakar. Such bamboo concrete composites are called 'bamcrete' structures and their use in bamboo bow beams are reported in companion papers. In this paper we describe our first attempt to come up with a structural element in the form of bamboo-concrete composite (bamcrete) column using the thin bamboo of dendrocalamus strictus. A structural design of the 'bamcrete' column is proposed and the same is fabricated. The preliminary experimental results are reported using a Universal Testing Machine under uniaxial loading.

### 1.2 *Sample preparation*

The bamboo concrete composite (bamcrete) column is made using bamboo of dendrocalamus strictus, concrete, steel rods and chicken mesh. Figure 1 shows the cross-section of a typical dendrocalamus strictus bamboo at different heights. It can be observed that this species provides thick skin and small hollowness. This property helps us against local buckling of the bamboo skin, unlike the bamboo species with thin skin of similar outer diameter. Figure 2 shows the final picture of the bamcrete column. Four bamboo culms are so chosen that they are straight enough for a length of 1.4. In real application, bamboos can be straightened by heating and need to be treated against insect and fungal attack. Each of these technologies is well known.

Figure 3 shows the bamboo skeleton along with the 3 pairs of 6 mm stirrups at the three levels. 6 mm diameter steel rods are initially bent into 'U' shape with the spacing between the parallel arms equal to the spacing between the opposite faces of bamboo column. In each pair of the stirrups, while still in 'U' shape, one pierces the bamboos in a direction perpendicular to the other. This ensures that the bamboos in the column get locked in all the three mutually perpendicular directions. The centre to centre spacing between bamboos in parallel faces is chosen to be 200 mm. Bamboo samples are accordingly drilled at three levels i.e. top, middle and bottom.

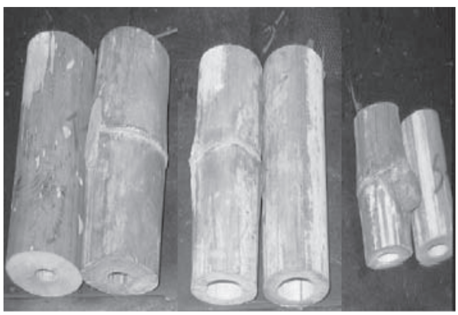

Figure 1. Bamboo samples.

Figure 2. Bamboo-concrete composite column.

Figure 3. Bamcrete column before casting.

At each level, the holes are drilled along mutually perpendicular diameters of the bamboo but separated by appropriate distance, in our case 100 mm. These holes should be properly aligned to minimize the twist in the bamboos.

Further, the connection is painted with a rich cement paste, Tapecrete P151, a polymer cementitious product of M/s Cico Plast India to get a water resistant coat in the band region of the bamboo. This prevents the absorption of water by bamboo from the concrete when it is allowed to set. To some extent, it also ensures a grip between the concrete and the bamboo.

These joints are wrapped with chicken mesh. This helps in good bonding between the concrete and the bamboo skeleton. The formwork is prepared by ensuring the requisite amount of cover. The central portion of the column is kept hollow to optimize the use of concrete. Concreting is done in the prepared formwork and well compacted. After 24 hours, the form work is removed and the concrete surface is painted with a solution of M/s Cico India to prevent evaporation and avoid the requirement of wet curing of the concrete.

### 1.3 *Sample testing*

Samples shown in Figure 1 are tested for the compressive stresses. The column is tested for its compressive strength in a Universal Testing Machine as shown in Figure 6 and 7 in order to study the behavior of the bamboo concrete composite column. The results obtained are presented in the form of axial stress. The experiment is stopped when global buckling is apparent as shown in Figure 6.

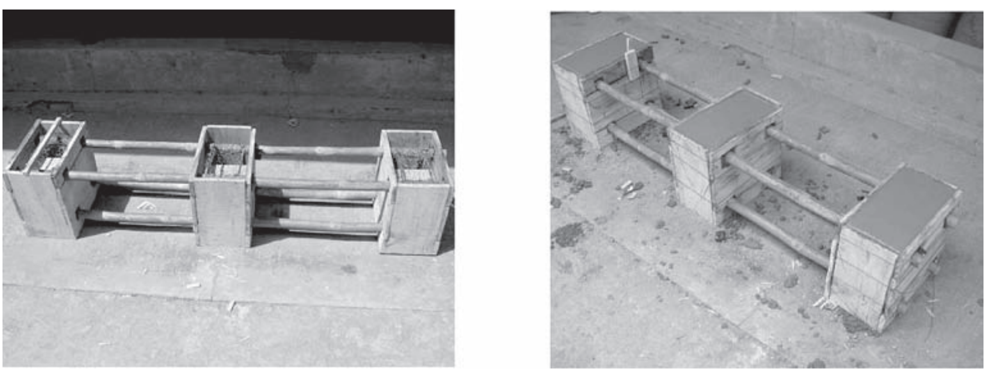

Figure 4. Casting of bamboo concrete composite column.

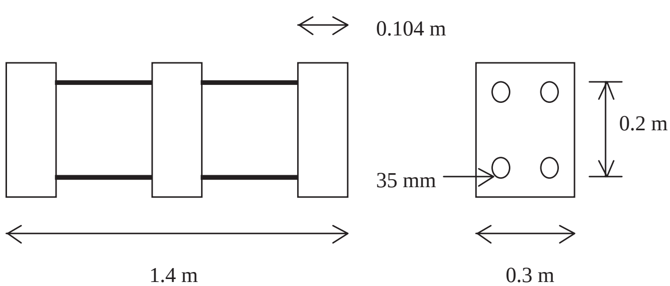


Figure 5. Details of bamboo-concrete composite column.

### 1.4 *Test results*

Table 1 presents data from compressive stress experiments on specimens shown in Figure 1. Table 2 shows the structural details of the column, where $I_{xx}$ is the moment of Inertia and $r_{xx} = \sqrt{I_{xx}/A}$. This is a symmetric section with equal properties in x and y directions. The loading of the structure is done up to 75 kN. It is observed that the column had undergone a significant amount of buckling at this load (Fig. 6). The stress at this load in each of the four bamboo culms is about 19 MPa. The maximum compressive strength of the bamboo is 45 MPa as can be seen in Table 1. It was observed that there were no cracks in either bamboo culms or the concrete band. After removal of the load, it was noticed that the bamboos almost became straight as shown in Figure 7. This is because the bamboos are still in the elastic stage. In this experiment on column, the

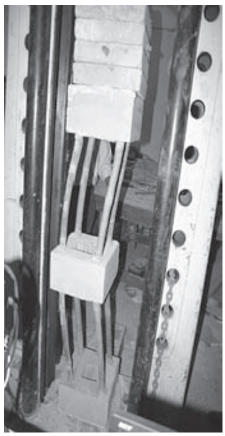

Figure 6. Column at 75 kN load.

Figure 7. Column after release of loading.

Table 1. Results of bamboo sample testing.

| S. No. | Sample | Av cross sectional area (mm$^2$) | Maximum compressive load (kN) | Maximum stress (MPa) |
|---|---|---|---|---|
| 1 | Bottom | 1720 | 77.3 | 44.9 |
| 2 | Bottom Nodal | 1762 | 88.3 | 50.1 |
| 3 | Middle | 940 | 33.5 | 35.6 |
| 4 | Middle Nodal | 956 | 37.2 | 38.9 |
| 5 | Top | 464 | 18.8 | 40.5 |
| 6 | Top Nodal | 564 | 21.6 | 38.3 |

Table 2. Structural Details.

| Sr. No. | Structural properties | Sym. | Value |
|---|---|---|---|
| 1 | Length of column | $L$ | 1400 mm |
| 2 | Outer Diameter | $D$ | 36 mm |
| 3 | Inner Diameter | $D$ | 7.5 mm |
| 4 | Spacing between two bamboo | $S$ | 200 mm |
| 5 | Area | $A$ | 3647 mm$^2$ |
| 6 | Moment of Inertia along X-axis | $I_{xx}$ | $36.6 \times 10^6$ mm$^4$ |
| 7 | Radius of Gyration along X-axis | $r_{xx}$ | 100.42 mm |
| 8 | Slenderness ratio | $l/r$ | 13.96 |

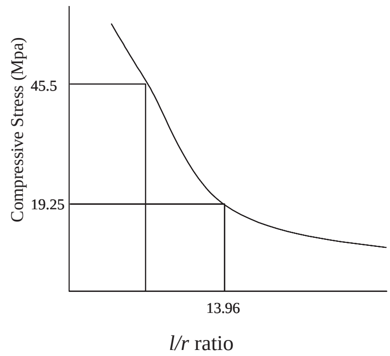


Figure 8. Expected allowable stress and *l/r* relationship.

compressive stress is considerably below the ultimate compressive strength and we should be able to design the bamboo column in such a way that we get a lower slenderness ratio ($l/r_{xx}$) as shown in Figure 8. This can be done by proper designing against global and local bucking. Figure 8 shows a general trend of permissible stress of a column and $l/r_{xx}$ along with material yield or compressive stress as a horizontal line.

## CONCLUSIONS

Experimental work is carried out to study the feasibility of the use of thick walled, but slender bamboo (dendrocalamus strictus) as a load bearing column for one level housing. Samples from top, middle and bottom are taken and maximum compressive stress measured. The dendrocalamus strictus is found to have a good potential for use in bamcrete column and the experimental column could take 75 kN of load at less than 50% of the maximum stress.

For the experiment conducted, we can see that the value of slenderness ratio *l/r* is 14.0 and the corresponding value of compressive stress is 19 MPa. The experiment can be repeated for other values of *l/r*. We can redesign the column with smaller *l/r* ratio such that it has proper design against global and local buckling.

The 'BAMCRETE' column provides a simple solution for rural housing using a rapidly renewable and sustainable source that is of bamboo. By replacing steel and concrete even partially, it contributes in our collective fight against global warming. The economic benefits of $CO_2$ trading as explained in the companion paper can be significant.

## ACKNOWLEDGEMENTS

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## REFERENCES

Hidalgo. Oscar & Lopez. *Bamboo - The Gift of Gods.* ISBN 958-33-4298-X.

Korde, C. et al. 2007. Experimental Verification of Bamboo-Concrete Composite Bow Beam With Ferro-Cement Band. *International Conference of Modern Bamboo Structures*. Changsha, China.

Limaye, V.D., 1952. *Strength of Bamboo (Dendrocalamus strictus)*. Indian Forester.

NMBA. 2004. *Building with Bamboo. a Training manual TM 01 02/04*. Published by NMBA (TIFAC, DST, GOI).

Naik, N.K. *Mechanical and Physico-Chemical Properties of Bamboo by Aerospace Engineering Department.* Mumbai, India: Indian Institute of Technology, Bombay.

Private communication with NMBA TIFAC, DST, Govt. of India, India.

Sudhakar, P. 2006. Engineering evaluation of Bamboo Bow Beams as Load Bearing Structures. *Project Completion Report* NMBA, TIFAC, DST, Govt. of India, India.

Sudhakar, P. et al. 2007. Conceptual Development of Bamboo Concrete Composite Structures in a typical tribal belt, India. *International Conference of Modern Bamboo Structures*. Changsha, China.

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# Wind analysis of bamboo based shed structure and design of base connection for bambcrete column

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ABSTRACT: This paper is one of the four papers in series dealing with various aspects of bamboo related research in Structural Engineering carried out in India. Specifically, this paper presents a detailed wind load analysis of a typical bamboo shed structure, $6 \times 6$ m in size, in accordance with the Indian standard IS: 875 (Part 3)—1987. Wind is considered both along as well as normal to the ridge. The columns are modeled as rigidly fixed at the base and tied together by bamboo bow beam at top in normal to the ridge and by bamboo beams in the longitudinal direction. No rotational restraint is assumed at the top in any direction. Final axial loads, shears and bending moments at the column based resulting from the combination of dead loads and wind loads are computed and utilized in the conceptual design of suitable base connection. Two alternative designs are presented for the base connection.

## 1 INTRODUCTION

There has been a growing interest in bamboo structures in India over the last few years. The recent work of Dr. Sudhakar, an eminent scientist, has acted as a catalyst in bamboo related research in India. Dr. Sudhakar has constructed a large number of bamboo structures with the help of rural/tribal people over the last decade and they have proved to be reasonably durable, environment friendly and most importantly cost effective for an average rural Indian. After the initial construction with the help of tribals, a dedicated team of researchers at the Indian Institute of Technology Delhi has recently started a comprehensive programme to scientifically design, built and test these structures so that conventional wisdom is integrated with scientific knowledge. It is in this endeavour that a thorough wind analysis of a typical bamboo structure has been carried out and the results presented in this paper. Based on the results, two different base connection details are conceived and details presented.

## 2 DETAILS OF STRUCTURE

This study considered a bamboo structure $6 \times 6$ m in plan area and 2.4 m height. Figs. 1 and 2 show the plan and elevation respectively of the proposed structure, to be constructed in the campus of Indian Institute of Technology Delhi very soon. The building shall rest on 'bambcrete'(bamboo + concrete) columns of the type shown in Fig. 3, consisting of four bamboo struts tied together by ferrocement bands at regular intervals. The bambcrete columns shall be anchored securely to a reinforced concrete (RC) pedestal. The roof shall be supported by bamboo bow beams of the type shown in Fig. 4.

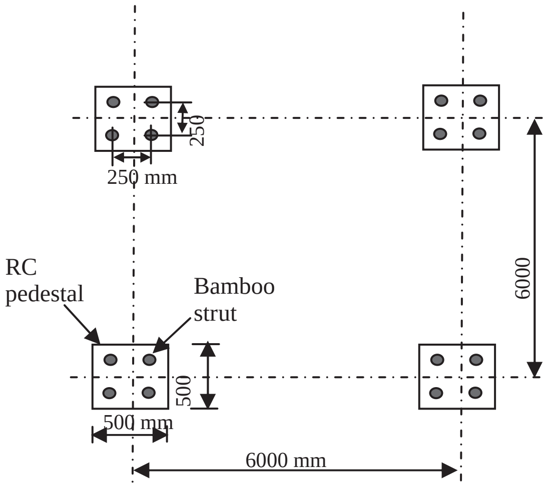


Figure 1. Plan at top of RC pedestal.

Figure 2. Elevation of building.

Figure 3. Bambcrete column.

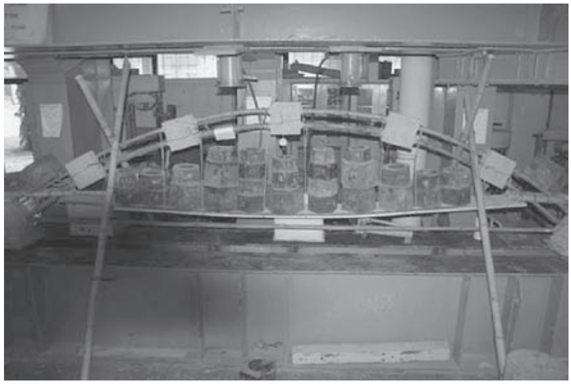

Figure 4. Bamboo bow beam for supporting roof.

## 3 DEAD LOAD AND IMPOSED LOAD ANALYSIS STRUCTURE

Dead load and live load analysis of the structure are straightforward since these loads do not induce any moment about the base of the column. For dead loads, the roof has been considered as a thatched one, imposing a dead load of 10 kg/m$^2$. The weight of the bow beam has been considered as 100 kg and that of the columns as 40 kg/m based on actual measurements. In accordance with IS 875 part 2 (1987), an imposed load of 41 kg/m$^2$ has been considered for the roof which slopes at 27°. The dead loads and the imposed loads result in an axial force of 2.4 kN and 3.7 kN respectively at the top of the concrete pedestal.

## 4 WIND ANALYSIS STRUCTURE

In this study, the structure is analyzed for wind forces in accordance with IS: 875 Part 3 (1987). For Delhi region, this code recommends a basic wind speed $V_b$ of 47 m/s. This study has considered the value of the probability factor (risk coefficient) $k_1$ as 1.0 assuming a mean probable life of 50 years. The terrain, height and size factor $k_2$ of 1.0 has been considered since the proposed structure belongs to class A and category 2 as per IS 875 part 3 (1987). Finally, the topography factor $k_3$ has been chosen as 1.0. These factors result in a design wind speed $V_Z$ $( = k_1\, k_2\, k_3\, V_b )$ of 47 m/s, thereby resulting in a design wind pressure of 1.325 kNm$^{-2}$ . The external and internal pressure coefficients on the wall and roof in accordance with IS 875 part 3 (1987) are shown in Fig. 5 for two wind directions- normal to the ridge and parallel to the ridge. An internal wind pressure of ±0.7 has been considered taking into account the large opening area, about 20% of the wall area. Fig. 6 shows the steps involved in the analysis of a typical cross frame, which supports the wind load on 3 m length of the building, for the case of wind load normal to ridge and inside pressure. The structure is analyzed as the superposition of two cases—A and B shown in the figure. The resultant horizontal component of the wind load acting on the roof, *f* is applied at mid height of the roof as a concentrated load. The vertical components are applied along their lines of action and the resulting axial forces in the columns have been computed. Fig. 7 similarly shows the analysis of the longitudinal frame for same wind direction and internal pressure conditions. In overall, following wind cases have been analyzed:

i. Wind normal to ridge, inside Suction.
ii. Wind normal to ridge, inside pressure.
iii. Wind along ridge, inside suction.
iv. Wind along ridge, inside pressure.

Fig. 8 summarizes the forces induced at the top of pedestal for all the four cases.

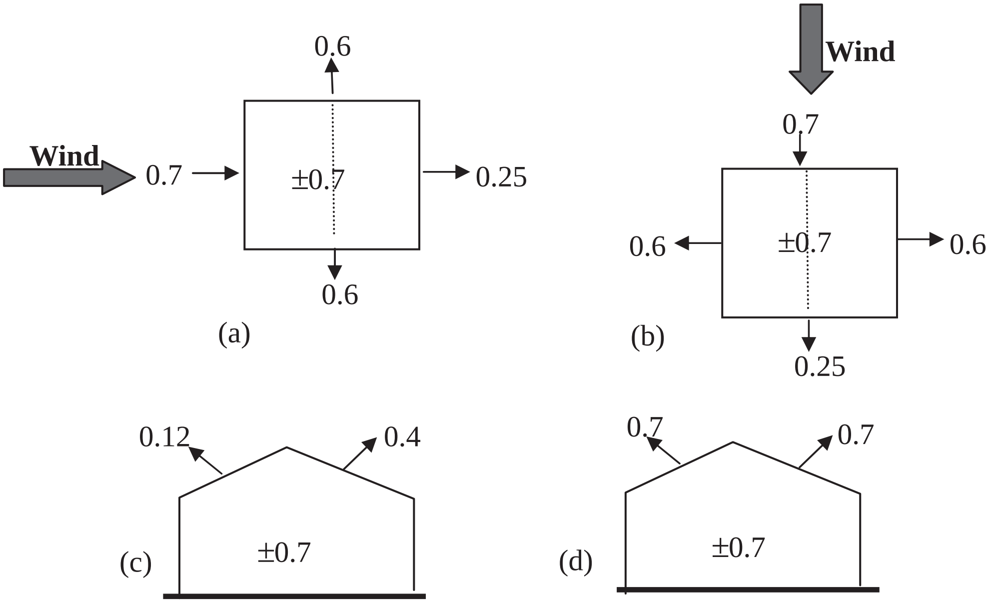


Figure 5. Wind pressure coefficients in accordance with IS 875: (a) Walls: Wind normal to ridge; (b) Walls: Wind along ridge; (c) Roof: Wind normal to ridge; (d) Roof: Wind along ridge.

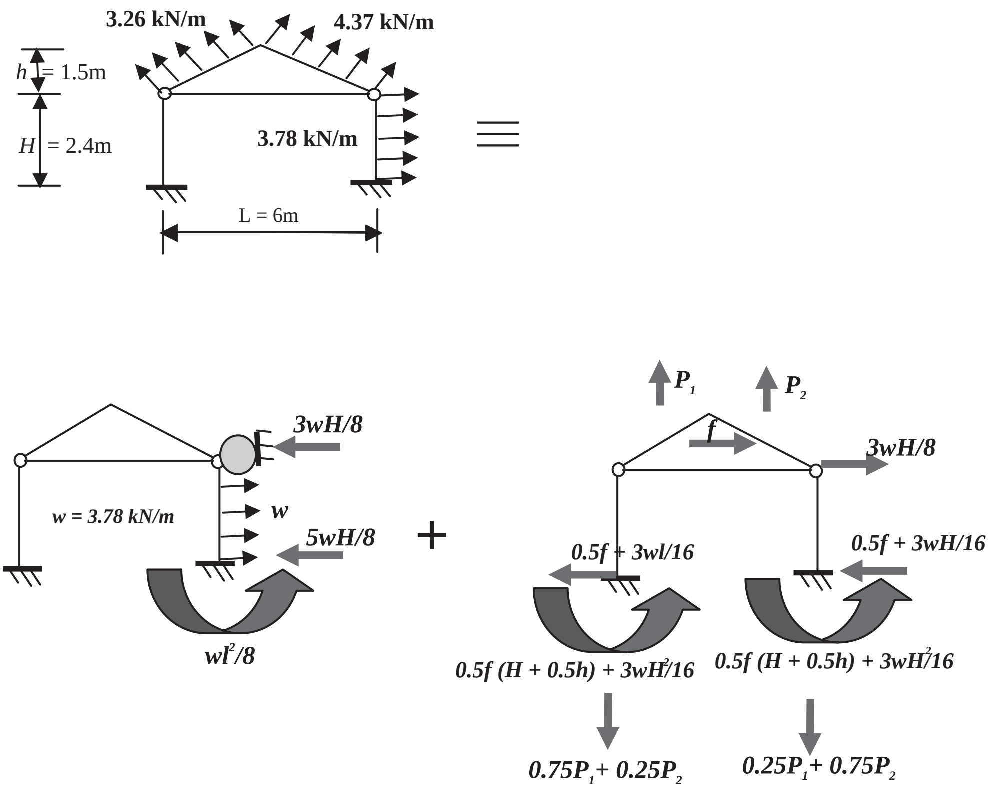


Figure 6. Analysis of cross frame for wind normal to ridge, inside pressure.

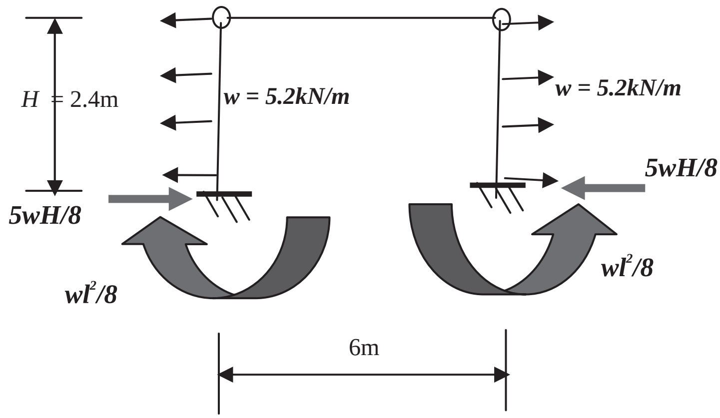


Figure 7. Analysis of longitudinal frame for wind normal to ridge, inside pressure.

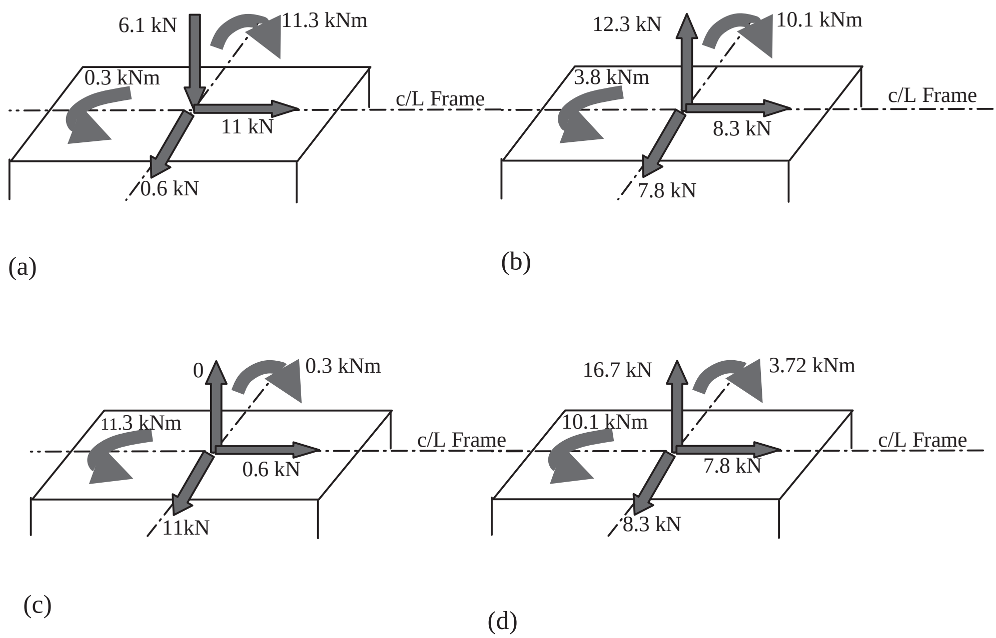


Figure 8. Wind induced forces at top of pedestal: (a) Wind normal to ridge, inside suction; (b) Wind normal to ridge, inside pressure; (c) Wind along ridge, inside suction; (d) Wind along ridge, inside pressure.

## 5 DESIGN OF BASE CONNECTION

Two possible types of base connections have been conceived. In the first type, shown in Fig. 9, the bamboo components are embedded inside concrete of the pedestal up to a length which is sufficient to provide an adequate force through bond with the surrounding concrete. From the above analyses, the axial force in tension in the bamboo component of the column would be 23.8 kN, 25.1 kN, 23.2 kN and 24 kN for the cases (a), (b), (c) and (d) of Fig. 8. These results have been obtained by converting the moments of Fig. 8 into push and pull and the axial forces shown have been divided equally among the four bamboo components. The required length of embeddment for the maximum force $F$ = 25.1 kN can be calculated as

$$L = \frac{F}{\pi D \tau} \tag{1}$$

where $\tau$ is the bond strength between bamboo and concrete, to be determined in the laboratory through a pullout test and $D$ the outer diameter of the bamboo. This type of connection is the simplest type. Further laboratory tests are needed to evaluate $\tau$ for bamboo-concrete combination. Fig. 10 shows the second type of base connection. In this type of connection, four mild steel tubes of internal diameter 40 mm and 6 mm wall thickness are first embedded inside concrete and suitable length left projected above the top of pedestal. The tubes have a centre to centre spacing of 250 mm. The development length can be easily computed using Eq. (1), taking $\tau$ = 1.4 Nmm$^{-2}$ (limit state) as per IS 456 (2000) for M 25 concrete. This comes out to be 220 mm for a force of $1.5 \times 25.1$ kN. Hence, the steel tubes are embedded 250 mm inside concrete. After the pedestal is ready, the bamboo components of the bambcrete column can then pushed inside these steel tubes

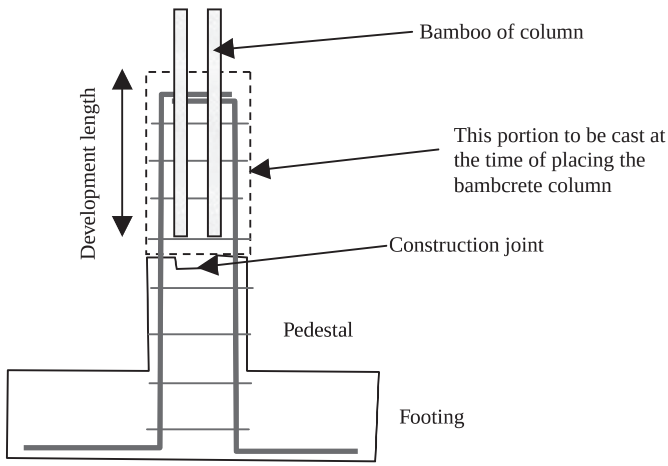


Figure 9. Type I base connection.

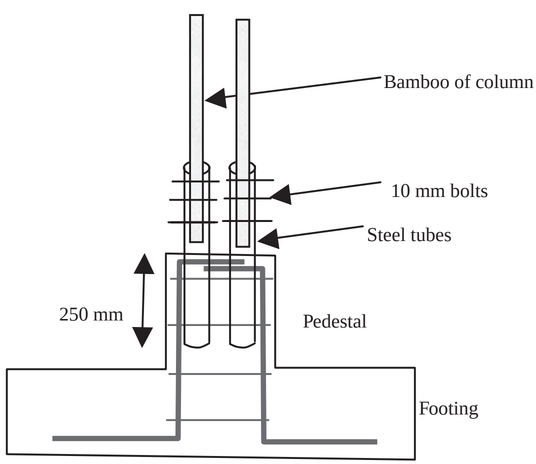


Figure 10. Type II base connection.

and secured by 10 mm bolts of class 4.6 as per IS 800 (1984). Considering a permissible stress of 80 MPa in axial tension and shear and 300 MPa in bearing, three bolts are more than sufficient for each bamboo component.

## 6 CONCLUSIONS

This paper has covered the analysis of a typical bamboo based shed structure under various loads and their combinations. Wind loads have been considered as per IS 875 part 3 (1987) and the structure analyzed in a simple fashion, by studying the behaviour of one typical frame in each direction. The resulting moments at the base of the column have been computed and three possible connections suggested for the base. Future experimental studies would focus on pullout tests to determine the bond stresses between concrete and bamboo. In addition, long term behaviour of such structures under static and dynamic loadings shall also be studied.

## REFERENCES

IS 456, Plain and reinforced Concrete—Code of Practice, Bureau of Indian Standards, 2000.

IS 800 Part 3, Code of Practice for General Construction in Steel, Bureau of Indian Standards, 1984.

IS 875 Part 2, Code of Practice for design loads for Buildings and Structures, Imposed Loads, Bureau of Indian Standards, 1987.

IS 875 Part 3, Code of Practice for design loads for Buildings and Structures, Wind Loads, Bureau of Indian Standards, 1987.

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# Status and future of the wood-bamboo composite panel industry in China

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ABSTRACT: Status of the wood-bamboo composite panel industry in china was reviewed in this paper. Analyzing difficult problems such as disorder products, small production scale, and narrow utilization scope and lacking of correlation standards and so on. Some suggestions are given out on researching and developing the wood-bamboo composite panel in the future in china.

## 1 INTRODUCTION

Bamboo and Wood belong to the forestry resource, they own the same characteristics, but many different characteristics are also showed. So wood-bamboo composite panel has many kinds of types (Zhao R.J. and Yu Y.S., 2002). Bamboo with the characteristics of high strength and toughness, fast-growing, but it is easy to decadent and difficult to process. Moreover, there is a serious shortage of timber resources in china. Currently, fast-growing timber is gradually coming into the market, but fast-growing timber is a material with low-strength, great variations and high content of the young wood. These shortcomings affect the utilization of wood seriously. Bamboo and Wood, particularly the fast-growing plants are produced into composite panels, which could improve the strength of the composite sheets, but also correct to the national conditions in China.

The wood-bamboo composite panels have numerous products, such as wood-bamboo composite plywood, wood-bamboo composite particleboard, wood-bamboo composite Laminated Veneer Lumber, wood-bamboo composite floor and other products made by wood-bamboo composite materials. The composite panels with different characteristics which are relate to the composite methods and morphological of the material. Bamboo is produced into mats, bamboo veneers and bamboo curtains as their composite forms, but timber is the form as wood veneer, wooden planks and other forms of participations. According to the different utilization of wood-Bamboo composite panel, both the bamboo and timber veneer can be used for the gaps of the plywood.

## 2 WOOD-BAMBOO COMPOSITE PLYWOOD

The wood-bamboo composite plywood is studied earlier, and the production process is more mature than other panels. Architecture template, bamboo flooring and other fields are the main application for the panels. In recent years, many researches are probed into to enhancing the adding value and expanding applications of the wood-bamboo composite plywood.

Wood-Bamboo composite plywood has several forms, mainly the plywood of veneer mats. Mats veneer including the cladding of veneer and the cladding of mats. The former use mats as its inlay and the veneer as the surface. The inlay mats layers are determined by the specific thickness of plywood. The surface veneer is determined by the special requirements. Generally speaking, the requirements of plywood are so high that we can choose hard-wood veneer as cladding, otherwise choose general soft-wood, such as poplar and so on. The physical and mechanical properties of veneer cladding plywood were higher than wood plywood, and the visual quality can be comparable with the wood plywood. So these panels can substitute for the wood plywood in many applications. Yu Y.S. et al. (2002) studied two different wood-bamboo composite panels whose core is thick bamboo curtain. They considered the panel that produced by thick curtain veneers those with the same thickness as its inlay and horizontal wood veneers as surface, is easy to regulate and control the thickness deviation of the panel. And it also simplifies the process of the production and reduces the quality of resin. Mats in the cladding of mats plywood are hand-woven, and the size of stripe is 8–12 mm in tangential direction and 1.0–1.2 mm in thickness direction. The inlays are hot-pressed by wood veneer which peeled from some good materials, such as Birch and forging. The strength, toughness and anisotropic of panels whose surface is made by mats have greatly improved, and the physical and mechanical strength is better than wood plywood. But the application of the boards which mainly used for packaging material and construction template is narrower than veneer cladding plywood. Guan M.J. et al. (2005) researched bending properties of the wood-bamboo composite plywood that is produced by bamboo surface plates and Poplar plywood. The panels can be used for transport vehicles and architectural templates floor.

The surface properties of both panels are all poor. The veneer plywood with mats as claddings, whose inlays is paved by bamboo mats. Because of the accidented surface, the traits reflect on the plate's surface when the plates were pressed. Researches also studied the surface with coating process or stickers, and mats woven texture still exist though light reflection. On the other side, the surface performances of mats plywood are affected by mats woven texture, which will lead to the poor surface smoothness. Sometimes, resin is lacking between the bamboo mats. Veneer cladding mats plywood has more advantages, because of the features and prospects of application. Yu Y.S. (2005) explored the wood-bamboo composition and the secondary cladding process, for the large thickness tolerance and the poor surface quality, which seriously affect the quality of products. And the results showed: the thickness tolerances, surface quality and the main physical and mechanical properties all meet or exceed the quality requirements of standards of bamboo plywood formwork JG/T156-2004. The recent processing technologies and equipments of plywood could produce Wood-Bamboo composite plywood. But mats are woven mainly by handcraft. Recently, to form a certain production scale, manufacturing broken and weaving equipments is the problem that we need to solve (He C.H., 1991).

## 3 WOOD-BAMBOO COMPOSITE FLOOR

Wood-Bamboo composite floor is a composite board that using bamboo as its surface and fast-growing wood or wood veneer as its inlays. It takes the advantages of the bamboo, such as strength, hardness and unique decorative effect. The physical properties of the wood-bamboo composite floor are so excellent, which owns clean natural appearance, delicate texture, antisepsis and damp proof properties, strong toughness and flexible. So the hardness of the surface can match to the general wooden floor (Zhang X.G. and Bao Y.P., 2002). Wood-Bamboo composite floor owns the benefits those in wood and bamboo floor, while fast-growing timber is a useful resource, which can relieve the tight supply of timber and accelerate implementing the "natural forest protection" project of China. It is extremely important to the reality of social and ecological significance.

Three forms exist in the wood-bamboo composite floor. The characteristics are determined by the structures. A composite panel uses multi-component structure, with peeling bamboo veneer as surface, thick wooden veneer as the center layer and wood veneer as other lays. The structure attribute to stability and unwrapping. Mildew, wool and other shortcomings can be easily prevented by the physical and chemical treatment.

The other panel is veneer bamboo jointing and adhibiting floor. The panel that bamboo jointing in the radial direction as its surface, poplar, Chinese fir and other soft wood veneer as inlays and pine or poplar as its soleplate, is three-lay structure. It has many benefits, such as fine texture, soft color, smoothly, clear grain, unique natural beauty. And the physical and mechanical properties is better than wood. The characteristics as none mildew and wool, wearable, high pressure-resistant and high temperature-resistant are showed after the treatment.

One-sided bamboo cladding bamboo-fir composite floor that is assembled by the width determined Bamboo veneer, Chinese Fir wood veneer sheets and wooden floors, is multi-storey (Yu Z.J., 2002). Bamboo and Chinese fir forests are grown fast, as its raw materials. Bamboo will be processed into width determined veneer and affix in the center as the plate of Chinese Fir, and the back is wood veneer. The structure of bamboo-fir composite floor appears unique texture and elegant, innovative decorative effects. Bamboo has many advantages, such as the dense structure, high strength and rigidity, good surface hardness, wear and impact resistance and so on.

## 4 DEBRIS BAMBOO COMPOSITE PANELS

Debris Bamboo composite panel is one-time bonding compressed panel that is assembled by the spatulate bamboo or wood veneer as its surface plane and back plane, and debris bamboo as inlay. Comparing to the advantages and disadvantages of bamboo plywood and bamboo particleboard, we produce it using softening Bamboo or wood veneer which with high strength, good smoothness as its surface, bamboo residues and trails those are processed into debris as its inlays, on the basis of mechanics principles of composite material structure. The strength, size stability, surface roughness of the panel is easy to the secondary processing, but also improves the utilization of bamboo. The panel can be used for cement template, the bottom and side panels of the compartment.

Debris Bamboo composite panel is developed by Zhang Q.S. who comes form the Nanjing Forestry University. Zhang Q.S. et al. (1995) studied the intermediate test for the debris bamboo composite panel, and concluded that the production technology is feasible. Moreover, the physical and mechanical properties of panels satisfy the requirement of structure material. Plane tensile strength can be greatly enhanced when the resin spread single-side or double-side on the bamboo. Majority of test samples are damaged among the hot-melt iron and plastic bonding surface of the bamboo, while bamboo veneer and debris bamboo own high intensity. Debris Bamboo composite panel can conserve resources and cost. The processes and equipments are improved on the basis of those in bamboo plywood and bamboo particleboard, which can attribute to industrialization production. Liu Z.S. et al. (2001) had done deeper research on the technology and structure of the debris bamboo composite panel. They considered that the key factor that affecting the physical and mechanical properties and the cost of production is the structural design. Pressing technology and pressing time must adjust to the increase of the resin. The structure design and bending properties of debris bamboo composite panel were studied further by Sun F.W. (1999). They concluded that the best structure design is following “stress equal design guidelines”. The strength of levels in composite panel can be equal to the correspond stress. In recent years, with the reinforcement of awareness in environmental protection and recycling industry, many new researches and breakthroughs are turned out. Zhao R.J. et al. (2006) use a variety of ways to cut bamboo, which without cutting debris. So bamboo, wood, lumber and peeling residues such as bark and core wood are processed into different forms, which could be paved into a reasonable structure for composite panel. The wood-bamboo composite panel that with a wood veneer on the surface is resource-saving and high-performance. Wu C.D. (2007) developed the wood-bamboo debris and wood fiber composite panel. According to the three-tier structure, the panel is pressed by wood fiber and bamboo particles with certain specifications and shapes, which are processed by the bamboo residues. These studies have a great effect in improving the utilization of bamboo and exploiting utilization areas. But we need to further explore the methods in realizing industrial production of the panel.

## 5 WOOD-BAMBOO COMPOSITE LAMINATED VENEER LUMBER

Wood-bamboo composite Laminated Veneer Lumber is paved by the Bamboo Curtains and wood veneers which parallel to the veneer texture. It mainly used in rail-car floor whose work conditions are particular bad. The panels have to bear the loads of tanks and heavy engineering machine, but also experience the sun and rain, intense heat and cold. (Xu B., 2002), Therefore, it need reliable mechanical strength, but also fine anti-vibration, wear resistance and decay resistance.

Xu B. et al. (2000) studied the lateral-cut static friction coefficients among Wood-bamboo composite Laminated Veneer Lumber, steel and rubber. And they were compared with the relatively Korean pine static friction coefficient. The results show that the static friction coefficients of this panel are higher than that of Korean pine, and it can be used as train-car floor. It provides a theoretical basis for the lading tests of this panel and understanding the physical and mechanical properties of wood-based panel. Jiang S.X. et al. (2002) design the structural of Wood-bamboo composite Laminated Veneer Lumber and text it on the base of composite mechanics laminated panel theory. The results show that: the panel that using high-density strengthen Bamboo Curtain as surface layer and masson pine veneers as inlay, is pressed by special secondary pressing production process. The panel with fine physics and mechanical properties, which could meet the special requirements of railway flat car floor, such as strength, weather ability, wear-resistance, grip performance. Recently, studies those refer to the group Blank in wood LVL to research Bamboo Strengthened Laminated Veneer Lumber and explore applications in floor, furniture, and the surface panel, engineering and construction structural materials. Wang X.Q. et al. (2005) developed Wood-bamboo composite Laminated Veneer Lumber by Poplar veneer that is impregnated in phenolic resin and Bamboo Curtain, and probed into the effects of properties. The results show that: the MOE and MOR all reached or exceeded relevant regulates in Japanese JAS standards. And the panel owns good dimensional stability. Veneer thickness, resin concentration and panel compression has significant impact on MOR and MOE. Group way also has impact on MOR. And the effect of water thickness swelling is rather complicate.

Some scholars studied Bamboo Strengthened Laminated Veneer Lumber using bamboo as material. It fully uses the features, such as high strength in the bamboo-fiber direction, low density, and compression and so on. It overcomes the defects which attribute to the high hardness and thickness deviation. This panel is an ideal load-bearing structural material, which can enhance the toughness of the panel significantly (Liu J.L., 2006).

Considering the timber characteristics in our country, fast-growing poplar and Chinese fir are used most in the LVL production, so many LVL enterprises only produce non-structural panel. Zhu Y.X. (2005) from Nanjing Forestry University studied the properties of the Laminated Veneer Lumber that adding bamboo as reinforcing material. And they considered the technology can significantly improve the impact toughness. If splits were joined into LVL in the next surface and middle layers, its toughness were increased 30.4% and 27.3%, and the total effect can be increased by 31.7% and 28.1%, respectively. The properties are in line with the requirement of the loading materials.

## 6 OTHER WOOD COMPOSITE PANEL

### 6.1 *Wood-bamboo composite Blockboard*

Wood-bamboo composite Blockboard is using bamboo mats and curtains as surface materials, and wood and bamboo interval with in the core. It was successfully developed and applied patent by The Nanjing Forestry University. The strength is much higher than general blockboard, and the density is less than bamboo gluing template. Therefore, wood-bamboo composite blockboard can be as an alternative to the general blockboard in wood structure materials, especially as the concrete formwork.

### 6.2 *Wood-bamboo composite medium-density fiberboard*

Wood-bamboo composite medium-density fiberboard is using bamboo and wood residues as raw materials. Then, the material was compressed into panels. It will take certain hot-pressing technology because of the differences between bamboo fibers and wood fibers. Song X.J. et al.

(2005) probed into the production process that manufacture bamboo or wood-bamboo composite high-density fiberboard which using bamboo and its Scraps as raw materials, and obtained the suitable production process. They concluded that the properties of the panels reach or exceed the LY/T1611-2003 standard which is for the fiberboard in substrate floor. Matsuda et al. (1995) preliminary studied the relationship between the ratio of mixed fibers and mechanical properties of the panel, and concluded that the properties of the panel produced with an appropriate ratio of mixed fibers are better than the properties of the wood medium-density fiberboard.

Wu Z.K. (2000) from the Southwest Forestry College studied the process conditions of wood-bamboo composite MDF. We can produce a good performance panel under a suitable process. Bending strength, modulus of elasticity and the thickness expansion rate of water absorbing are increasing with the bamboo-wood ratio increases. And it is one of composite products with abroad application prospects.

### 6.3 *Impregnated resin overlaying of radical wood-bamboo composite panel*

Impregnated resin overlaying of radical wood-bamboo composite panel use bamboo curtain that were woven by radial cut bamboo strips as its inlay, and the wood veneer as its surface. The slabs will be sanding to certain thickness after pressing, and overlaying the paper impregnated with phenolic resin on the surfaces (Du C.G., et al., 2003). This panel owns good physical and mechanical properties, high utilization of bamboo, Small deviations thickness and uniform surface color. It is a high-grade concrete formwork.

### 6.4 *Bamboos veneered bamboo-framed laminated veneer lumber*

Bamboo veneered bamboo-framed laminated veneer lumber is using the inside lay of bamboo, which through weaving, spreading adhesive, grouping and pressing into a panel (Zheng Z.F., 1995). It was developed by YongAn forest products processing company. It with fine physical and mechanical properties, and maintains the natural texture of wood, meet the requirements of concrete formwork construction. It can also replace the wood-based board, and can be used in packaging and furniture industries.

### 6.5 *Bamboo veneered oriented strand board*

This panel is pressed by Bamboo and timber flakes which are paved in directional form. Wang S.Q. et al. (1991) probed into the development of bamboo overlaying composite OSB produced by bamboo and Italy poplar. Yin S.Z. et al. (1997) overlaid mats and Bamboo Curtain on the surface of OSB, and considered that the density of this panel is a little higher than the OSB mats, but the mechanical properties is much better than OSB mats. That is to say, the ratio of strength and density is so high. The dimensional stability and other mechanical properties are significantly higher than the OSB mats. So bamboo can be used as cladding material for the enhancement processing.

### 6.6 *Bamboo sandwich plywood*

Bamboo sandwich plywood is a panel that reinforced by the sandwich material as bamboo and bamboo slabs (Sun J.N. et al., 2000). The sandwiched orientation between the panel are 0°/90°, 45°. Study shows: 45° orientation in bamboo plywood owns the best physical and mechanical properties, which can greatly improve the shear strength of the panel. The adhesion force of the panel with jute as sandwich is best, but shear-rigid can not compare to the bamboo when orientation is 45°. The physical and mechanical properties significantly increased when the orientation is 45°. This method can produce other types of bamboo sandwich plywood.

## 6.7 *Bamboo and wood hybrid scrimber*

Though reasonable test design, wood fiber tress which is the cell of scrimber intermix with bamboo tress which is the cell of Bamboo scrimber are made into bamboo and wood hybrid scrimher, which high strength, good toughness and process properties, and all the benefits both in scrimber and Bamboo scrimber, at the base of scrimber and Bamboo scrimber (Zhu Y.X. et al, 2003). Zhu Y.X. et al. (2004) researched the bamboo and wood hybrid scrimher that produced in three different hybrids Structure types with different hybrid ratio of bamboo tress to wood tress. The results showed that specific MOE of bamboo and wood hybrid scrimber is lightly higher than that of scrimber made by poplar, but the specific M0R of bamboo and wood hybrid scrimber is sharply higher than that of the scrimber. The bending properties of bamboo and wood composite scrimber is increased by the ratio of bamboo tress.

# 7 DISCUSSION AND PROSPECT

In China, bamboo panel develops relative late. But the rate of its development keeps a high speed, particularly in the 1990s. In recent years, the progress is little slower than the last years. But the wood-bamboo composite panel suddenly appears and develops rapidly, which also adjust to the characteristics of the development of composite materials. The trait of fast growing of Bamboo provides the resources for the development. And the implementation of "natural forest protection" project provides an opportunity and for a broad space for the development of the wood-bamboo composite panel. In china, various products, small production scale, narrow scope and few relative norms and standards of bamboo composite wood-based panel, which all restrict the promotion and applications of the wood-bamboo composite panel.

## 7.1 *Promoting industrialization of wood-bamboo composite panel and increasing utilization of bamboo*

A great many products of wood-bamboo composite panel exist in china, but only the wood-bamboo plywood, wood-bamboo floor and a small number of varieties can be produced industrially. Because of the repetition functions of other wood-bamboo composite panel, it is very difficult to develop the market prospects, even if the mature technology they have. In China, the production cost of wood-bamboo composite panel is similar, but the utilization of bamboo varies considerably. Relatively, China's bamboo is rich, but generally speaking, its resource is limit for it account for only 4%. Two areas of considerations can be applied to improving the utilization: First, making full use of bamboo processing residues, second, improving the bonding properties of surf green and Shiraia bambusicola. This is also the development direction of wood-bamboo Composite Panel.

## 7.2 *Developing new applications of wood-composite panel*

Developing new applications is a way to improving production scale and products industrialization. Wood-bamboo composite panel mainly for the Concrete Formwork in china and the application in this field has a certain impact. However, it is not a patch on the other panels in wooden structure buildings, train floors, siding, containers, packaging and other areas. While these areas require materials with high properties, so we use good hardwood commonly. With the increasingly tenseness of world timber resources, the cost is much higher. As to the wooden structures and containers industry, 75% floor in containers those in domestic and foreign are all wooden floor. Moreover, more than 70% wood is used in wood structure. Residential Wood structure become popular gradually, it will have great potential and space in china because of the unique properties. (Ren H.Q. et al., 2006). Currently, more than 2,000 residential wood structures have been built in china, and 600 are still in building. Because of running short of timber resource seriously in

China, the development will be restricted if we use wood as a building material simply. Using bamboo composite materials in engineering industry will be a well-established method. The physical and mechanical properties of bamboo composite materials such as bamboo veneered oriented strand board, bamboo strengthened laminated veneer lumber, bamboo and wood hybrid scrimber, long bamboo-wood composite materials et al, is equal or better than other panels'. (Wang C.Y. et al. 2006) generally, it will be wide applied because of the hardness, strength and toughness of bamboo and the advantages of wood. And they all can be used for wood structural construction. In addition, the secondary processing product of wood-bamboo composite panel is less intensive, which restrict its application in furniture industry. The characteristics of density, stiffness and rough processing have brought great difficulties in furniture production. Some wood-bamboo composite panel products could satisfy manufacturing plate furniture and control the low cost, relatively, however, there are few studies in this area. Developing wood-bamboo composite panel application should not be bound to the applications of traditional wood plywood, and it can be with a wider area.

### 7.3 *Perfecting standard system of wood-bamboo composite panel*

The emergence and utilization of wood-Bamboo composite panel products lacks of appropriate standards, so the markets and utilization are confused. Currently, the national standards and industry standards all about the bamboo Panel in china, but the wood-bamboo Composite Panel have not been addressed. The norms and standards have a major affect on promoting market-oriented products. At the same time, we should also make some norms and standards on wood-bamboo composite panel. With the development of wood-bamboo composite panel, perfecting the system of national and industry standards also is a healthy way to develop it.

## REFERENCES


Du C.G.; Zhao R.J.; Jin C.D.; Yang Y.Z. 2003. Study on paper impregnated resin overlaying of radical bamboo-wood composite concrete-form, *Journal of Agricultural Science, Yanbian University*, July–August, pp. 254–258.

Guan M.J.; Zhu Y.X.; Zhang X.D.; et al. 2005. Bending Properties of Wood-bamboo Composite Plywood in Differently Hygrothermal Conditions, *Journal of Nanjing Forestry University (Natural Sciences)*, November–December, pp. 106–108.

He C.H. 1991. Report of wood-bamboo composite plywood Preparation, China Wood Industry, July–August, pp. 50–51.

Jiang S.X.; Zhu Y.X.; Zhang Q.S. 2002. The Structure and Properties of Laminated Bamboo-wood Composite Lumber, *Journal of Nanjing Forestry University (Natural Sciences)*, November–December, pp. 10–112.

Liu J.L. 2006. Study on The Process of Wood-Bamboo Composite Strengthen LVL, *Science and Technology in China*, February, pp. 64–65.

Liu Z.S.; Zhang Q.S.; Zhang Q.L. 2001. Study on Bamboo Particle Composite Board Used as Concrete Shuttering, *China Forest Products Industry*, May–June, pp. 13–15.

Matsuda T. et al. 1995. Manufacture of Medium Density Fiberboard from Malaysian Fast Growing Tree Species and Bamboo, bulletin of the Forestry and Forest Products Research Institute, Ibaraki.

Qiu E.F.; Hong W.; Zheng Y.S. 2001. Review on Diversity and Utilization of Bamboo in China, *Journal of Bamboo Research*, April–June, pp. 11–14.

Ren H.Q.; Zhou H.B.; Fei B.H.; et al. 2006. Opportunity and challenge on development of modern wood frame house in china, *Wood Processing Machinery*, January–February, pp. 28–31.

Song X.J.; Ye Z.H.; Liu X.H.; et al. 2005. Study on manufacturing technology of bamboo-wood HDF, *China Forestry Science and Technology*, November–December, pp. 39–41.

Sun J.N; Jin D.Z. 2000. Study on the Physical Properties of Plywood Sandwiched with Jute and Bamboo, *Forestry Science & Technology*, January–February, pp. 51–63.

Sun F.W. 1999. The Prediction Theories of Structure Design and Bending Properties for Bamboo Particle Composite Board, *Journal of Nanjing Forestry University*, May–June, pp. 45–50.

Wang C.Y.; Yang W.B.; Chen G. 2006. The processing of the long bamboo-wood composite materials, using method of the cold-hot-cold press, *Journal of Fujian College of Forestry*, May–June, pp. 197–201.
Wang X.Q.; Guo L.; Liu J.L. 2005. Processing Technology of Strengthened Bamboo/ Wood Composite LVL, *China Wood Industry*, September, pp. 7–9.
Wang S.Q.; Hua Y.K.; Dong S.Q., 1991. A study on the strength of composite OSB made from bamboo & wood, *China Wood Industry*. July–August, pp. 6–10.
Wu Z.K.; Zhang H.J.; Huang S.Y.; Yuan Y.S. 2000. Effects of Manufacturing Technology on Properties of MDF from Bamboo and Wood, *China Wood Industry*, May–June, pp. 7–10.
Wu C.D.; Han J.; Liu M.B. 2004. Study on bamboo/wood composite board, *Wood Processing Machinery*, July–August, pp. 22–25.
Xu B.; Jiang X.S. 2002. Bamboo composite wood stripes stratification coefficient of static friction, *China Forestry Science and Technology*, November–December, pp. 22–23.
Yu Z.J. 2002. develops on bamboo-Chinesefir composite floor, *China Forestry Science and Technology,* November–December, pp. 39–40.
Yu Y.S. 2005. A Study on the Technology of Secondary Veneer Overlaying for Bamboo-Wood Composite Plywood. *Forestry Science and Technology*, November–December, pp. 40–42.
Yu Y.S.; Tang Z.R.; Wang J.X.; et al. 2002. Investigating bamboo curtain plywood of core and Bamboo-wood composite, *Hunan Forestry Science & Technology*, September, pp. 37–39.
Yin S.Z.; Li B.G.; Hu D.B. 1997. Study on the Properties of Oriented Strand boards Overlaid with Bamboo Sheets, *China Wood Industry*, July–August, pp. 8–11.
Zhao R.J.; Yu Y.S. 2002. Bamboo Panel Technology. Beijing: China Forestry Press.
Zhang X.G.; Bao Y.P. 2002. Research for bamboo with wood parquet, *Wood Processing Machinery*, September–October, pp. 29–32.
Zhang Q.S.; Sun F.W.; Wang J.H. 1995. A study on the structure and technology of bamboo composite board, *Scientia silvae sinice,* November–December, pp. 53–54 .
Zheng Z.F. 1995. Study on the production Process of bamboo veneered bamboo-framed LVL, *Building Artificial Boards*, January, pp. 13–15.
Zhu Y.X.; Guan M.; Zhang X.D. 2005. Studies on Impact Performance of Bamboo Strengthened Laminated Veneer Lumber of Poplar, *Journal of Nanjing Forestry University (Natural Sciences)*, November–December, pp. 99–102.
Zhu Y.X.; Rao W.B.; Guan M.J.; et al. 2003. Future and develop of Bamboo and Wood Hybrid Scrimber, *China Forestry Science and Technology*, November–December, pp. 6–7.
Zhu Y.X.; Guan M.J.; Rao W.B.; et al. 2004. Research on Bending Properties of Bamboo and Wood Hybrid Scrimber, *Journal of Nanjing Forestry University (Natural Sciences)*, July–August, pp. 59–61.

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# Experimental study of mechanical behavior of bamboo-steel composite floor slabs

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ABSTRACT: In order to widen the applied range of bamboo and implement the diversification of component materials and forms in building structures, this paper forwards a new kind of bamboo-based composite slabs, which sticks bamboo plywood and profiled steel sheet together into bamboo-steel composite floor slabs by structural glue, and takes a series of experimental studies on the new kind of composite slabs. Taking thickness of the bamboo plywood and profiled steel in the core and the span of slabs as parameters, mechanical properties are tested on 6 pieces of the composite slabs. The results of experiments indicate that the service behavior as a whole of the bamboo-steel slabs is fine; there is excellent composite effect between bamboo plywood and profiled steel sheet to provide upper bearing capacity and stiffness; the mechanical properties of the composite slabs can meet the requirement of building floor slabs.

## 1 INTRODUCTION

Bamboo is rich around the world and it grows fast belonging to the short period renewable resources (Ian R. 2001), which can be utilized in three or four years, therefore it is enormously worthy of exploitation. With the development of science and technology and wide application of rapid propagation technology of bamboo, the output of bamboo per elemental area is fold increased. The exploitation of bamboo and its product involves the fields of human everyday life, construction, traffic etc (Wang et al. 2000).

Bamboo has pretty good mechanical properties, which is being looked upon as the most efficient material in the nature in terms of strength and cost. The tensile strength of bamboo is about twice times as high as that of lumber, the compressive strength is about 1.5 times and the strength to weight ratio of bamboo is higher than that of lumber and plain steel. Therefore, bamboo processes super performances as an engineering material. If bamboo can be exploited as a kind of rational structural material, the applied range of bamboo is widened and it is an efficient path to use the plentiful bamboo resources. In the area of modern construction, bamboo is limited to and just used as construction formwork and interior decoration in the field of building and is not applied to the area of engineering structures. Based on the excellent mechanical performances of bamboo, obeying principles of saving materials and structural rationality, this paper puts forward a new kind of bamboo composite slabs, which sticks bamboo plywood and profiled steel sheet together into bamboo-steel composite floor slabs by structural glue, and takes a series of experimental studies on the mechanical properties of the new kind of composite slabs to discuss the feasibility of its application in the field of building structures.

## 2 BAMBOO-BASED PANELS AND BAMBOO-STEEL COMPOSITE SLABS

*Bamboo-based panels:* Since bamboo is a hollow cylinder with small diameter, it can not meet the requirement of modern engineering structures from shape to function. If bamboo is used as structural component, the crude bamboo has to be modified into board and sectional material, which adapt to the modern engineering structures. Currently the main modified bamboo product which can be used as structural components is bamboo-based panels. Bamboo-based panels are made from bamboo and its scrap stock, which is processed by physicochemical treatment and mechanical cutting into different kinds of components that have varied geometrical shapes and then adhered and hot pressed into panels. Bamboo-based panels can be classified into the following types (Zhao et al. 2001; Li et al. 2000; Tang 1997).

Bamboo mat board: After the procedure of spitting bamboos into thin slivers, the slivers are weaved into bamboo mat (Figure 1) through manual work or machines. After dried, mats are gelatinized or dipped into adhesives and hotly pressed into a board that is composed of several layer mats.

Bamboo curtain board: Bamboo is spitted into thin slivers with about 1~3 mm thickness and 10~15 width and the slivers are weaved by cotton thread, twine or mixture yarn into bamboo curtain (Figure 2). After dried, curtains are gelatinized or dipped into adhesives, and then hotly pressed into a board with crisscross assembly of curtains.

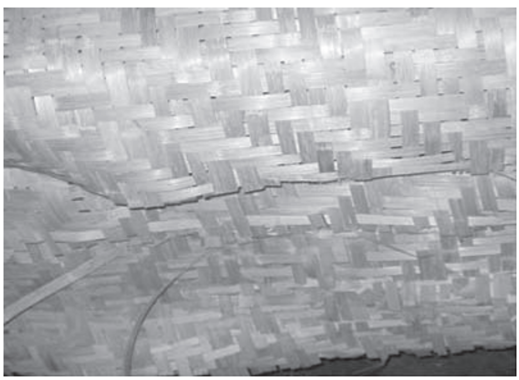

Figure 1. Bamboo mat.

Figure 2. Bamboo curtain.

Bamboo mat and curtain board: As shown in Figure 3, taking bamboo mats as the surface and crisscross assembly of bamboo curtains as the core, after dried, dipped into adhesives, assembled and hotly pressed, bamboo mat and curtain board is made up, which develops fastest and is used widest among all kinds of bamboo-based panels in China. Many bamboo-based panel factories make bamboo mat and curtain board.

Bamboo laminated board: Split bamboo into thin slivers, then dip these slivers into adhesives without weaved. Dry them until they have a certain water ratio and assemble these slivers in the same direction (Figure 4), then hotly press the assembly into the bamboo laminated board. Because of slivers assembled in the same direction, the strength and rigidity are high in that direction.

Plybamboo: Bamboo culm is firstly softened and flattened into pieces with the width of 60–120 mm, after then the pieces are laid up and hot pressed to make plybamboo according to plywood procedure.

Bamboo particle board: Bamboo particle board is made from small bamboo culms, top parts of moso bamboo, irregular culms, and processing residues according to the principle of wood particleboard.

Bamboo composite board: The kind of bamboo-based panel, taking bamboo as a major kind of raw materials, and assembling two or more than two kinds of materials into one board by using synthetic resin or other adhesives and through particular processing technology is called bamboo

Figure 3. Woven mat and curtain board.

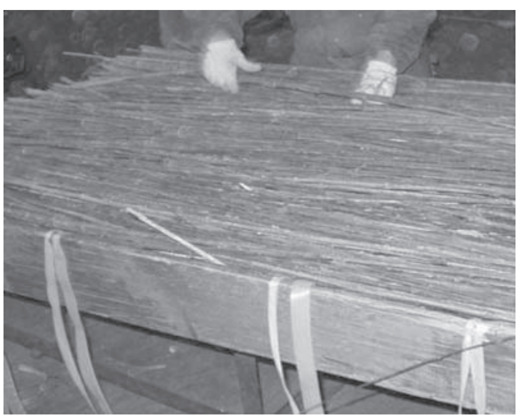

Figure 4. Assemble method of laminated bamboo board.

composite board. There are many kinds of bamboo composite board such as intensive covering bamboo board, bamboo particle composite board, bamboo-wood composite board.

Bamboo-based panels are mainly used as making furniture, interior decoration, construction formwork, the platform floor of truck and the floor of bus. So far, it is limited to and just used as construction formwork in the field of building and is not applied in the area of engineering structures. However, bamboo can be processed into beams, columns, slabs, walls and other structural components because of its excellent mechanical properties. In the products mentioned above, the mechanical properties of plybamboo and bamboo laminated board are more excellent and they are prone to commercial process. These kinds of bamboo-based panels can be used as structural materials. The small diameter moso bamboos or other kinds of bamboos with diameter 5~6 cm or above can be used as the raw materials of bamboo laminated board, so raw materials are rich. The bamboo laminated board fits to be used in the unidirectional weighted components because of the high strength in the longitudinal direction.

*Bamboo-steel composite floor slab:* So far, Bamboo-based panels are the main products of modified bamboo products, with about 20 mm thickness, which cannot be used in long span structures. And the panels with great thickness cannot be produced easily due to the manufacturing technique and the components of solid section cannot make full use of high strength of bamboo. Now, the technique of produce bamboo-based panels becomes mature, and the bamboo composite components made from thin bamboo-based panels can reduce the weight and the raw materials of the components.

The bamboo-steel composite floor slab is composed by two pieces of bamboo-based panel and one piece of profiled steel sheet in the center adhered by high strength structural adhesives (Figure 5, Figure 6). The slab has cavity which can be filled by benzene particle or other insulation materials and can be traversed by wires or other pipelines. Bamboo-based panel has high strength, which can not be made full use of its strength with solid section. Because the bamboo-based

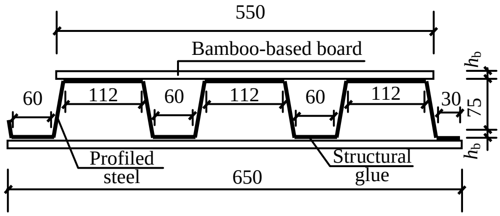


Figure 5. Section of composite slab.

Figure 6. Specimens of bamboo-steel composite slab.

panel and the profiled steel can work cooperatively by adhered together and it has enough bearing capacity and stiffness to span long distance, the bamboo-steel composite floor slab reduces the raw materials needed and the weight of components. The profiled steel sheet is in the center, covered by two pieces of bamboo plywood top and bottom and the bamboo texture can meet the requirements for the comfort of inhabitation. If the surface is wrapped round with metal skin, the surface flatness of the component can be improved and the inside bamboo plywood can avoid be affected by moisture, damaged by insects, and can avoid ageing. However, some experiments indicate that the metal skin will conceal a fault inside (Zhang et al. 2000). The properties of bamboo plywood such as flame retardance, inoxidizability, insect prevention, insulation, decoration, etc, can meet the operating requirements, therefore, the bamboo-steel composite floor slab with the profiled steel sheet inside, which can be used in structures and decoration projects, has excellent application perspective in construction and market development value.

## 3 EXPERIMENT

### 3.1 *Design and manufacture of specimens*

Mechanical properties were tested on 6 pieces of the composite slabs (Table 1). Bamboo curtain board was used in the composite slabs with perpendicular layers on the top and the bottom and parallel layers in the core, which was produced in a professional factory. The profiled steel sheet in the core was 7520 which thickness was 0.7~0.8 mm, and the height of the flank was 75 mm. The profiled steel sheets were also ordered in a professional factory. The bamboo curtain board and the profiled steel sheet were stuck by high strength structural adhesives. The spans of the composite slabs were 3.0 m and 3.6 m.

When the bamboo-steel composite floor slabs were made, firstly, the zinc coating on the profiled steel sheet were removed by wire brush, then the sheet was polished by flat grinding wheel till the mental luster appears and grains well distributed on the surface of the steel sheet, at last the surfaces were cleaned by absorbent cotton with acetone. The facing of bamboo plywood was polished by sand-paper and cleaned by absorbent cotton with acetone. When the structural adhesive was being confected, the main agent and the firming agent were poured into a clean container pro rata, stirred till the color and luster totally homogeneous. After the process, the structural adhesive was laid on the steel sheet evenly with 250~300 g/m$^2$. The surface of the adhesive should be leveled, and the layer should not be too thick. After gelatinized, the bamboo plywood and the profiled steel sheet should be superimposed, position fixed, solidified by pressure. Load was put on the composite slab, which was kept for 2 days, and the time for solidified was 7 days.

Table 1. Test specimens.

| NO | Thickness of bamboo plywood (mm) | Thickness of steel sheet (mm) | Height of composite slab (mm) | Span (m) | MOR of bamboo plywood (N/mm$^2$) | MOE of bamboo plywood (N/mm$^2$) | The maximum deflection in the mid-span (mm) | The ultimate load (uniform load) (kN/m$^2$) |
|---|---|---|---|---|---|---|---|---|
| B-1 | 9 | 0.8 | 93 | 3.6 | 76.7 | 7098 | 39.72 | 7.96 |
| B-2 | 11 | 0.8 | 97 | 3.6 | 82.8 | 7272 | 37.58 | 9.37 |
| B-3 | 5.2 | 0.7 | 85.4 | 3.0 | 66.6 | 5904 | 22.51 | 6.64 |
| B-4 | 6.2 | 0.7 | 87.4 | 3.0 | 81.2 | 6632 | 16.1 | 6.24 |
| B-5 | 7.6 | 0.75 | 90.2 | 3.0 | 91.0 | 8481 | 26.97 | 13.33 |
| B-6 | 8.9 | 0.75 | 92.8 | 3.0 | 127.3 | 11766 | 29.71 | 15.51 |

The strength grade of the profiled steel sheet was Q235, and the experimental values of MOR and MOE of bamboo plywood had comparatively great discreteness, as shown in the Table 1. Figure 5 is the section of the composite slab and Figure 6 is the picture of specimens of the bamboo-steel composite floor slab.

### 3.2 *Loading and measuring*

B-1 and B-2 were loaded by sandbags uniformly and B-3~B-6 were loaded by jack with 4 concentrated forces and 8 points of division in order to imitate uniform load. Figure 7 is the picture of jack loading setup. Incremental loading was adopted in the experiment.

In order to measure strains of bamboo, strain gauges were affixed longitudinally on the outside and inside of the bamboo plywood at the midspan of the composite slab. In order to measure strains of the profiled steel sheet in the core, stain gauges were affixed on the top and bottom of the crest slab and the flank. The specific positions are shown in the Figure 8.

Two displacement meters were fixed at the section of the midspan in order to measure the deflection accurately and one displacement meter was fixed at each end to measure the deflection of the supports.

Strain data was collected by data acquisition system installed in the computer and the displacement meters were read manually.

### 3.3 *Destroying process and characters*

The composite slabs deformed vertically under the load and the load-deflection relationship kept elastic in a relatively large range. With the increment of the deformation, the local layer of weakness between the bamboo plywood and the steel sheet began being destroyed and the sound of adhesive failure could be heard. Taking B-2 as an example, when the load was increased to

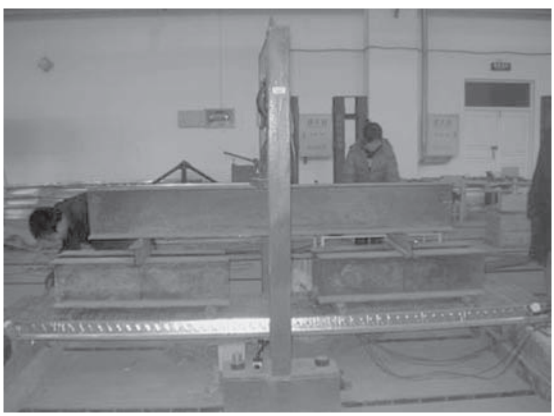

Figure 7. Loading setup.

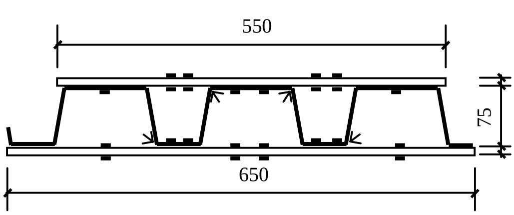


Figure 8. Arrangement of strain gauges.

6.3 kN/m$^2$, a weak sound of adhesive failure could be heard and the deflection at the midspan was 26.18 mm; when the load was increased to 7.04 kN/m$^2$, the sound of adhesive failure could be heard twice continuously. From then on, the sound of adhesive failure could be heard in beginning of every stage of loading and disappears after the load and the deformation became stable. When the load was increased to 8.18 kN/m$^2$, the sound of adhesive failure became loud and continuous, some local damages happened at the interface of the adhesive, which can be seen on the lateral face of the composite slab (Figure 9).

When there were many local damages happening at the lateral face of the steel sheet (Figure 10), the load was increased to 9.53 kN/m$^2$ which was defined as the ultimate load. From the observation and analysis on the destroying experiment of bamboo-steel composite floor slab, with the incremental load, the vertical deflection grows; when the deflection is too large, the adhesive layer is gradually destroyed, bamboo plywood separates with the steel sheet and they can not work cooperatively well. The separation makes the steel sheet flexural buckling under the load.

Finally, due to the flexural buckling of the steel sheet in the core after separated with the bamboo plywood, the whole slab is destroyed.

Figure 9. Damage of glue interface.

Figure 10. Buckling of profiled steel sheet.

When the specimens were loaded by jack, the slabs bore concentrated forces. Because there was no pressure from the weight, the separation between the bamboo plywood and the steel sheet was heavier than that in the specimens loaded by sandbags. In the experiments of B-3~ B-6, all the composite slabs were destroyed due to the local buckling of the steel sheet caused by the separation between the top bamboo plywood and the profiled steel sheet at the midspan (Figure 11 and Figure 12).

### 3.4 *Analysis on the experimental results*

The load versus mid-span deflection curves are shown in Figure 13, from which, during the stage of loading, the relationship of the load versus deflection is linear, and almost does not show nonlinearity. There are inflexions in the curves generally, which show that the rigidities of the composite slabs change slightly, but it is quit different when the inflexions show up. The ones of B-1 and B-2 show up later than others due to the different loading styles. The inflexion means the layer of adhesive is damaged. B-1 and B-2 were loaded by sandbags, and the top of the composite slab was pressed by the sandbags, which can restrain the trend of coming unglued between the bamboo

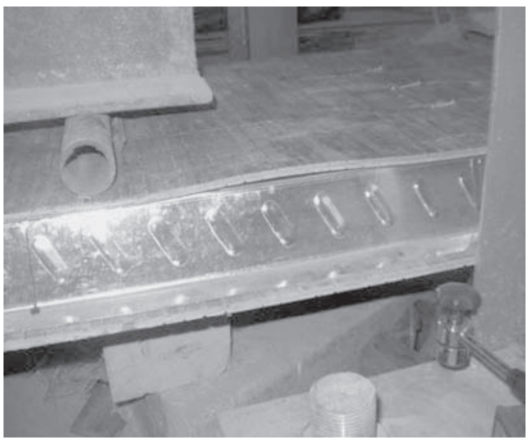

Figure 11. Damage of glue interface.

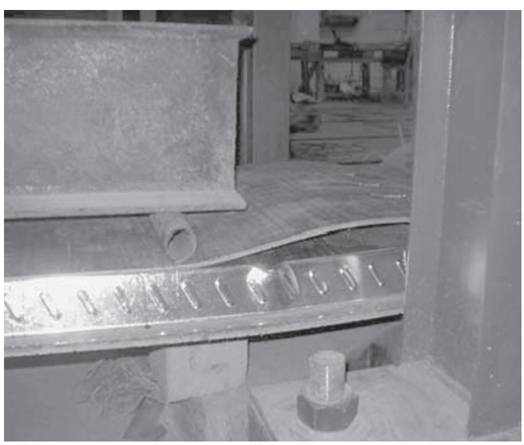

Figure 12. Buckling of profiled steel sheet in midspan.

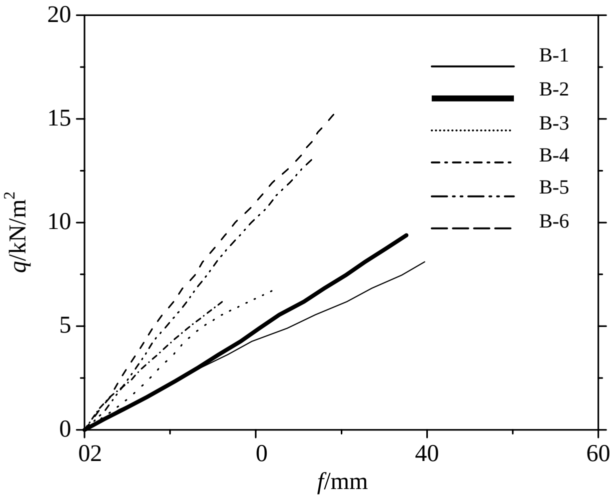


Figure 13. Load vs. mid-span deflection curves.

plywood and the steel sheet. Other slabs were loaded by four concentrated forces, and there was no pressure on the top of the composite slabs, therefore the trend of damage in the layer of adhesive could not be controlled and it showed up earlier. Apart from the loading style, the damage in the glue layer is related to the quality of structural adhesive and gelatinizing. Because new batch adhesive was used when specimen B-4 manufactured, whose ductibility was not good, the quality of gelatinizing was not ideal. The damage in the specimen happened earlier and the load bearing was lower than that of B-3 whose thickness of bamboo plywood is thinner. In the experiments after that, the structural adhesive was changed after communicating with the factory, the qualities of gelatinizing were guaranteed.

From the observation of the experiments of 6 specimens and the analysis on the results, when the load and the deflection are large, the weak layer of the adhesive is damaged firstly, which affect the rigidities of the composite slabs which are reduced. But the reduction is not large and can be limited for a long time. The reason why the composite slabs are damaged is the buckling of the steel sheet in the core after separated with the bamboo plywood. When the slabs are damaged, the top and the bottom of the steel sheets yield, while the flank does not yield. From the results of the experiments, the composite slabs have high ultimate bearing capacity and large deformation ability, which can meet the requirements as the structural components.

## 4 CONCLUSIONS

The following conclusions can be gotten from the experimental study of 6 pieces bamboo-steel composite floor slabs.

1. It is feasible to make the composite slab by sticking two pieces of bamboo plywood on the surface and one piece of profiled steel sheet in the core by high strength structural adhesive. The bamboo plywood and the steel sheet can work cooperatively well during the loading.
2. The composite slabs show elastic characters under the load, especially the deformation during the serviceability state. Therefore the deflection can be calculated by taking the slabs wholly as ideal elastic materials.
3. The qualities of the adhesive and gelatinizing at the layer of glue affect the flexural capacity of the composite slabs very much, and reliable qualities can guarantee higher flexural capacity.

4. The process of damage on the composite slabs is that with the load growing, the layer of the adhesive is damaged and the bamboo plywood and the steel sheet separate with each other due to the large deflection, then the whole slab is destroyed because of the buckling at the steel sheet. When the slab damaged, the top and the bottom of the steel sheet are yield, while the frank are not.
5. The results of the experiments indicate that the bamboo-steel composite floor slab has high bearing capacity and rigidity and can meet the requirements as the building floor.

According the results of the experiments, some suggestions are proposed:

1. The strength and the elastic modulus of the bamboo plywood used in the experiments are discrete. In order to be used as the structural components, the quality of the bamboo plywood should be guaranteed to provide reliable support on the theoretical calculation.
2. The elastic module of the bamboo plywood is about 1/20 of that of steel. When the two material deformation harmoniously, the stresses in them are quit different. When the steel yield, the stress of bamboo is rather small, which will affect the full use of the strength of bamboo. Therefore the processing technic should be improved to look for the method of increase the elastic modulus of the bamboo plywood, for example, invent the new adhesive stuffing improving the mechanical properties, which can make full use of the strength of the bamboo.
3. Bamboo plywood and the profiled steel sheet can work cooperatively together because of the adhesive layers between them. Once they are damaged, the composite effect will disappear gradually and the rigidity of the slab is reduced. Therefore the qualities of the adhesive and gelatinizing should be guaranteed, and setting studs in the composite slab should be taken into consideration which can increase the ultimate bearing capacity and the rigidity of the slab after the adhesive layer damaged locally. Meanwhile, for the composite slabs, the limit state is controlled by the deformation, therefore the slabs without studs can meet the requirements of structural components.

## REFERENCES


Hunter I.R. 2001. Bamboo—solution to problems, *Journal of Bamboo and Rattan*, April, pp. 101–107.

Li Q.; Hua X.Q.; Xu X.W.; and Fu Q.T. 2000. Status of Development of Artificial Bamboo Board and Its Research Direction, *Journal of Zhejiang Forestry Science and Technology*, July, pp. 79–85.

Tang Y.Y. 1997. The Industrial Development and Utilization of Bamboo Timber Resources in China, *Journal of Bamboo Research*, April, pp. 26–33.

Wang K.H.; Li Q.; and Gao X.H. 2000. Present Utilizational Situation and Deep Exploitation of Bamboo Resources. *Journal of Bamboo Research*, October, pp. 72–75.

Zhao R.J.; and Yu Y.S., 2002. Technology of Bamboo-Based Panels, China Forestry Press.

Zhang J.Y.; Yu T.X.; Kim J.K.; and Sui G.X. 2000. Static Indentation and Impact Behaviour of Reformed Bamboo/Aluminium Laminated Composites, *Composite Structures*, Feb, pp. 207–216.

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# Chemical composition analysis of hybrid bamboo

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ABSTRACT: The objective of this study was to determine the chemical properties of (*B.Pervaribilis* × *D.Latiflorus*) No.7 with some transformations of Chinese fibrous raw material national standards for understanding its chemical composition and inherited characteristics. In this paper, the chemical compositions of two years old bamboo culms, including holocellulose, acid-insoluble lignin, 1% NaOH solubility, benzene-ethanol extractives and ash content, were tested. The test results were also compared with those of female bamboo *Bambusa pervariabilis* McClure and male bamboo *Dendrocalamus Latiflorus* Munro that are commonly planted and utilized in pulp industry in China. This study indicated that there were significant differences of selected chemical compositions between inner part and outer part of bamboo culm but no obvious variation among (*B.Pervaribilis* × *D.Latiflorus*) No.7 culms. The comparison of average culm height, diameter at breast height and chemical composition indicated that (*B.Pervaribilis* × *D.Latiflorus*) No.7 showed its individual stability and good inherited characteristics of female and male bamboo.

## 1 INTRODUCTION

The main purpose of biotechnology application in Bamboo cultivation is genetic improvement of bamboo species (Chen, Y.Y and et al., 2005). (*B.Pervaribilis* × *D.Latiflorus*) No.7 is a Hybrid bamboo species, the female bamboo is *Bambusa pervariabilis* McClure (*B. pervariabilis* McClure), and male bamboo is *Dendrocalamus Latiflorus* Munro (*B. Latiflorus* Munro). Well adaptability was observed in Hainan, Guangxi, Guangzhou province in China and found growing in clump, straight culm and high production. This hybrid bamboo can tolerate –3°, namely, it was stronger low temperature resistibility than the male bamboo *B. Latiflorus* Munro. The end use of the hybrid bamboo was considered to be pulp industry materials and edible shoots. It was reported that if this hybrid bamboo was planted for Shoots and bamboo culm double usages forest, 6000–15000 kg bamboo shoots and 2000 culms can be harvested per hectare each year.

Bamboo culm is a major raw material of paper making industry for fast growth, low cost and high-yielding pulp in China. Chemical composition is one of the most important properties of bamboo culm for pulp industry since cellulose content is positively related to pulp yield and lignin and extractives are correlated with alkali-consumption in pulping processing. Many reports on chemical composition of bamboo culm are available (Fengel, 1984; Su, 2005; Wang, 2001; Zhang, 2002; Hui, 1994), however, little is know about this hybrid bamboo. In this paper, the chemical properties, including holocellulose, acid-insoluble lignin, 1% NaOH solubility, benzene-ethanol extractives and ash content, were determined to know its chemical composition and understand its characteristics by comparing with its female and male bamboo.

## 2 MATERIALS AND METHODS

### 2.1 *Materials*

Sound culms with similar diameter at breast height (DBH) were collected as samples from Hua'an County, Fujian province, which were signed in the north direction on each sample with

Table 1. Detail information of (*B.Pervaribilis* × *D.Latiflorus*) No.7 and its female and male bamboo.

| Species | Average height (m) | Average DBH (cm) | MC (%) |
|---|---|---|---|
| (B.Pervaribilis × D.Latiflorus) No.7 | 12.3 | 8.26 | 186% |
| *B. pervariabilis* McClure | 8~10 | 4~5 | — |
| *B. Latiflorus* Munro | 15~20 | 8~20 | — |

numbers. Some culms data, such as height and DBH, were also recorded. Samples with the size of 10 mm × 5 mm × *t* (*t* means the culm wall thickness) were cut from bottom position each culm, which were used to test the moisture content (MC) in green culms. Detail information of (B.P × D.F) No. 7 and female bamboo (Wei, 1998) and male bamboo (Liu and et al., 2005) can be seen in Table 1.

### 2.2 *Sample preparation*

Three culms were selected for chemical composition analysis. Each culm was divided into three positions (bottom, middle and top) along height of culm, bottom position was determined in this study. Internodes of each position were cut into about 5 cm cirques as nodes weren't analyzed. Cirques were divided into two parts (inner and outer) along radial direction of culm wall, and every part was cut into strands (about 50 mm × 2 mm × 2 mm) for milling by Wiley mill. Then, particles (40–60 mesh, moisture content is about 4%–6%) of about 50 g were stored in air-tight containers for chemical analysis.

### 2.3 *Experimental methods*

The chemical compositions were determined with some transformations of fibrous raw material standards. The standards in the test are as follows: Determination of Moisture Content Standard of Fibrous Raw Material (GB/T 2677.2 - 1993). Determination of Holocellulose Standard of Fibrous Raw Material (GB/T 2677.10 - 1993), with some transformation of this standard: sodium chlorite used is industry sodium chlorite with 69.77%, so add 0.86 g industrial sodium chlorite each time and repeat for 5 times. Determination of Acid-insoluble Lignin Standard of Fibrous Raw Material (GB/T 2677.8 -1993). Solubility extractives of 1% NaOH: Determination of 1% Sodium Hydroxide Solubility Standard of Fibrous Raw Material (GB/T 2677.5 - 1993). Benzene-ethanol extractives: Determination of Solvent Extractives Standard of Fibrous Raw Material (GB/T 2677.6 -1994). Determination of Ash Standard of Fibrous Raw Material (GB/T 2677.3 - 1993), with some transformation of this standard: due to magnesium peracetic acid - ethanol solution of 5 mL could not imbue bamboo sample of 2 g, in this test, magnesium peracetic acid—ethanol solution of 10 mL was used. Place crucible with samples on electric oven until all the carbon was eliminated, then put the crucible in the muffle furnace with (475 ± 5)ºC for 5 hours or 6 hours, respectively for inner part or outer part.

## 3 RESULTS AND DISCUSSIONS

### 3.1 *Chemical composition of (B.Pervaribilis × D.Latiflorus) No.7*

Table 1 lists the chemical components of (B.P × D.F) No.7. The results of each test have been evaluated by analysis of variance. The *F* values obtained from analysis of variance among bamboo culms summarized in Table 3 and from analysis of variance between inner part and outer part of bamboo culm were shown in Table 4.

Table 2. Chemical composition contents of (*B.Pervaribilis* × *D.Latiflorus*) No.7 in different positions.

| No. | Position | Holocellulose (%) | Acid-insoluble lignin (%) | 1%NaOH solubility (%) | Benzene-ethanol extractives (%) | Ash (%) |
|---|---|---|---|---|---|---|
| 1 | | 64.3 | 20.5 | 27.91 | 4.38 | 2.09 |
| 2 | Inner part | 67.61 | 20.15 | 29.18 | 3.52 | 3.46 |
| 3 | | 59.30 | 19.08 | 35.74 | 2.53 | 3.52 |
| Average | | 63.74 | 19.91 | 30.94 | 3.48 | 3.02 |
| SD | | 4.18 | 0.74 | 4.20 | 0.93 | 0.81 |
| 1 | | 73.42 | 24.96 | 16.45 | 1.58 | 0.97 |
| 2 | Outer part | 73.16 | 23.03 | 17.68 | 2.35 | 1.52 |
| 3 | | 69.21 | 24.57 | 19.63 | 2.61 | 1.58 |
| Average | | 71.93 | 24.19 | 17.92 | 2.18 | 1.36 |
| SD | | 2.36 | 1.02 | 1.6 | 0.53 | 0.34 |

*SD-standard deviation.

Table 3. Summary of analysis of variance among bamboo culms.

| | Holocellulose | Acid-insoluble lignin | 1% NaOH solubility | Benzene-ethanol extractives | Ash |
|---|---|---|---|---|---|
| F values | 2.875 NS | 0.406 NS | 0.956 NS | 0.103 NS | 2.245 NS |

*$\alpha$ 0.05(2,15) = 3.682; NS Nonsignificant; **significant at the 0.05 level; ***significant at the 0.01 level.

Table 4. Summary of analysis of variance between inner part and outer part of bamboo culm.

| | Holocellulose | Acid-insoluble lignin | 1% NaOH solubility | Benzene-ethanol extractives | Ash |
|---|---|---|---|---|---|
| *F* values | **21.789 | **121.008 | **62.745 | *6.285 | **27.025 |

As indicated in Table 3, differences in chemical components among culms were not significant, as expected before the study was initiated. Nonsignificant variation indicated that cultivation mode was proper to this hybrid bamboo and this bamboo inherited the good charicteristics from its female and male bamboo.

Significant differences between inner part and outer part of bamboo culm were shown in Table 4, the results of statistic analysis were similar to female bamboo (Zhou, 1991), which indicated that the hybrid bamboo keeped the character of its female bamboo. As shown in Table 3, holocellulose and acid-insolubility lignin contents in outer part were more than in inner part, but outer part contained lower extractives, including 1% NaOH solubility and benzene-ethanol extractives, and ash content. From culm anatomy structure, it was clear that most part of fibers distributed around vascular bundle and the number of vascular bundle in unit area in outer part was more than in inner part (Liese and Weiner, 1996), higher holocellulose content in outer part can be speculated, which associated with the test results. From manufacture of view, the significant differences between inner part and outer part of bamboo culm would be make bamboo processing more complicated.

Table 5. Comparison of chemical composition content between species.

| Species | Cellulose (%) | Acid-insoluble lignin (%) | 1% NaOH solubility (%) | Benzene-ethanol extractives (%) | Ash (%) |
|---|---|---|---|---|---|
| (*B.Pervaribilis* × *D.Latiflorus*) No.7 | 67.83 | 22.05 | 24.43 | 2.83 | 2.19 |
| Female | 52.14 | 23.63 | 29.12 | - | 2.28 |
| Male | 44.59 | 21.03 | 31.25 | 8.29 | 1.29 |

Cellulose of female and male bamboo is nitric acid-alcohol cellulose. Chemical composition data of female bamboo from Zhou (1991), and male bamboo from Lin (2000).

### 3.2 *Comparison between (B.Pervaribilis × D.Latiflorus) No.7 and its female and male bamboo*

Average height and DBH were main estimation characteristics of bamboo species from bamboo processing of view. As shown in Table 1, (*B.Pervaribilis* × *D.Latiflorus*) No.7 inherited the good characteristics from its female and male bamboo that the average height and DBH of (*B.Pervaribilis* × *D.Latiflorus*) No.7 are between female bamboo and male bamboo.

1% NaOH solubility (24.43%) and benzene-ethanol extractives (2.83%) were lower than those of female and male bamboo. Lower 1% NaOH solubility would reduce alkali-consumption in alkali pulping process if this bamboo would be used in pulping and paper making. There was no significant difference in acid-insolubility lignin content, although the content of (*B.Pervaribilis* × *D.Latiflorus*) No.7 was between female and male bamboo. It was difficult to compare holocellulose content for data deficiency, it would be important to study this hybrid bamboo and its female and male bamboo together in the coming studying.

## 4 CONCLUSION

Selected chemical compositions of (*B.Pervaribilis* × *D.Latiflorus*) No.7 have been analyzed. Significant variation of chemical composition between inner part and outer part was one of character of (*B.Pervaribilis* × *D.Latiflorus*) No.7 bamboo culm, such difference couldn't be regard as good or bad feature for different properties associating with different end use.

Results of analysis of variance of chemical composition indicated that there were no significant differences among bamboo culms, which was the expected result of genetic improvement. The compared analysis of chemical composition and growing situation among this hybrid and its female and male bamboo also suggested that this hybrid bamboo inherited the advantages of its father and mother.


## ACKNOWLEDGMENTS

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## REFERENCES


Chen, Y.Y; Zhong, Y.; and Li, D.Z. 2005. Statistical Analysis on Adaptive Evolution of SQUA Genes in Angiosperms, Progress in Natural Science, 15(1), pp. 93–96.

Fengel, D.; and Shao, X. 1984. A Chemical and Ultrastructural Study of the Bamboo Species *Phyllostachys makinoi* Hay, Wood Sci. Technol, 18, pp. 103–112.

Su, W.H.; and Gu, X.P. 2005. Study on Chemical Compositions of *Bambusa wenchouensis*, Journal of Zhejiang Forestry College, 22(2), pp. 180–183.

Wang, Z.H. 2001. The Research on Variability in Bamboo Timber Properties and its Influence on Bamboo Processing, (Dissertation). Beijing: Chinese Academy of Forestry, pp. 144–150.
Zhang, Q.S.; and Guan, M.J. 2002. Variation of Moso Chemical Compositions during Mature Growing Period, Journal of Nanjing Forestry University, 26(2), pp. 7–10.
Hui, C.M.; Wang, W,J.; and Liu, C. 1994. A Study on the Chemical Compositions of 14 Timber Bamboo Species in Yunnan Province, Journal of Bamboo Research, 18(2), pp. 74–78.
Huang, H.D.; and Lin, F.W. 2005. Structures of Optimal Mother Bamboo of High-Yielding Dendrocalamus Latiflorus, Journal of South China Agricultural University, 11(1), pp. 15–17.
Wei, X.Z. 1998. The Comparative Anatomy of Four Bamboo Clums in Guangxi, Journal of Bamboo Research, 17(1), pp. 18–23.
Lin, J.G.; and Dong, J.W. 2000. Research on Variation of Chemical Composition of Dendrocalamus latiflorus, Journal of Plant Resources and Environment, 9(1), pp. 55–58.
Liese, W.; Weiner, G. 1996. Ageing of Bamboo Culms, Wood Sci. Technol, 30, pp. 77–89.
Zhou, F.C. 1991. Chemical Composition of Bamboo Clums, Journal of Bamboo Research, 1, pp. 222–228.

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# Preliminary study on the application of bamboo in blast protective wall

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ABSTRACT: This paper presents some preliminary findings in the performance of bamboo reinforced brick wall against blast load. The high specific strength and high ultimate strain of bamboo make it ideal as an energy absorptive material for protective structures. High fidelity physics based Finite Element Method program LS-DYNA was used as a tool to simulate the mechanical response of bamboo reinforced structures under blast loading. This paper is part of a preliminary study to investigate the feasibility of using bamboo in protective structures.

## 1 INTRODUCTION

The use of bamboo as construction materials had been an ancient practice (Dunkelberg 1992). As an ecologically friendly natural material, bamboo exhibits well recognized high specific strength and elastic modulus compared to concrete and steel and many other conventional construction materials. But it is also well known that the mechanical properties can be affected by moisture content of the bamboo and it is vulnerable to deterioration as a result of organic decomposition.

Brink and Rush (1966) reported the use of bamboo as reinforcement in Portland cement concrete, precast concrete elements and soil-cement slabs. Since then, the study of bamboo as construction material has received increasing attention (Anon 1972, Farrelly 1984, Tewari 1992) etc.

However, the application of bamboo in protective structures is still lack of study. This paper targeted at examining the feasibility of applying bamboo fabric reinforced wall against blast load by using numerical simulation. The performance of bamboo in protective structure are investigated by comparing the numerically simulated results from an unprotected wall, a wall protected with bamboo fabric at both side and a wall reinforced with steel rebars. Qualitative indicators in favour of bamboo fabric protected wall are registered from this feasibility study.

## 2 LS-DYNA MODELS DESCRIPTION

To study the confinement effect of bamboo panel to the wall under blast loading, three wall models with different material were set up. The full dimensions of the walls are 5 m (Length) $\times$ 3 m (Height) $\times$ 0.25 m (Thickness). The blast loading are generated by 1000 kg TNT at 10 m stand off distance from the wall and 1.5 m above the ground.

### 2.1 *Brick wall model*

A quadrant of an un-protected wall model was set up (see Figure 1). The mesh sizes are 5 in X direction, 50 in Y direction and 30 in Z direction. The *SOLID_ELEMENTS was used for the wall and *Mat_Pseudo_Tensor and *Mat_Add_Erosion material models were used for brick. The compressive strength of brick is 30 MPa.

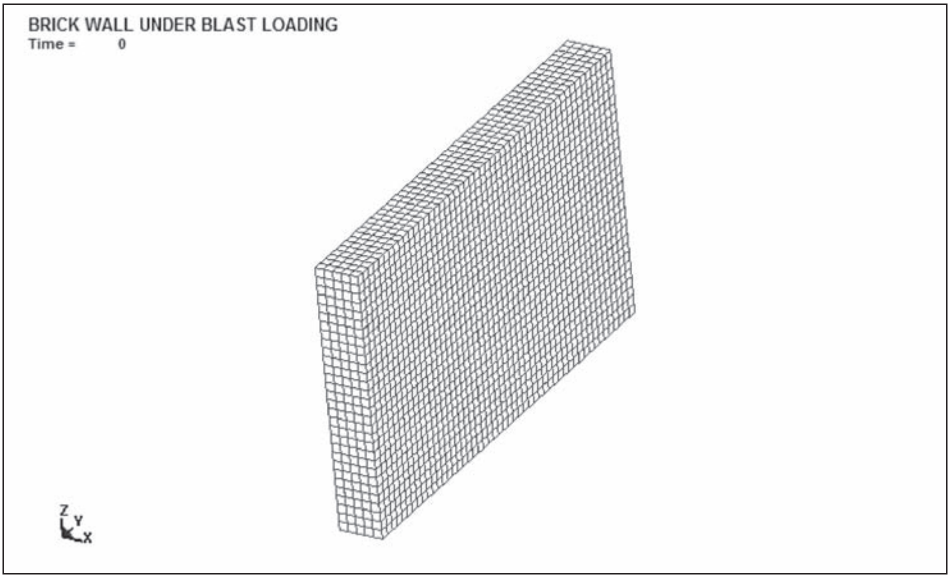



Figure 1. Un-protected brick wall.

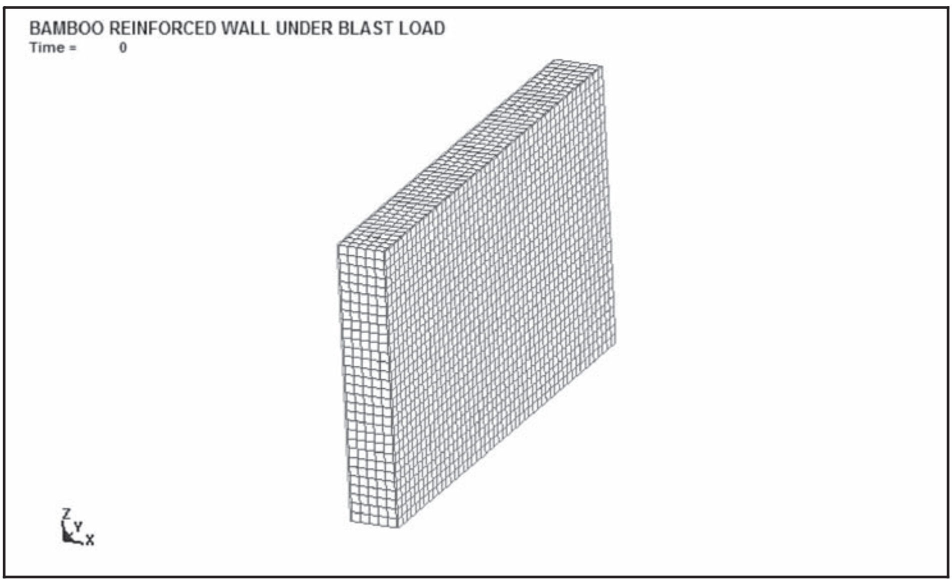



Figure 2. Bamboo reinforced wall.

## 2.2 *Bamboo panel reinforced brick wall model*

Based on the model of Figure 2, A quarter of bamboo panel reinforced brick wall model was set up (see Figure 2). Two bamboo panels were attached to both sides of the wall and anchored into ground. The thickness is 10 mm. *SOLID_ELEMENT was used for the bamboo panel. The *Mat_Plasticity_Compression_Tension material model is used for bamboo material. There is 1 mesh along X direction, 50 meshes along Y direction and 30 meshes along Z direction.

### 2.3 *Steel bar reinforced brick wall model*

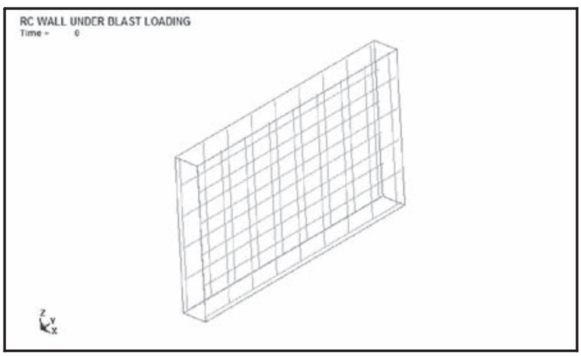
A steel bar reinforced wall was also set up to compare the confinement effect with bamboo panel reinforced wall. The layout of the steel bar is show in Figure 3a, e.g. Φ16@300 in both X, Y direction and in both sides of the wall. The cover thickness is 25 mm. The mesh size is 25 mm × 25 mm e.g. 10 meshes along X direction, 100 meshes along Y direction and 60 meshes along Z direction (see Figure 3b). *BEAM_ELEMENT was used for the steel bar and merged with wall.

## 3 SIMULATION RESULT

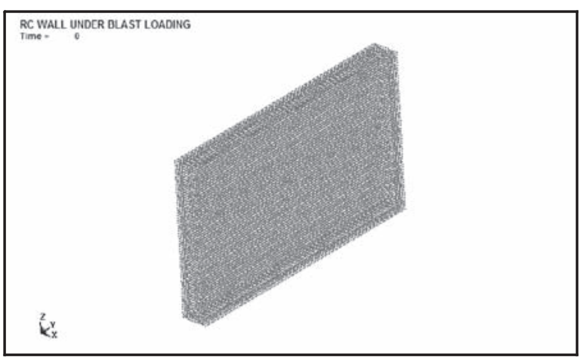
1000 kg TNT was placed 10 m in X direction away from the wall and 1.5 m above the ground. The blast loading was generated by *LOAD_BLAST in LS-DYNA.

### 3.1 *Un-protected brick wall*

Figure 4a–f show the response of un-protected wall under blast loading. Figure 4a, b show the front view and perspective view of the wall at time 0.0056s. From these two figures, the wall failed due to shear failure at the bottom of the wall at the moment of 0.0056s. Figure 4c–f show the fracture process of the wall under blast loading and the wall fragments were blown off by blast wave. The flying debris of the wall may kill people or damage properties.

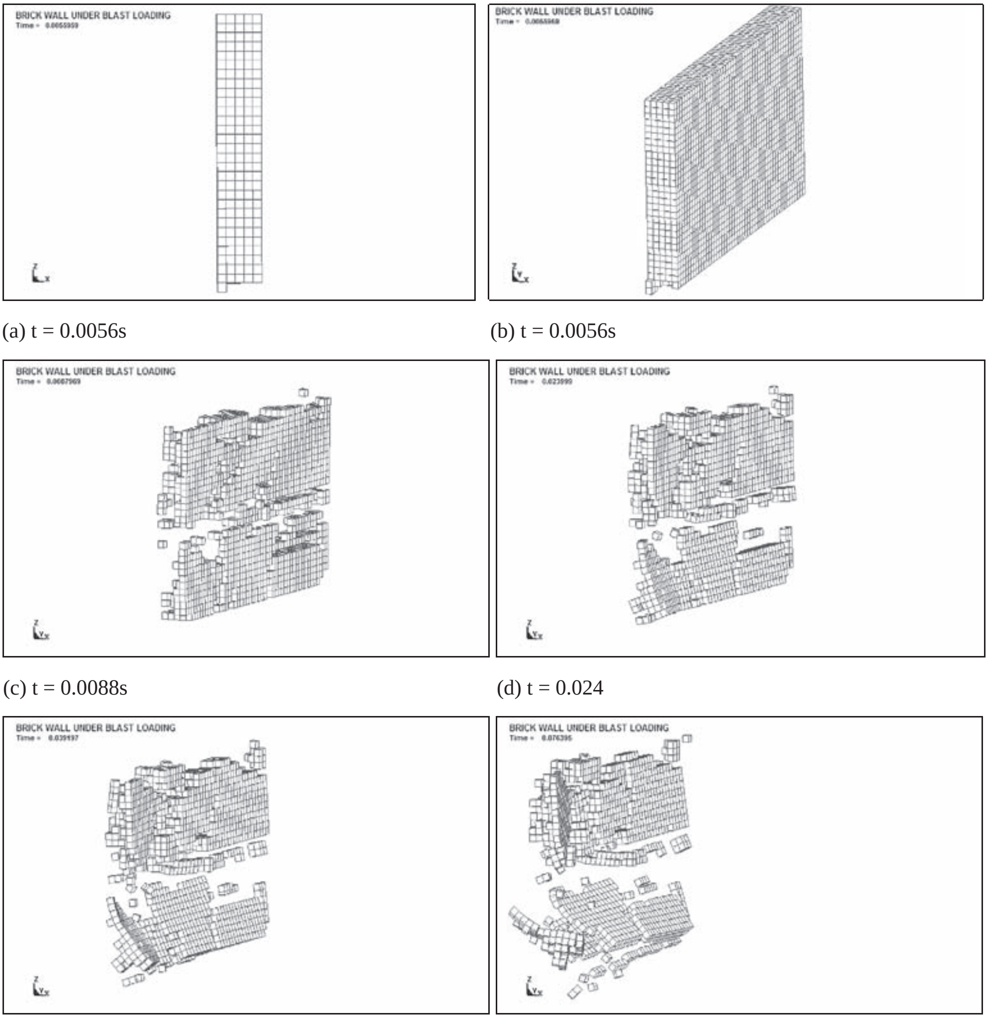



(a)




(b)

Figure 3. Steel bar reinforced wall: (a) steel bar mesh; (b) mesh.




(a) t = 0.0056s (b) t = 0.0056s

(c) t = 0.0088s (d) t = 0.024

(e) t = 0.040s (f) t = 0.076s

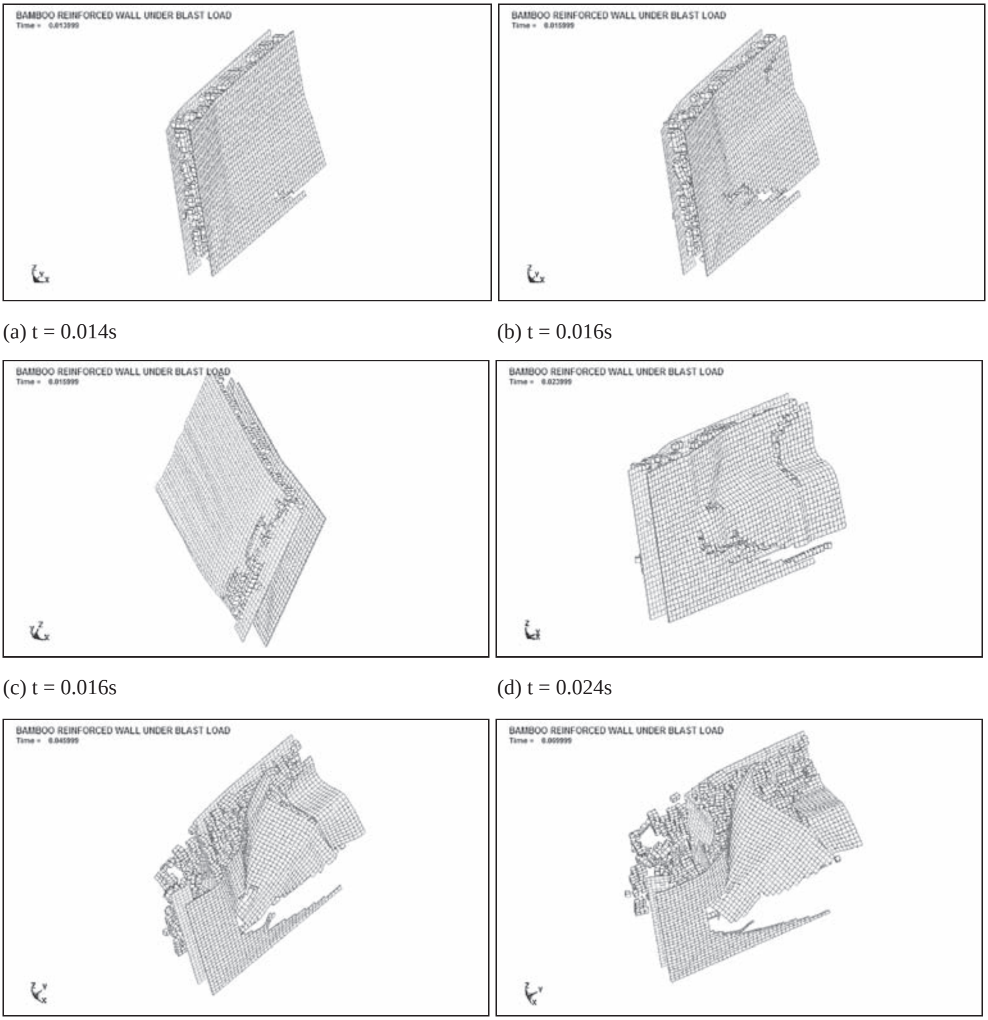
Figure 4. Response of un-protected brick wall under blast loading.

### 3.2 *Bamboo panel reinforced brick wall*

Figure 5 shows the simulation result of bamboo panel reinforced wall under blast loading. From Figure 5a–f, a clear fracture development and damage process of the bamboo panels reinforced brick wall are presented. Due to the reinforcement of bamboo panels, most of the wall debris were confined between two panels when subject to blast loading.

### 3.3 *Steel bar reinforced brick wall*

Figure 6a–d show the response of steel bar reinforced brick wall under blast loading. The wall failed under blast loading but due to the confinement of steel bars, the debris generated by the explosion is significantly less than that of brick wall without any reinforcement. This is attributed to the confining effect of reinforcement which holds up the debris as a net.




(a) t = 0.014s (b) t = 0.016s

(c) t = 0.016s (d) t = 0.024s

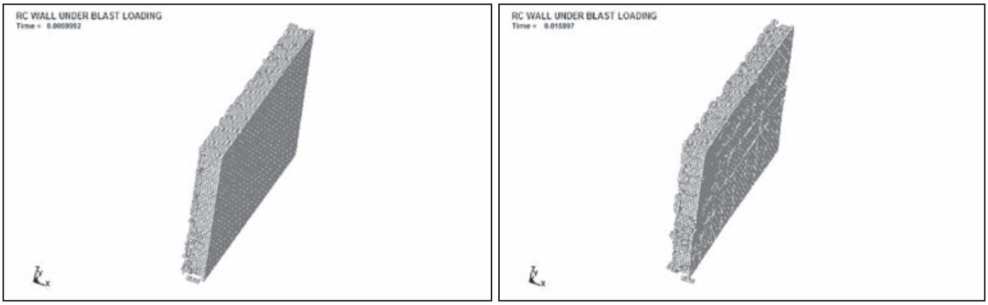
(e) t = 0.046s (f) t = 0.070s

Figure 5. Response of bamboo panel reinforced wall under blast loading.

## 4 DISCUSSION

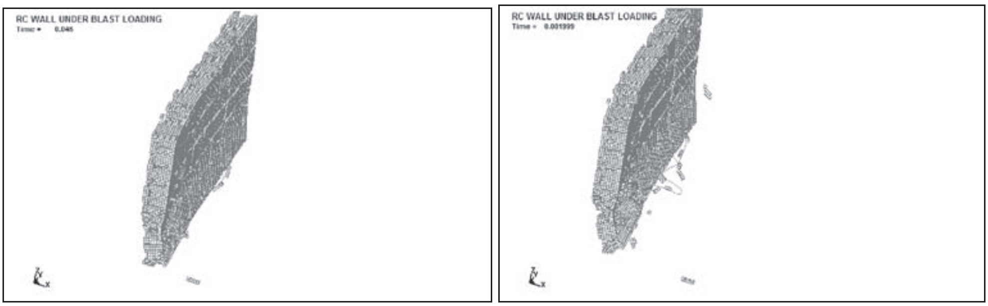
From Figures 5–6, both bamboo panels and steel bars can improve the blast resistant capability of brick wall by reducing the number of debris as compared to the case of unprotected wall. This verifies the numerical result as it matches with our common sense.

Figure 7 to Figure 9 show Y-stress distribution of three wall models under blast loading. The stress distribution of bamboo reinforced wall is more uniform (see Figure 8) than the other two walls (Figure 7 and 9). This is mainly due to the "membrane" effect of bamboo panels which act as a buffer to regulate the redistribution of stress within wall. At the same level of external loading, a more evenly distributed stress distribution means less problem of localized stress concentration hence will mitigate the damage or hazards generated if the damage is inevitable. In fact, this kind of membrane effect is well known in practices of protective structures with polymer coating. One of the key issues in successfully applying bamboo fabric to protective structure lies in how well




(a) t = 0.006s

(b) t = 0.0016s




(c) t = 0.046s

(d) t = 0.082s

Figure 6. Response of steel bar reinforced wall under blast loading.

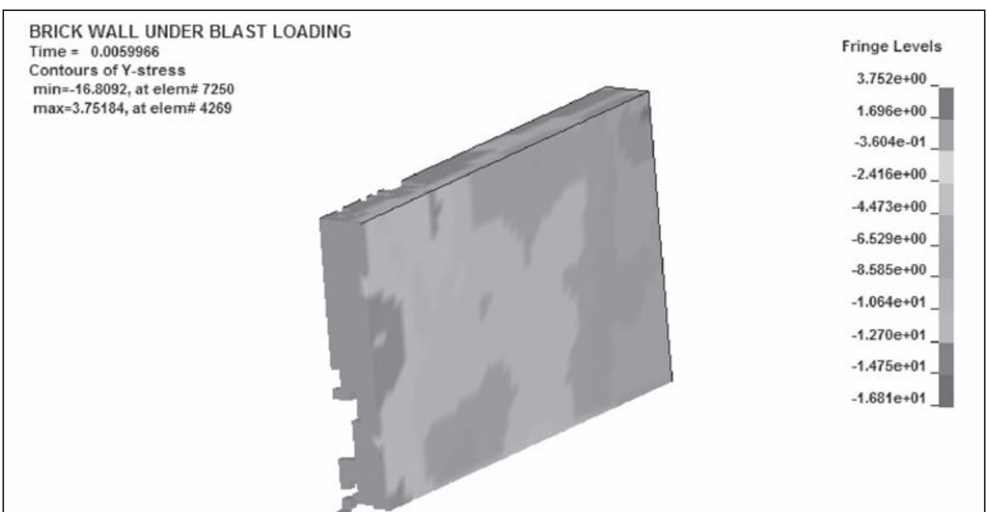



Figure 7. Y-stress of un-protected brick wall under blast loading.

the bonding between bamboo fabric and structures can be ensured. More studies are need on this issue. On the other hand, as can be seen from Figure 7, which is the stress distribution of wall without any reinforcement, the undulated stress distribution is one of the causes for the spalling type of damage to wall at the rear side of the wall. Furthermore, the starting of spalling will aggravate the stress concentration problem further and thus may lead to progressive failure of the wall panel.

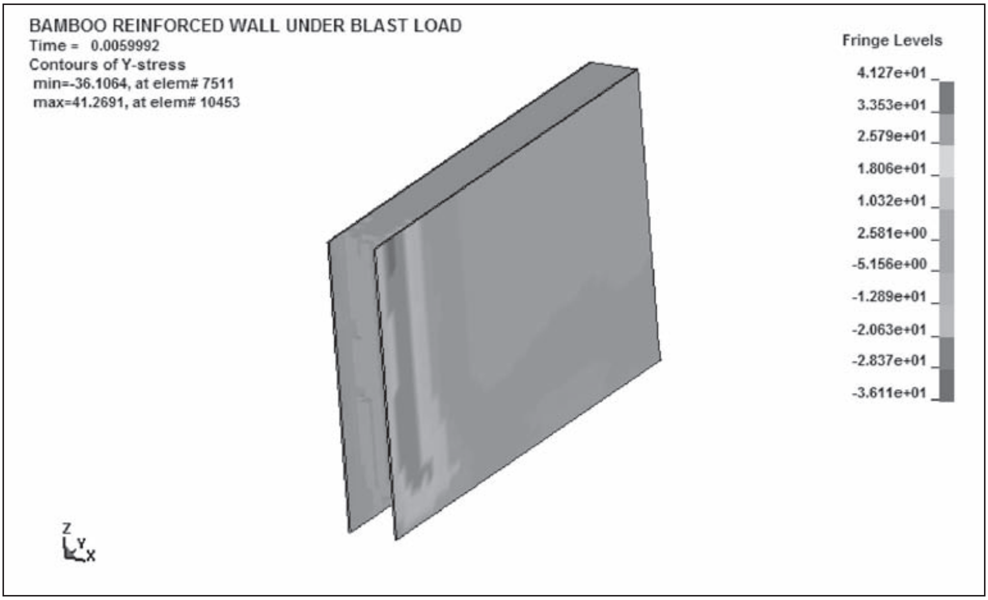



Figure 8. Y-stress of bamboo reinforced wall under blast loading.

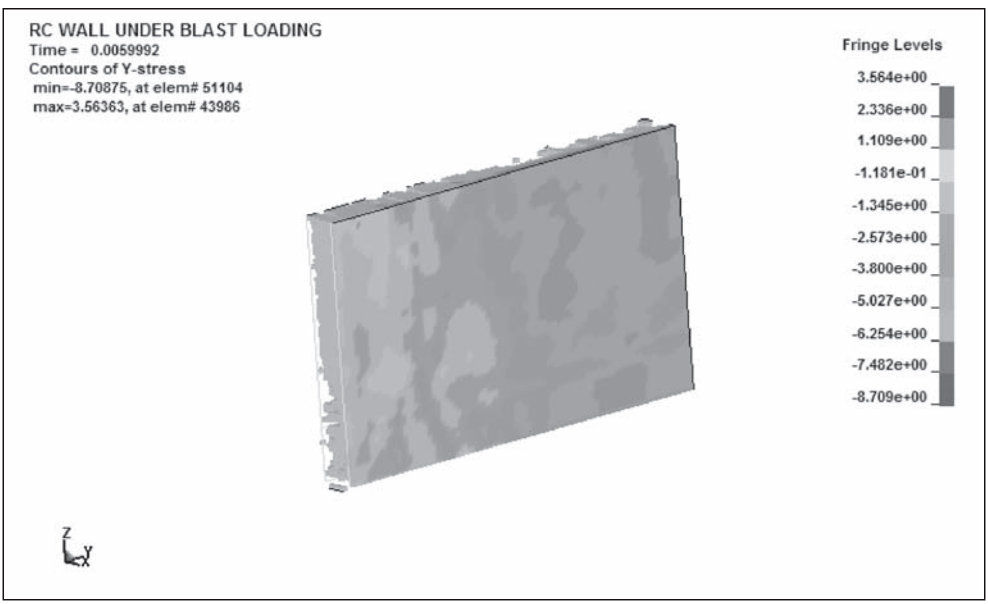



Figure 9. Y-stress of steel bar reinforced wall under blast loading.

The stress distribution of steel bar reinforced wall, as shown in Figure 9, is more uniform than un-protected wall but less than that of bamboo protected wall. This is obviously due to the differences in action mechanism between and wire mesh of rebar. The thin sheet of bamboo fabric and the thin sheet bamboo fabric is better than wire mesh rebar in regulating the stress redistribution to achieve a more evenly distributed stress in the structure.

## 5 CONCLUSION

From the study in this paper, based on limited number of numerical runs, bamboo panel has the feasibility to be used in blast-resistant structures due to high specific strength and high ultimate strain. Compared to steel, bamboo could provide similar blast resistant capability enhancement but bamboo is lighter and more economic. Further and in depth investigations on applying bamboo to protective structures are needed.

## REFERENCES

Anon. (1972). “The Use of Bamboo and Reeds in Building Construction.” Dept. of Economic and Social Affairs, United Nations, New York.

Brink, F.E. & Rush, P.J. (1966). “Bamboo Reinforced Concrete Construction.” US Naval Civil Engineering Laboratory.

Dunkelberg, Klaus. (1992). “Bamboo as a Building Material.” in: IL 31 Bambus, Karl Kramer Verlag Stuttgart.

Farrelly, D. (1984). “The Book of Bamboo, Sierra Club Books.” San Francisco, California.

“LS-DYNA 971 Keyword User’s Manual.” (2007). Livermore Software Technology Corporation, Livermore, California, USA.

Tewari, D.N. (1992). “A Monograph on Bamboo.” International Book Distribution, Dehra Dun (India).

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Bamboo materials are well available in the world. Bamboo has much shorter maturity than trees, thus can be harvested with shorter cycles of plantation. Despite the fact that human society has a long history of using bamboo, there is still a lack of modern and industrialized application of bamboo materials in construction. Promoting the application of bamboo in construction could provide a potential solution to the sustainable, green and environment-friendly development of construction industry.

**Modern Bamboo Structures** is the first of its kind covering the applications of bamboo materials in modern structures. The following topics are covered in this book:

- Properties of bamboo materials, components;
- Design, experimental testing, analysis of bamboo structures and components;
- Modern bamboo buildings and bridges;
- Composites of bamboo, timber and other materials;
- Bamboo reinforced concrete;
- Comparative studies of timber and bamboo structures;
- Adhesives, joints, engineered bamboo products;
- Environmental, sustainability and ecological issues, and
- Structural and constructional applications of other natural and non-conventional materials.

These proceedings of the First International Conference on **Modern Bamboo Structures** (ICBS-2007, Changsha, China, 28-30 October 2007) include the state-of-the-art on materials, design, analysis, testing, manufacturing, construction of modern bamboo structures.

**Modern Bamboo Structures** will be essential for researchers, engineers and administrators involved in structural engineering, civil engineering, agriculture engineering, forestry, environmental engineering and urban development.

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