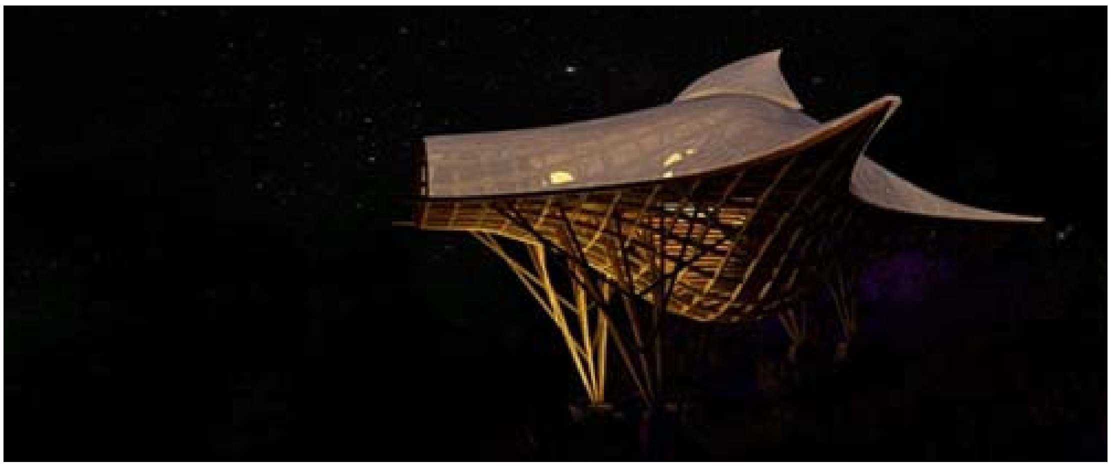
VOLUME 10

Architecture and Engineering

Table of Contents

The Den, Soneva Kiri Resort, Koh Kood Island, Thailand

Olav Bruin
Project Architect
24h-architecture, the Netherlands
Boris Zeisser & Maartje Lammers



Artist's impression

Introduction

On the lush green tropical Island of Koh Kood in the Gulf of Thailand the ecological 6-star Soneva Kiri Resort is being built. All activities for the resort's children are accommodated in the Den. This bamboo structure encloses a small theatre, art room, fashion room, music room and library.

Birds-eye view towards the bay

Concept

Situated on a rocky hillside, the building is overlooking the resort's bay. The organic shape of the building is inspired by the manta ray fish below in the water and acts as an inspiring and exciting environment for the children's activities. With its muscular fin-shaped bamboo columns the sculpture seems to be ready to jump from the rock back into the crystal clear water.

View from below

Design & climate

The design adopts all bioclimatic aspects to suits its humid tropical environment. The roof cantilevers up to 8m acting like a big umbrella providing shade and protection from the heavy rains. The elevated rooftop and setback floors allow a natural airflow inside.

Steam oven

Adjustable formwork for making the curved beams

Construction

All beams have been generated from a 3D computer model. After the individual bamboos have been heated in a specially developed steam oven, they were assembled in an adjustable formwork with a coordinate system, forming each of the more than 70 individually curved beams.

Roof structure under construction

Bamboo

The main structure has been made using *Pai Tong* bamboo (*Dendracolamus asper*) in lengths up to 9m and a diametre of 10-13cm. The secondary roof- and ‘belly’ structure is made from *Pai Liang* bamboo (*Bambusa multiplex*) in 4m lengths and a diametre around 5cm.

Both types of bamboo come from plantations in the neighboring Thai province of Prachinburi.

Bamboo shingle roof being installed

Conference

The presentation at the conference will mainly focus on the process from an abstract design concept towards the actual construction details.

Detail of back column

Front column

Interior under construction

Going Multi-Storied With Bamboo

Ar.Jaigopal G.Rao

Inspiration, an architecture and construction firm based in South India has been shaping bamboo buildings for the past 6 years, Inspiration's own office being the first major attempt in this field. (Figure 3, Figure 4)

Bamboo has been used in combination with optimized RCC members, ferro-cement and limited reinforced plaster, so as to arrive at an aesthetic, functional and cost-effective technology option. (Figure 2)

All the bamboo utilized has undergone adequate preservative treatment with water-borne preservatives like CCB and liquid organic solvents. Split bamboos used for floors, roofs and walls span between ferro-cement, wood or steel members spaced at 1.30m centre-to-centre. The dead load of the composite has been taken as 1500N/m^2 and it was found to take liveloads of over 4000N/m^2. (Figure 1) It has further been observed that the fibrous nature of the material makes design for lateral loads such as earthquakes and cyclones easier. This effort went on to win several National and International Awards including 'Urban Building' Category Award in the International Bamboo Designs Competition 2007 based in Hawaii, USA.

Ensuing this, 10-12 buildings have been erected by Inspiration. Fine-tuning the above basket of technologies, (Figure 5) the use of bamboo steel composite was observed to be advantageous with regard to 1. The carbon footprint of the building, 2.Self weight of the building which is reduced by 40%, 3.The duration of construction which is reduced to 1/3rd, 4.Temperature reduction averaging 3-4degrees Celsius owing to lower conductivity of material; the costs remain comparable to conventional buildings.

The advantage of considerably reducing the self weight favoured Inspiration to explore the possibility of introducing these technologies in multi-storied buildings. Care is being taken in making bamboo fire retardant too. Currently, the design of a Ground+12 structure housing a 76-room hotel is underway; construction is scheduled to begin by Sept.2009. (Figure 6)

The design makes extensive use of bamboo-reinforced mortar composite for floors and walls resulting in the reduction of self weight of the building. The highlight of the same is the consequent lessening of the volume of cement, steel and other chemicals used in pile foundations, building frames and floor slabs.(Figure 7) It is determined that a reduction of over 6150 bags of cement and around 100 tonnes of steel is possible. This leads to an eventual considerable decrease in carbon footprint and a 10% reduction in construction cost of the structure of the building in Indian conditions.

Comparison of Use of Steel and Cement							
Conventional building with DMC piles, RCC slabs, beams and Brick Masonry walls			Building with friction piles and strip raft foundation, RCC frames, Bamboo-reinforced mortar floor slabs and walls				
	Unit	Quantity		Unit	Quantity	Difference in Quantity	Unit
Total Qty. of RCC	m^3	1966		m^3	1259	707	m^3
Total Qty. of Cement	bags	16990		bags	10870	6120	bags
Total Qty. of Steel	Tonnes	220		Tonnes	130	90	Tonnes

Figure 1 – Inspiration Office: Ground Floor Plan and First Floor Plan

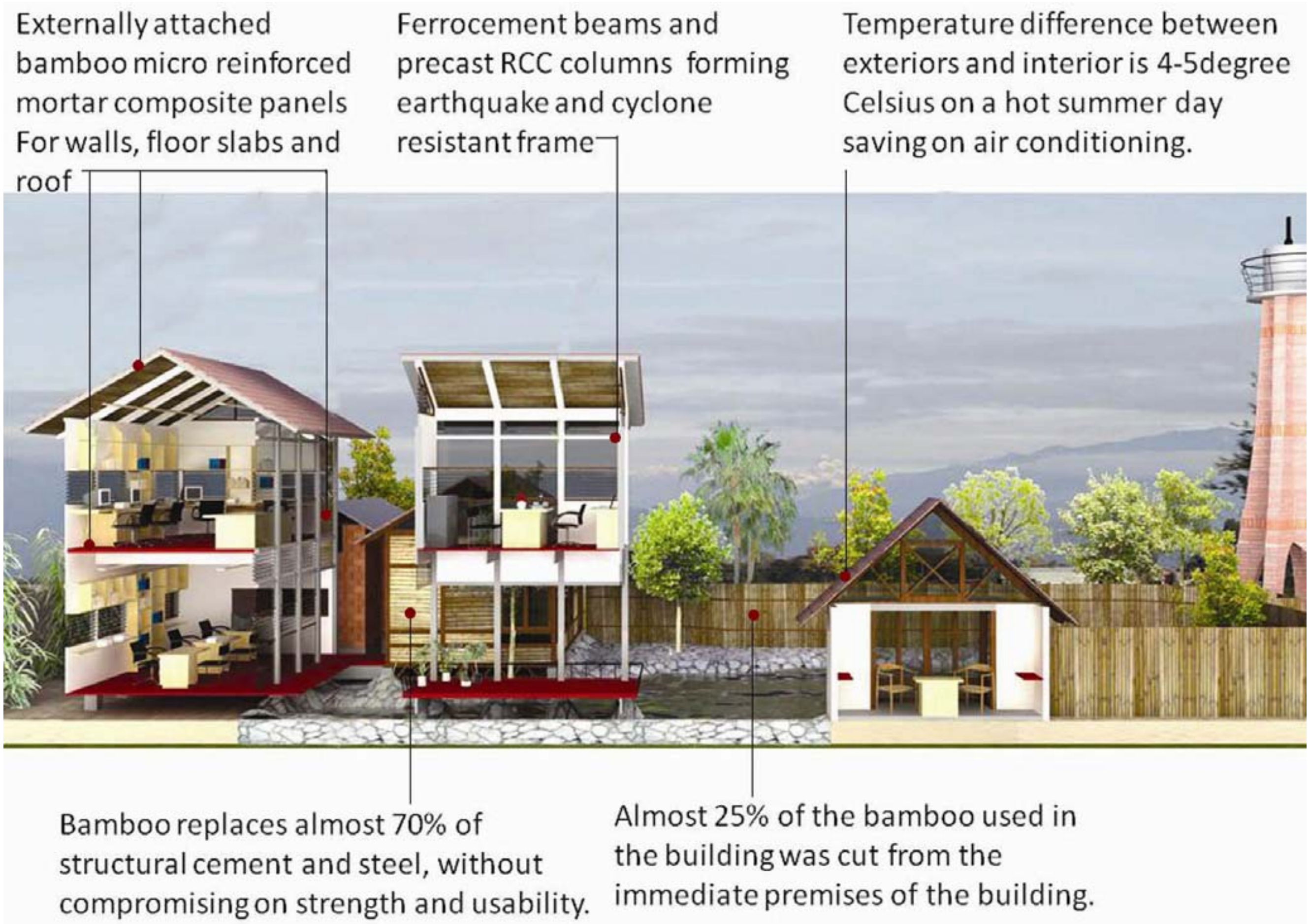


Figure 2 – Inspiration Office: Section

Figure 3 – Inspiration Office: Exterior Front View ;
Bamboo-reinforced Mortar Floor Slab finished with Polished Red Oxide

Figure 4 – External View with Central Pond in Foreground; Interior of Design Studio

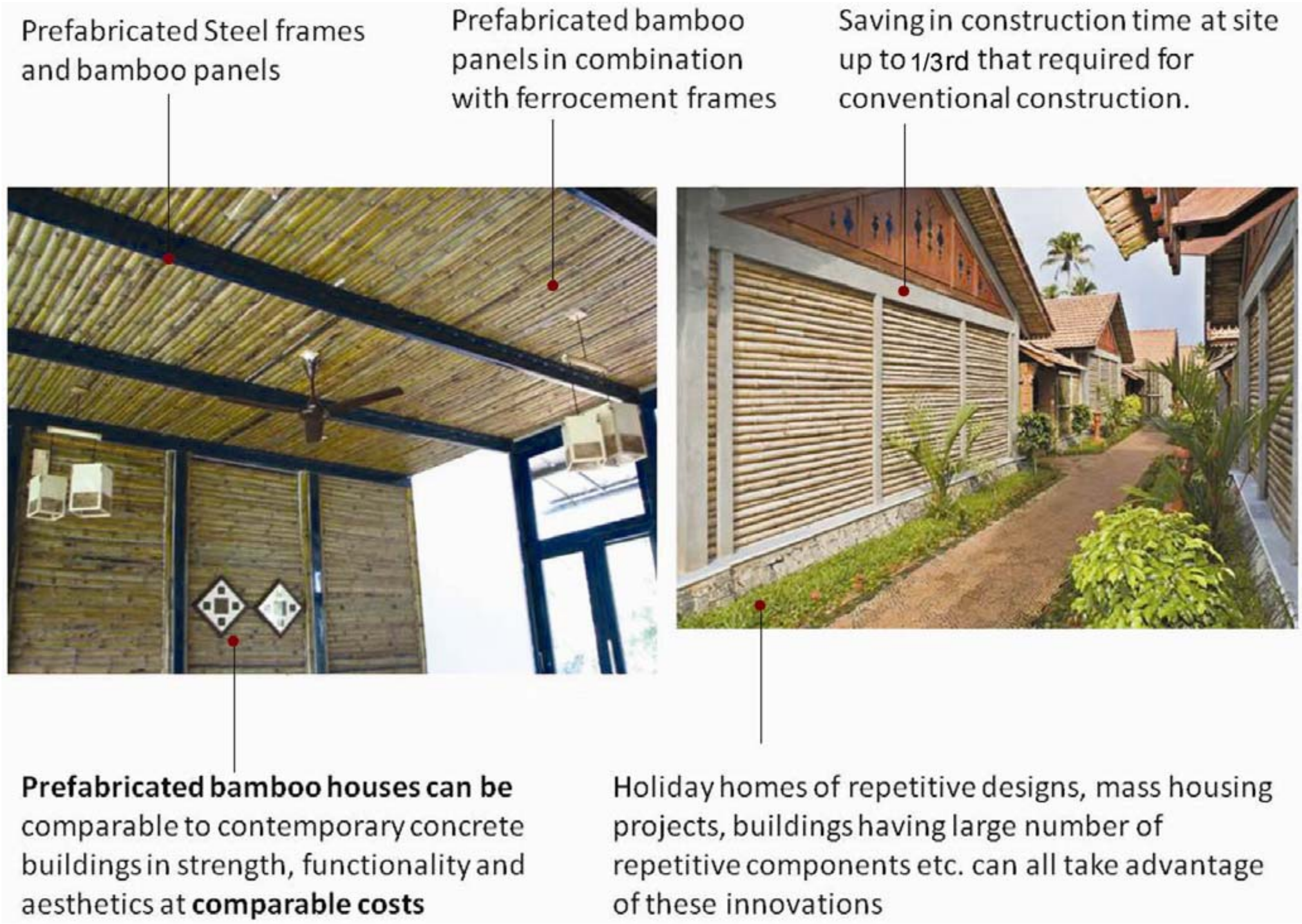


Figure 5 – The Technology Basket

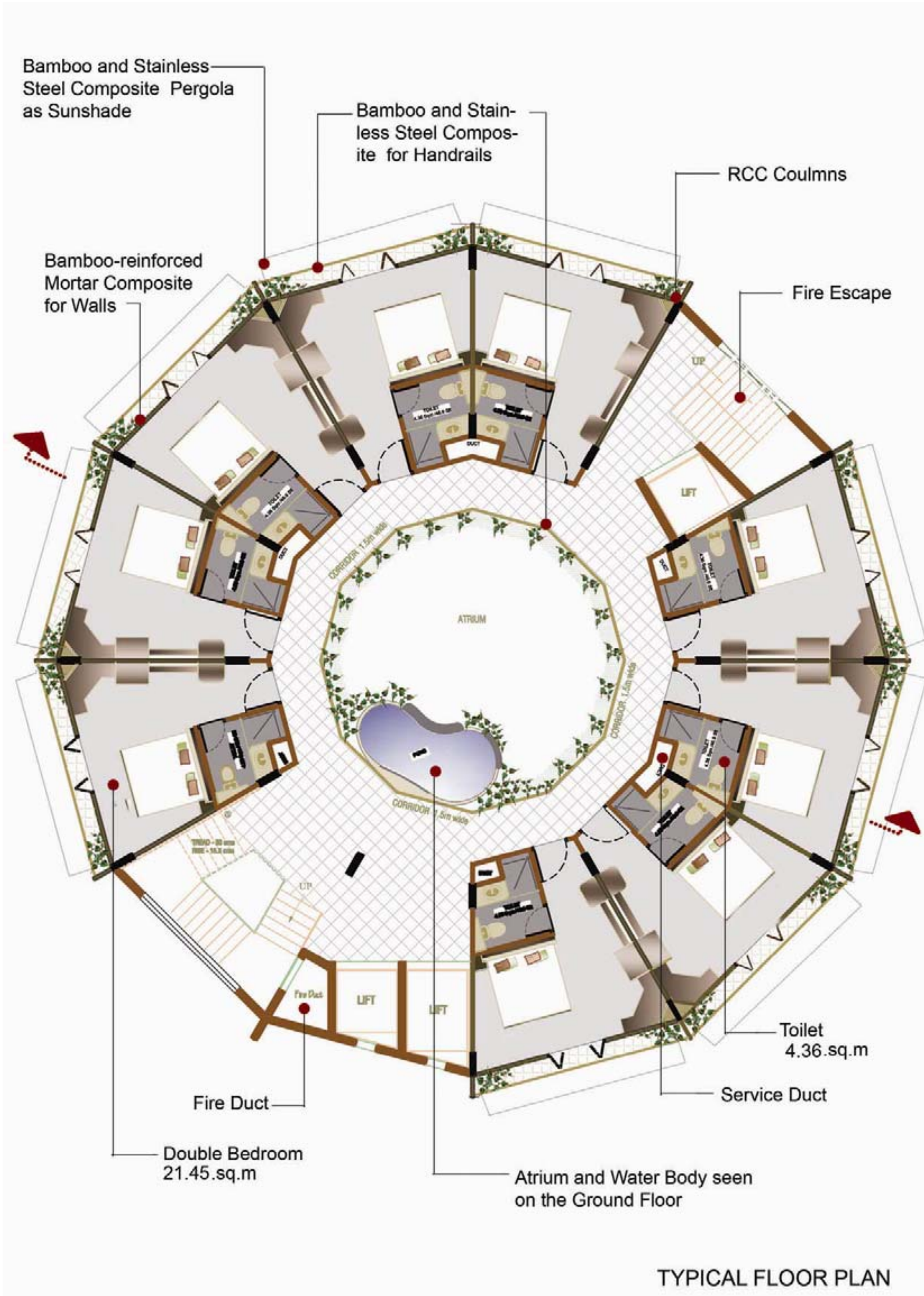


Figure 6 – Sarovaram Hotel – Floor Plan

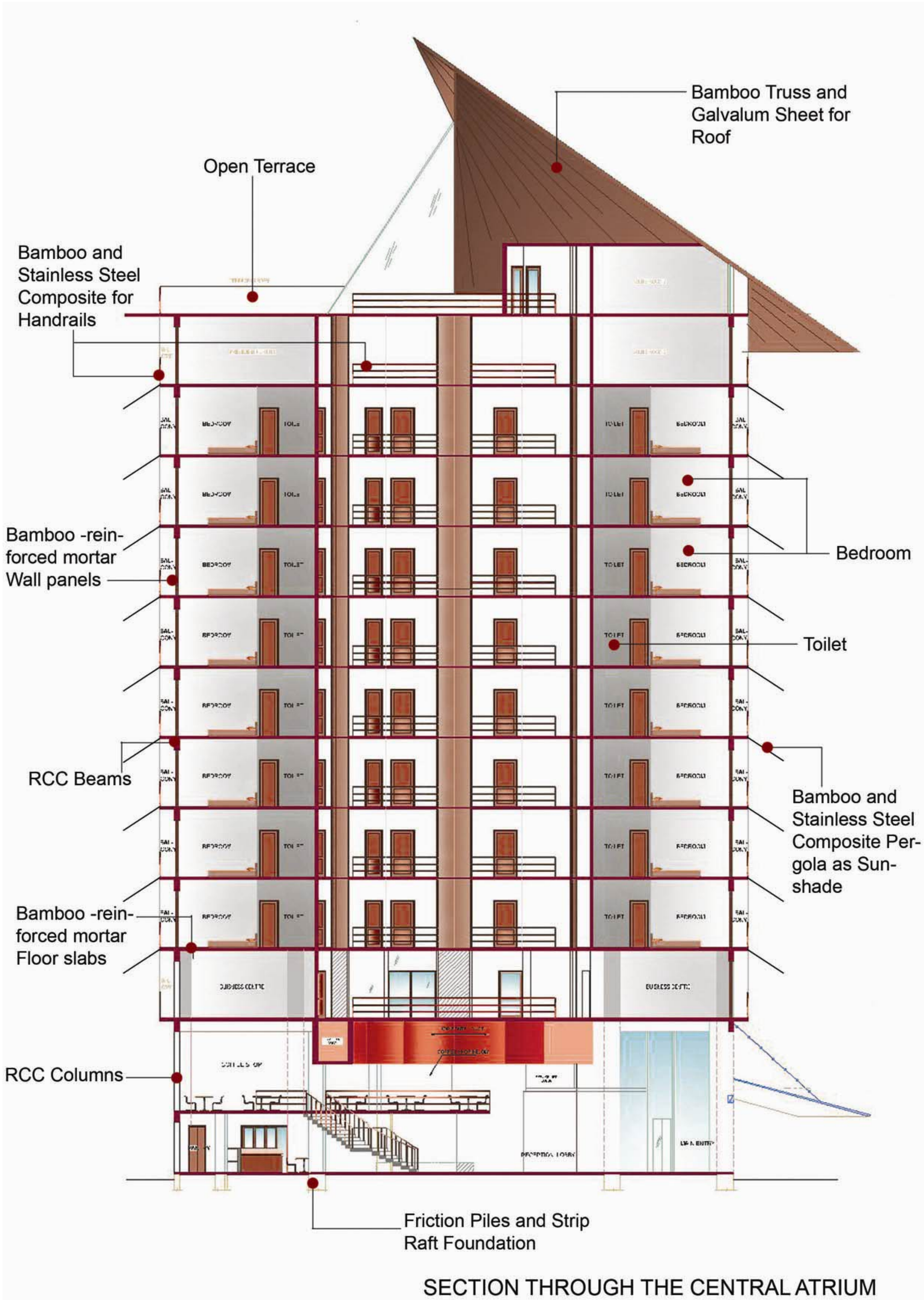


Figure 7 – Sarovaram Hotel – Section

Conventional vs. Substitutive Bamboo Construction: The Classification of Bamboo Construction

Andry Widyowijatnoko[1], Martin Trautz[2]
[1]Ph.D Candidates, [2]Professor, Institute of Structural Design, Faculty of Architecture, RWTH Aachen, Germany

Abstract

Based on numerous past studies and field experiences dealing with bamboo construction and the ongoing development of bamboo utilization, it is widely recognized that bamboo construction can be found in a very wide variation. Bamboo can be used in all parts of the building, either as structural or architectural elements. It can stand alone or in combination with other materials. Bamboo also can be simple-transformed or high-tech-transformed to become a new material that has specific characters and properties and thus can be constructed in a different way.

In these wide ranges of variations, the question ‘how was bamboo originally constructed?’ become interesting to be answered. In the form of original or simple-transformed, bamboo has specific characteristics and these will distinguish between other constructions. But in spite of using ‘original’, the term ‘conventional’ is purposed to represent a wider variation of bamboo construction that takes directly from the specific nature of bamboo, a ‘convention’ of bamboo construction.

Nowadays bamboo is often used to replace other materials, lead by the issue of sustainability. In this case, bamboo is treatted and constructed with a different kind of material logic. One example is the replacement of timber construction with laminated bamboo. Therefore part of bamboo construction can be classified as a substitution of other construction, such as timber construction. This will be categorized as “substitutive bamboo construction”.

This paper presents a classification of bamboo-based construction world-wide. This categorization is based on the way bamboo is constructed. It is different with other literature which distinguishes it based on the building elements or building types, such as footings or roof construction, housing or bridge construction, etc. It does not depend on where the bamboo construction will be placed or what it is for, but how it will be constructed.

Introduction

Bamboo plays an important role everywhere it grows naturally. The culture of bamboo grows in line with the civilization and makes many human activities inseparable from the existence of this amazing grass.

One of the important uses of bamboo is for building construction. It is believed that bamboo became the first option as a building material when people began to occupy area where bamboo grows naturally. The common reasons are its availability and ease of use. And later due to its lack of durability, most of people replaced the use of bamboo with other, more resistant material, such as wood and brick. According to Hidalgo (2003), “due to the low durability of most of giant bamboo species of Southeast Asia, at present most countries in this area do not use bamboo for the construction of the main structure of their houses”.

In recent years, with the issue of sustainability the use of bamboo has regained a new value. Bamboo offers many advantages that fulfill most of the criteria of a sustainable material, especially as timber replacement to reduce deforestation. This awareness is followed by a massive amount of bamboo research and utilization. Bamboo is used with minimum preparation or even with high-tech transformation. Great bamboo buildings out of preserved bamboo-poles and as well as for luxurious interiors out of bamboo lamination or plybamboo can be found at the present time. Traditional or vernacular bamboo construction is also still prevalent in rural areas.

In the hands of artists, architects and engineers, bamboo becomes a challenging material to be constructed to fulfill as many building types as possible, as small gazebos, long-span building, bridge, etc. And the bamboo itself is applied as a building material in many possible ways, like as flexible splits or a rigid laminated-beam, in order to fit with a specific type of construction.

It can be understood, these circumstances drove many authors to classify bamboo construction in different ways, based on building type, building element, time frame, material combination, transformation, etc. This paper will present another bamboo construction classification, which is based on the method on how the bamboo is constructed. It does not depend on the building type or building element, but it of course has a close correlation with the form of bamboo-based material, structural system and connection.

The Form of Bamboo as Building Material

As a building material, bamboo takes many forms (Figure 1). There are at least 4 basic forms of bamboo of building materials: bamboo poles; splits, including flattened bamboo (*pelupuh*, *esterilla*); woven and rope. These basic forms have a long history of use. Most are still used except a limitation in bamboo rope application.

Bamboo also can be mixed with other materials for several purposes. The main reason for this mixture of materials is to replace other materials or one part of a composite material. Laminated bamboo can replace almost all kinds of timber product or construction. The high tensile strength of bamboo led to further applications such as the replacement of rebar in steel reinforced concrete construction.

Classification of Bamboo Construction

The question ‘how was bamboo originally constructed?’ is always interesting to be answered, since utilization of bamboo as building material become wider and already replaced other established material. Solid proofs of hundred years old bamboo constructions in many variations are also hard to find in existing bamboo buildings nowadays, because of lack of bamboo-durability without proper preservation.

But in this widespread variation of bamboo construction, there are some types of construction and joinery that are specific to the characteristics of bamboo and there are other types of construction that are using bamboo to replace a different kind of material logic. Therefore bamboo constructions are classified into two main categories (Figure 2):

1. Conventional Bamboo Construction
2. Substitutive Bamboo Construction

In spite of using ‘original’, ‘conventional’ bamboo construction is used to describe a construction of bamboo which is based on the specific character of bamboo and have been in practice since previous generation. A convention is a set of unwritten rules, a set of agreed, stipulated or generally accepted standards, norms, social norms or criteria. Conventional bamboo construction stands for the construction which based on a convention of bamboo construction that lived in the community. This convention is not only used in traditional building, but also applied in the modern bamboo building with or without development.

The term ‘original bamboo construction’ is not used because it is so hard to say that there is no influence of other construction, especially timber construction. But within this conventional bamboo construction, there are ‘original bamboo connections (not constructions)’ which is made of bamboo poles. This connection can only be made by using bamboo poles, not other materials.

Newer utilization of bamboo is to replace other possible materials, thus bamboo will be constructed with the logic of other materials. For example, bamboo construction in the form of laminated bamboo is used to be constructed in the same way as wood construction. There are many other uses of bamboo such as replacing steel as concrete reinforcement or replacing steel member in a space frame or space truss structure. These bamboo constructions thus will be classified as “substitutive bamboo construction”.

Conventional Bamboo Construction

Conventional bamboo construction is based on a set of unwritten rules or conventions of bamboo constructions. The construction technique has been passed down through generations of working closely with specific characteristics of bamboo. This rules or standards grow from one generation to next generation with enrichment. That is why it cannot be separated with the time line. For that reason, conventional bamboo construction can be divided in two main categories:

1. Traditional (Vernacular) Bamboo Construction
2. Engineered Conventional Bamboo Construction

Traditional (Vernacular) Bamboo Construction

The term "vernacular architecture" refers to structures made by empirical builders, without the intervention of professional architects. It is the most traditional and widespread way to build (Arboleda 2006). Sometimes it is also called as traditional architecture, although some references distinguish these two terms.

The term ‘vernacular’ is not to be confused with so-called "traditional" architecture, though there are links between the two. Traditional architecture can also include buildings which bear elements of polite design; temples and palaces, for example, which normally would not be included under the rubric of "vernacular" (Brunskill 2000).

In traditional way of building with bamboo, a bamboo is used in its original form (bamboo poles) or in its simple transformation as split, woven or rope. It is also used in combination with plastering process.

Bamboo Poles/Tubes

Traditional bamboo pole constructions came from a long empirical experience and it became a basic of conventional bamboo construction. In this construction the specific character of bamboo is highly benefited. Therefore some specific connections (such as fish-mouth and rope connection) are considered as ‘original bamboo connection’ which could not be duplicated with other material.

The joinery most often used in this category are fish-mouth (Figure 3, 4), rope (with coco-fiber, bast, rattan, bamboo rope), plug-in, and positive-fitting connection (Figure 5). Rope connection is regarded as one of the oldest type of bamboo connection because the circular cross section of bamboo makes the friction of bamboo and the rope more effective. To make a strong rope connection in most cases, bamboo has to be pinned, holed or fish-mouth shaped and it is easy because of the hollowness of bamboo, even with simple or traditional tools.

In most traditional bamboo buildings the supporting structure is formed from straight full-section canes. They are almost always under compressive or bending stresses. Canes under tensile stress are rarely found (Dunkelberg 1985). Although bamboo has a very high tensile strength it is difficult to connect the bamboo poles to afford that strength, especially when the connector is made of traditional material that commonly out of natural resource.

Most of traditional bamboo buildings consist of planar frames (Figure 6). Commonly this two dimensional frame is composed of one layer (Figure 7). In Asian culture, where bamboo in different culm diameter is easy to find, this planar and one layer frame is constructed with a positive-fitting connection, a smaller diameter of bamboo as beam is connected through a bigger diameter bamboo as column (see also Figure 5).

The other specific character of conventional bamboo construction is the existence of eccentricity of load transfer in the connection. It is very important to make a connection close to a node and it is not easy to connect many bamboos at once in one point (Figure 8, see also Figure 7). Splitting bamboo pole is one of the most essential problems to be overcome in bamboo connection. Trujillo (2007) mentioned a function of node to stop cracking, “Shear strength is relatively low, and becomes quite critical due to the relatively thin walls of the culm and the action of the all too frequent cracking of culms, which greatly reduces the shear strength of a section. The only favourable factor is the nodes that act as ‘stirrups’ stopping the progression of any cracking or splitting”.

Bamboo Split and Woven Bamboo

Splitting bamboo to become a flexible strip is one of the most ancient uses of bamboo. Bamboo’s ease of splitting since it only has fibers in the longitudinal direction. Mostly these strips or bamboo splits were weaved to become a wider sheet and then attached to bamboo-poles or timber frame. Hidalgo (2003) reported an interesting traditional use of bamboo split/woven as housing in Ethiopia, Africa (Figure 9).

Bamboo Rope

One of specific utilizations of bamboo compared with timber is bamboo rope (Figure 10). This application is benefited from the longitudinal bamboo fiber. In China, bamboo plaited or twisted ropes have had applications in many fields of engineering, e.g., in the construction of suspension bridges, for tracking junks on the upper Yangtze River, in the construction of gabions and fascine bundles used in the construction of dikes, and the hogging trusses that were used in the construction of boats (Hidalgo 2003).

Bamboo Plaster

Basically a bamboo plaster construction is a construction of a sheet of bamboo woven (South-East Asian) or flattened bamboo (Latin America) that attached to a bamboo pole or timber frame and in the end was covered with plaster mixture. Traditionally, mud, clay, cow or horse dung, or lime is used as plaster material (Figure 11). Rough surface of woven/flattened bamboo and gaps between its split members make them possible to be plastered although there is a lack of adherence between plaster and bamboo. Traditional '*Quincha'* wall from Peru showed the use of woven bamboo in combination with bamboo poles and plaster.

Engineered Conventional Bamboo Construction

Based on traditional or convention techniques of bamboo construction, many architects, artists and engineers developed a further utilization of bamboo that is scientific acceptable. Scientific approached such as basic research and calculation, had been conducted to determine constructability of bamboo building. Therefore this utilization is categorized as engineered conventional bamboo construction.

In this category, there are three type of bamboo-based material which can be found in today practice: bamboo poles, bamboo splits and plastered bamboo, but only bamboo poles and plastered bamboo that are used excessively.

Bamboo Poles/Tubes

Engineered conventional bamboo poles construction is also part of conventional bamboo construction which is based on a basic principle of bamboo construction. The greatest development of traditional to engineered conventional bamboo construction is the use of nut-bolt connection with mortar injection, benefitted a modern tools electrical drill machine. This connection provides an easy workability, high durability and capability to connect many bamboo poles at once because of availability of long bolt. The great impact is easier to make a building frame with more than two layers (Figure 12, 13). A column of four poles of bamboo in three layers is widely used in engineered conventional bamboo construction. Different with traditional bamboo construction, three dimensional frames is also introduced in this category (Figure 13).

Like in most traditional bamboo construction, in this category bamboos are almost always under compressive or bending stresses. Canes under tensile stress are also rarely found. There are also eccentricities of load transfer in this type of construction because of benefiting the existence of nodes and difficulty of making connection in one point (Figure 14).

Bamboo Split

Nowadays bamboo splits were used to make many building with new forms that was not recognized in traditional bamboo building. But the principle is the same as the use of bamboo in traditional craftsmanship. Bamboo split can be use easily to make a curve form and can be weaved to have a rigid form. Most of these applications are in the field of experimental building or for temporary shelter (Figure 15).

Bamboo Plaster

The basic principal of the plastered bamboo construction in traditional way is same as in engineered way. Bamboo woven is treated as a sheet of wall cover or partition and then plastered. In Colombia, the new '*bahareque'* system use cement-based mortar as replacement of mud or cow-dung as plastering material. In order to improve the adherence between mortar plaster and the flattened bamboo wall, chicken wire is added.

Another improvement in engineered conventional bamboo plaster construction is the use of halved bamboo pole to replace bamboo pole or timber frame in traditional construction (Figure 16). The basic idea of this construction is to have a better adherence between bamboo and mortar as building frame. Therefore the frames as well as the walls are made of bamboo plaster (Widyowijatnoko 1999).

Substitutive Bamboo Constructions

Beyond the conventionality, bamboo is utilized to replace other established material in building construction. Many types of construction with many kinds of building material exist today. Parts of these materials were produced in a high cost or endangered the sustainable development or not available in some places. Therefore the new idea came to replace those materials with bamboo. Once again, its sustainability and flexibility are the main reasons of using bamboo as replacement. For that reason, this type of bamboo construction is so called 'substitutive bamboo construction'.

In this category, bamboos are transformed, combined or connected with other material to fit with existing type of construction. The forms of bamboo-based building material are at least as follow:

1. bamboo poles
2. bamboo split
3. laminated bamboo
4. bamboo composite

Bamboo Poles/Tubes

In this category bamboo pole is used to replace other material in its type of construction although the construction is foreign to the nature of what bamboo wants to be. Therefore bamboo is sorted or treated to fit with the requirement (Figure 17). Different with previous bamboo pole construction, in this category bamboo are also utilized under tension.

An example of this category is the use of bamboo in a typical steel space frame. In this construction there must be no eccentricity of load transfer (Figure 18). Therefore the connections of bamboo are created to fulfill this requirement. In a specific connection which nodes have an important role, the process of sorting become very crucial to find a number of poles in a certain length with certain distance to an end-nodes.

Bamboo Split

Mostly bamboo splits are used in conventional way, but there is at most an example of utilization as truss member (Figure 19). It is already well known that most of truss systems are made of steel or timber construction.

Laminated Bamboo

Both laminated bamboo, glued and non-glued, are created especially to replace timber in building constructions, both architecturally and structurally. Therefore the constructions of this bamboo composite are almost the same with timber construction (Figure 20). An experiment also had been conducted to use laminated bamboo as I-beam which is commonly made of steel.

Bamboo Composite

Another unconventionality of using bamboo as building material is in combination with other building material to become a composite material. There are many experiments that have been conducted to create bamboo composite. At least the forms of bamboo composites are as follow:

1. bamboo reinforced concrete
2. bamboo-fiber reinforced concrete
3. plybamboo (in combination with timber)
4. bamboo reinforced wood
5. bamboo reinforced polypropylene

The constructions of all these bamboo composite are the same with original composite material which have been replaced with bamboo except more variation in the use of bamboo as concrete reinforcement. Bamboo-fiber reinforced concrete will be constructed in the same way as glass-fiber reinforced concrete. Plybamboo construction is similar with plywood construction.

Up to the present time, bamboo has been the natural fiber most used experimentally as reinforcement in concrete due to its high tensile strength (Hidalgo 2003).The advantages of using bamboo as a reinforcing material in concrete are: (a) the high tensile strength and (b) the low price. The common tensile stress in steel reinforcement is 160 N/mm2 and in bamboo 20 N/mm2, a ratio of 8 to 1. The mass per volume of steel is 7 850 kg/m3 and of bamboo is about 500-600 kg/m3, a ratio of 16 to 1. Evidently, bamboo will be cheaper because the price of bamboo per weight will be less than half that of steel (Jannsen 2000). As concrete reinforcement, bamboo mostly is in the form of split (Figure 21) and the rest is in the full bamboo pole (Figure 22) and halved pole with some treatment.

Conclusion

Bamboo can be used in its original form or in a simple transformation with a conventional way of construction that is based on a set of unwritten rules, agreed, stipulated or generally accepted standards, norms or criteria of bamboo construction. This construction is classified as conventional bamboo construction.

The newer utilization of bamboo is to replace other possible material with bamboo, thus bamboo will be constructed in other material logic. For example, bamboo construction in form of laminated bamboo is used to be constructed in the same way as wood construction. There are many other utilizations of bamboo such as replacing steel as concrete reinforcement or replacing steel member in a space frame or space truss structure. These bamboo constructions thus will be classified as 'substitutive bamboo construction'.

This classification of bamboo construction describes more detail about the variety use of bamboo in building construction. This is very important to people or organization dealing with bamboo to have a wider perspective of bamboo construction and in the end to focus in some particular bamboo construction that fit with their need or the properties of available bamboo.

With a better understanding, hopefully in the future a wider cooperation will be conducted in research and development of bamboo construction, not only in conventional bamboo construction, but also in the field of bamboo as substitutive material. And the participation in this cooperation also become wider, not only in country where bamboo grow, but also everywhere in the world (such as Europe), because bamboo is one of sustainable biomass source that can fullfil some parts of the need of building material in the world.

Reference

Arboleda, G. 2006. What is Vernacular Architecture? Berkeley, CA: Ethnoarchitecture.com. Available from World Wide Web: http://www.vernaculararchitecture.com/web/articles/article/497

Brunskill. W. 2000, Vernacular Architecture: An Illustrated Handbook, 4th ed. Faber & Faber.

Dunkelberg, K. 1985. Bambus als Baustoff [Bamboo as a building material]. In IL31, Institute for Lightweight Structures, Stuttgart, Germany.

Hidalgo, O. 2003. Bamboo the gift of the gods. Oscar Hidalgo Lopez, Bogota, Colombia.

Jannsen, J. 2000. Designing and building with bamboo. INBAR Technical Report No. 20. International Network for Bamboo and Rattan, Beijing, China.

Kalberer, M. 2007. Das Bambus Bau Buch. AT Verlag, Baden und München, Germany.

Trujillo, D. 2007. Bamboo structures in Colombia. The Structural Engineer, 25-30.

Velez, S. 2000. Grow your own house. Vitra Design Museum, Germany.

Widyowijatnoko, A. 1999. Kajian konstruksi bambu plaster dan konsep pengembangannya. Master’s Thesis, Department of Architecture, Institut Teknologi Bandung, Indonesia.

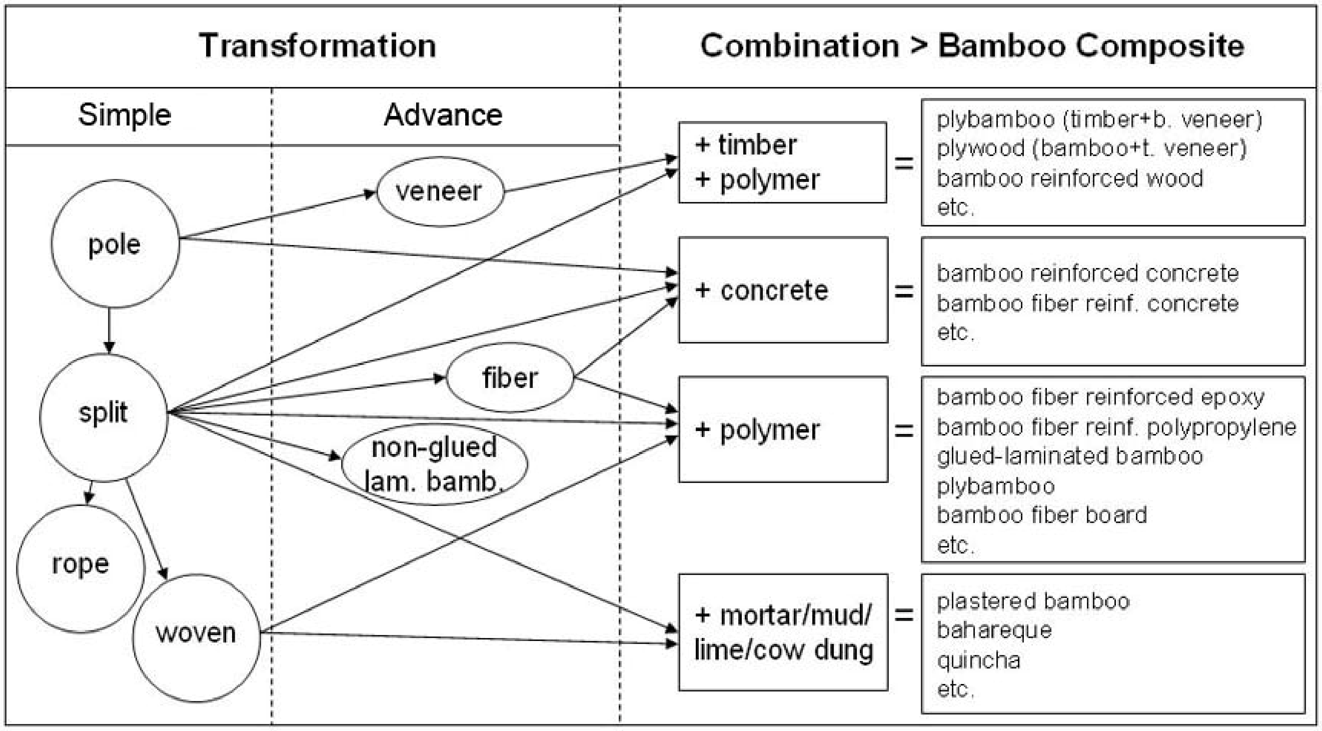


Figure 1 Maps of bamboo-based building material

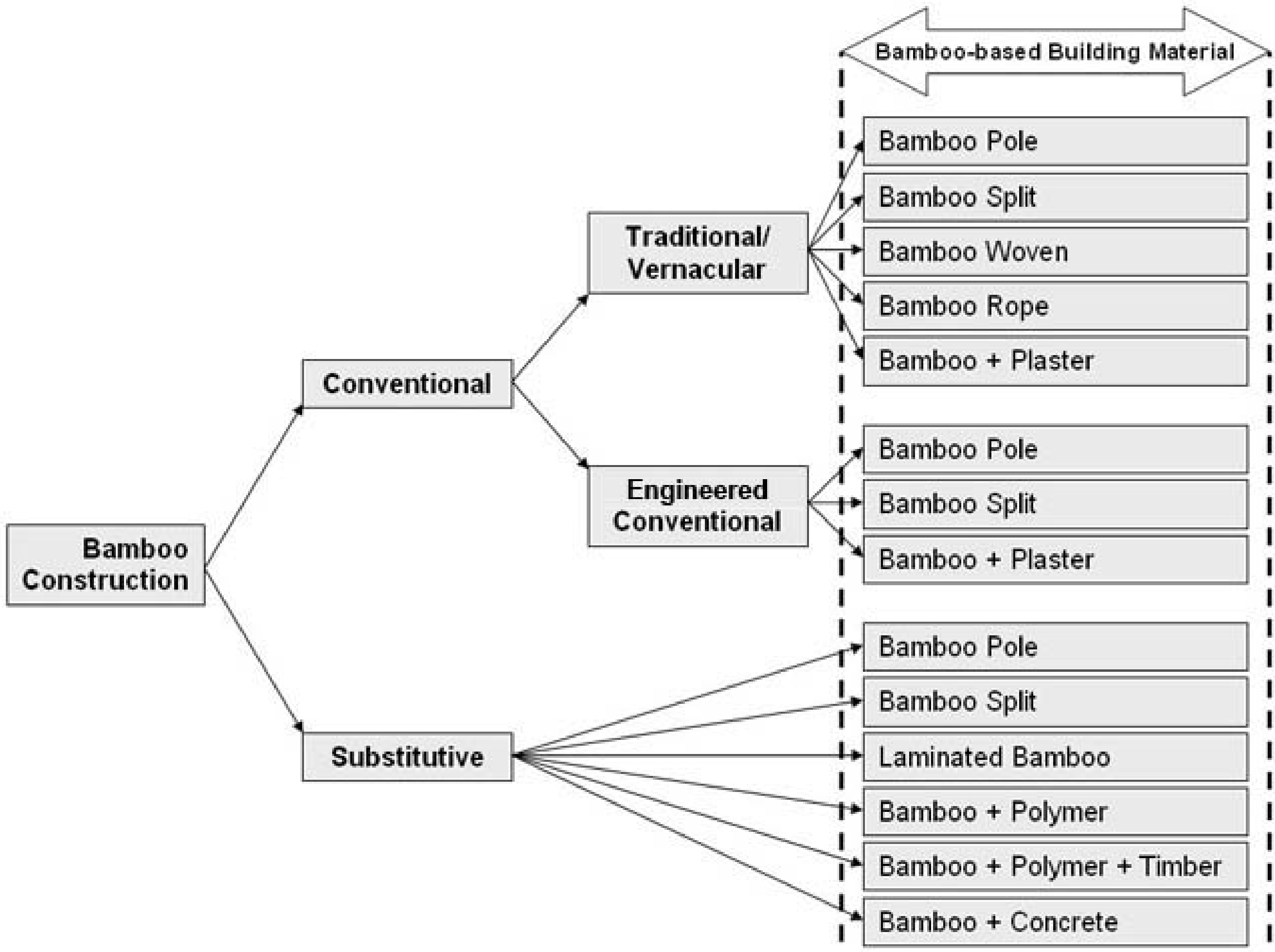


Figure 2 Tree of bamboo construction classification

Figure 3 Fish-mouth joint with two pinned flanges (Courtesy of Benjamin Brown)

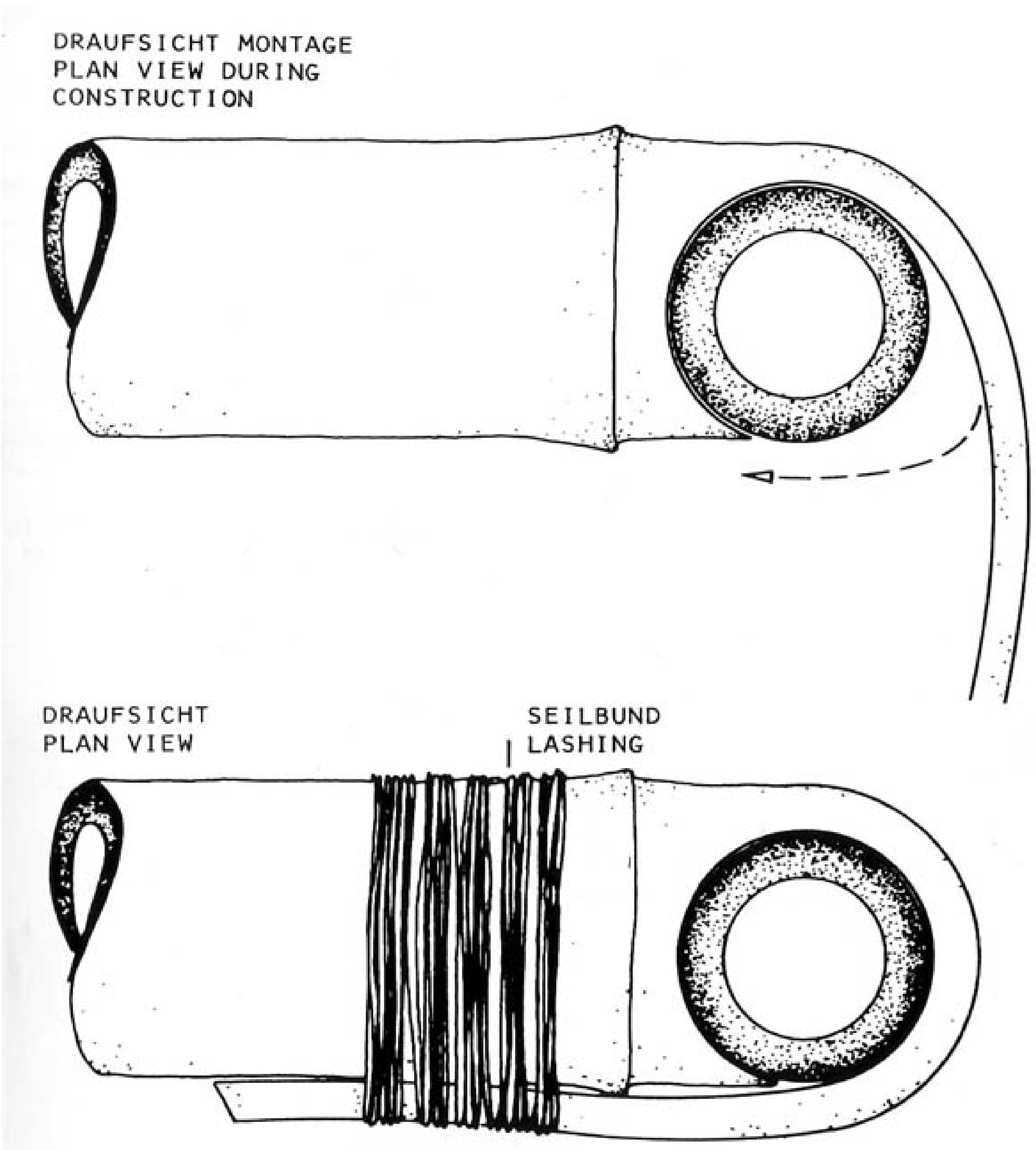


Figure 4 Fish-mouth joint with bended thin flange and lashing (Dunkelberg 1985)

Figure 5 Traditional bamboo gazebo in Indonesia with positive fitting and rope connection

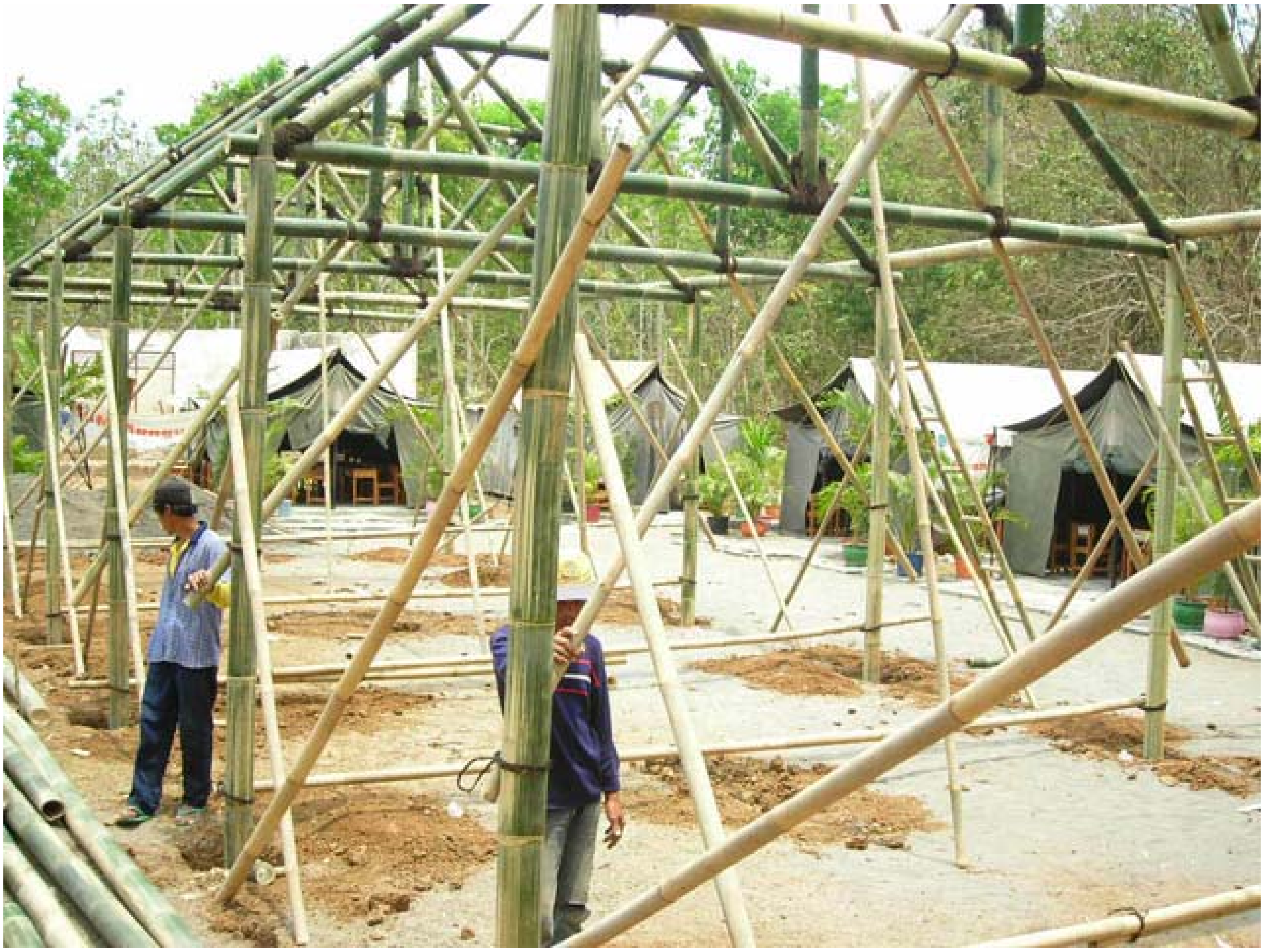


Figure 6 Planar frame in common traditional bamboo constructions (Courtesy of AMURT)

Figure 7 Traditional bamboo housing in Colombia (Courtesy of Lionel Jayanetti)

Figure 8 Eccentricity in traditional bamboo connection and the effort to place the connection near to the node

Figure 9 Traditional bamboo construction that made of split or woven bamboo (Velez 2000)

Figure 10 Himalayan Suspension bridge using bamboo cable (Hidalgo 2003)

Figure 11 Traditional plastered bamboo from Nepal (Courtesy of Lionel Jayanetti)

Figure 12 Two dimensional frame with many layers (Courtesy of Jörg Stamm)

Figure 13 Three dimensional frame (Courtesy of Simon Velez)

Figure 14 Eccentricity of load transfer in a connection (Courtesy of Jörg Stamm)

Figure 15 An innovative form made of bamboo split (Kalberer 2007)

Figure 16 The development of plastered bamboo construction in Indonesia

Figure 17 Bamboo as compression element in combination with steel tension wire

Figure 18 The development of bamboo connection to avoid eccentricity of load transfer with a space frame connector (Courtesy of Evelin Rottke)

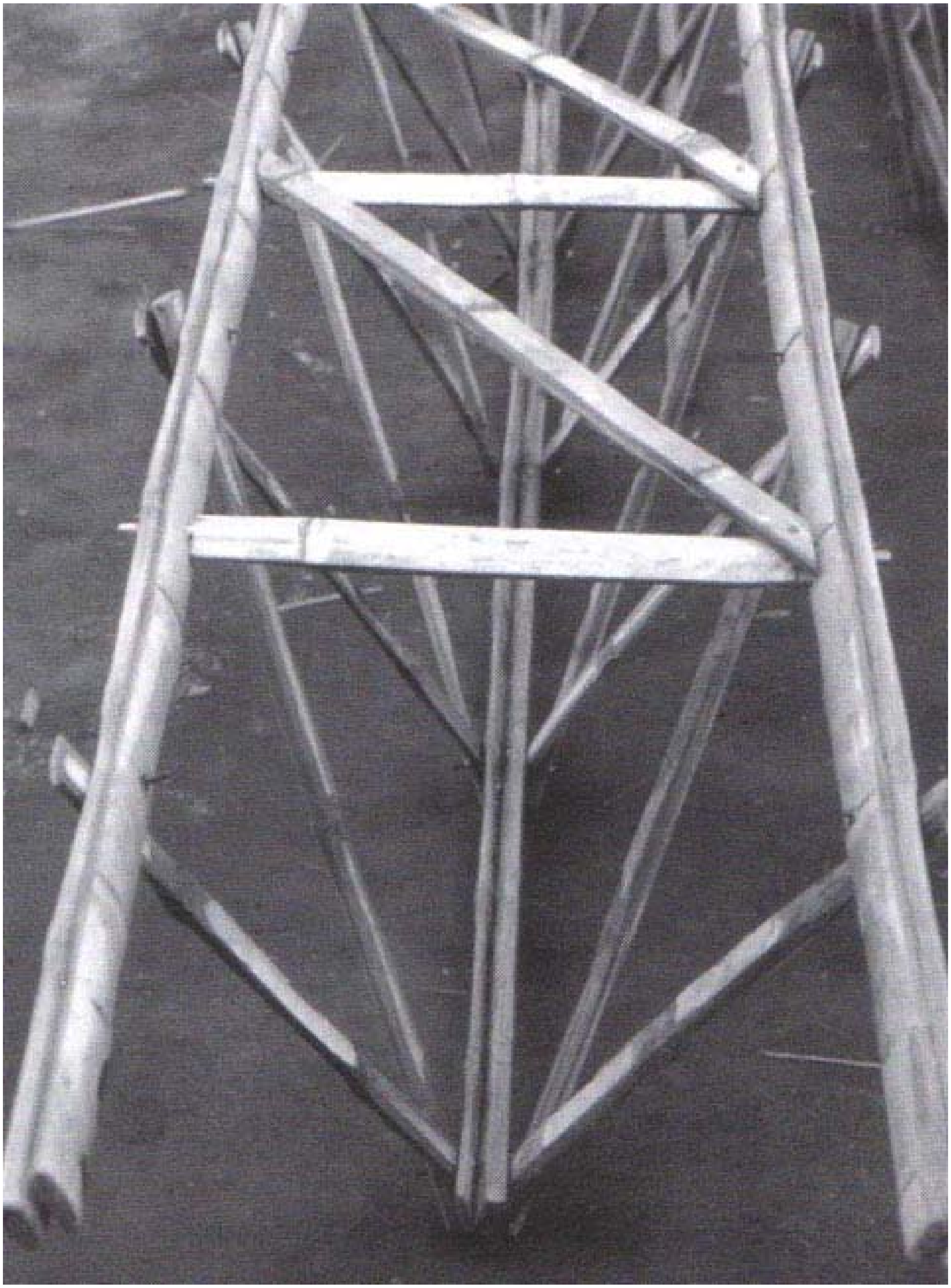


Figure 19 Space truss beam out of bamboo split (Hidalgo 2003)

Figure 20 Glued laminated bamboo as roof frame (Courtesy of Chen Xiaoan)

Figure 21 Bamboo split as concrete reinforcement in Bali, Indonesia

Figure 22 Utilization of bamboo pole as reinforcement for prefabricated concrete beam

Our Explorations in Bamboo Constructions

Munir Vahanvati, Mittul Vahanvati
Institutional Affiliations: Co-M Design Studio

Abstract

Bamboo, as an ecologically sustainable, aesthetically pleasing and structurally high performing material has fascinated us since the time we came to know it. We see a great potential in bamboo as an alternative material for the modern society's housing industry. Though our main intention is in promoting the use of bamboo in small-scale building industry, we have explored a wide array of possibilities with bamboo by making small products, furniture, temporary stalls and permanent sheds.

The paper talks about our explorations with bamboo as a material for a sustainable future. By the term 'explorations' we mean the new designs we've created and the experimentation we have done with various connection details and sculptural forms. Although we have explored bamboo design at various scales, the paper will mainly focus on the bamboo structures that we have designed. All these projects were made possible by the involvement of various people like tribal craftsmen who were highly skilled in bamboo skills, local community who had wood-working skills but no knowledge of bamboo or University undergraduate students who did not know anything about bamboo nor had the skills of working with various basic tools. The projects were mainly conducted as construction workshops for the participants to learn the skills in working with bamboo through hands-on experience.

Each project has enriched our knowledge of this material and provided a better understanding on working with bamboo. Through this paper, we intend to be able to share our learning from our past projects with the interested community from around the world as well as to be able to learn something new from other's experiences. We end the paper with future directions that we intend to take, after reflecting upon the lessons learnt from these construction projects.

Introduction

We were introduced to this amazing natural material by Professor M P Ranjan from the National Institute of Design (NID) India. With a background in architecture, we were immediately fascinated by the works of the great bamboo architects like Simon Velez, Darrell DeBoer, Marcelo Villegas and others from around the world. At the time we were working in India which has vast bamboo forests especially in the north-east, but found an overall lack of contemporary bamboo architectural designs which used this beautiful material in an appropriate manner. We immediately realized this gap and started exploring the potential of using bamboo for the construction of contemporary structures along with products and furniture items.

The beginnings

In mid 2003 an opportunity came our way to work with Professor M P Ranjan as part of NID team stationed at Bamboo and Cane Development Institute (BCDI) in Agartala, NE India. At the time only one of us was able to go to Agartala due to other commitments and hence it was decided that Mittul would work at NID-BCDI with the local craftsmen. The task at NID-BCDI was to teach the craftsmen basics of design and develop new designs. Being part of NID-BCDI was a big learning curve for Mittul and was a satisfying experience to work in close collaboration with the local craftsmen.

In year 2004, The Mayor of Dang commissioned us to conduct a Skill and Product Development Workshop, which involved training the local craftsmen in the contemporary use of bamboo. This was our first project in bamboo and we were very excited to work on this project which involved designing and constructing bamboo products and a small structure. Immediately after finishing the structure we moved to Sydney Australia for higher studies. Having successfully completed a structure out of bamboo before leaving India provided us a good background to continue our work with bamboo in Sydney.

During our studies at the University of New South Wales (UNSW) Sydney, we got to know Peter Graham- a lecturer at the Faculty of the Built Environment (FBE). Peter was highly impressed with our passion for bamboo and with the work that we had done in India. With rising concerns about sustainability and the need for fostering thinking about alternative materials amongst students, Peter asked us whether it was possible to build a structure designed for steel patented as *The Loveshack*, out of bamboo. We readily accepted the challenge and responded positively. Hence in July 2005, a modified version of *The Loveshack,* named the *Bamboo Loveshack* was designed and constructed under our guidance by undergraduate students of UNSW. *Bamboo Loveshack* was a great success for the university and it also became a showcase project of our skills with bamboo.

We began to spread our experience in bamboo construction by engaging in various hand-on construction workshops and giving talks about bamboo architecture at various eco-living and sustainability festivals. We got opportunities to teach short courses at the University of Canberra and University of Adelaide. Some of our bamboo projects include Greenfield Stage Entrance, Peats Ridge Festival Walkway, Chicken Shed at Eco-living Centre and Bamboo Spiral at the Earthdance Festival.

Our approach

Our interest in bamboo is grounded in the intention to foster the widespread use of this structurally high-performing, low cost and ecologically sustainable material in small-scale building industry. There is a vast amount of information available for building with bamboo but it is very important to have hands-on experience to be able to successfully understand the qualities of this amazing material. This statement would hold true for working with any natural material. Since bamboo is not a product of an industrialized process, its form is not perfectly cylindrical, its skin is not of the same thickness and it tapers along its length. Hence active, hands-on, experiential engagement is required with bamboo to be able to understand the material and successfully work with it.

After moving to Australia we wanted to continue our work with bamboo, but without local craftsmen and the required skills it seemed difficult to get anything built out of bamboo. So we decided to conduct workshops teaching people about bamboo construction and develop the required knowledge and skill base for 'do it yourself' construction. This slowly developed our 'active learning' approach to all the bamboo projects and workshops. During workshops we spend very little time over theory or lectures and encourage our participants to have experiential learning by working with bamboo. Each hands-on project is followed by reflection on our learning by writing papers, photo documentations and passing it onto the participants of future workshops during open discussions. With each structure we have tried and experimented with bamboo's building form and connection details. Each new project brought new challenges and opportunities which enabled us to 'break the grounds' expanding our understanding of this fabulous material.

All these projects have enabled us to work with varied strata of people ranging from craftsmen, local community and University students. It has always been a two way learning process during these hands-on workshops. We are here to share our experiences during various bamboo explorations in this discussion and learn from others' experiences.

Design and construction

Exhibition Stall, Dang, May 2004

Our first bamboo structure was a small 'Exhibition Stall' built by the craftsmen of the tribal village of Ahwa in western India. Ahwa is a small town in Dang district in the state of Gujarat and has vast bamboo and teak forests which are managed by the Department of Forest. The two main species of bamboo growing in Dang are *Dendrocalamus Strictus* and *Bambusa Bambos*, locally known as *'Katas*' and '*Manvel*' respectively. The tribal people of Dang have used bamboo for their day to day purpose since centuries and are highly skilled in working with bamboo. Some local craftsmen also produce small handicraft items from bamboo to earn their living. Although the local people are skilled in working with bamboo they have little knowledge of contemporary design and lack the skills required to make furniture and structures.

We were invited by the local government of Dang to conduct a Skill and Product Development Workshop and train the local craftsmen in more contemporary use of bamboo. The Exhibition Stall structure was designed and constructed as a part of this workshop and was used to display various other bamboo products at a state wide festival called '*Gujarat Diwas*' held in the city of Surat.

The Exhibition Stall was a rectangular structure consisting of eight portal frames arranged parallel to each other. Before finalising the design of the portal frames we had experimented with various connection details and tested their strength and rigidity. A connection detail which utilised the corbelling of bamboo members was finalised to achieve a rigid joint. The portal frames of the structure were fabricated in the workshop and transported to the site for assembly. Since the structure was temporary in nature the portal frames were directly fixed in the ground by digging a trench and backfilling with earth. Rigidity for the structure was achieved by tying the frames laterally on the top and from the sides by beams (Figure 1).

The main purpose of the structure was to exhibit bamboo products and hence we had designed a display system that utilised the hollow characteristic of bamboo. Support for the display shelves were made by cutting and bending a strip of bamboo from the culm and the shelves were made from flattened bamboo boards plugged with whole bamboo on either side. The display shelves spanned across the portal frames and connecting them enhanced the rigidity of the structure. The structure and the new product range were highly appreciated at the festival and the craftsmen were satisfied with the final outcome with some visitors placing orders for the exhibited products. During the course of this project we learnt a lot more about bamboo and became more confident is using this material for structures which are more permanent in nature.

Bamboo Loveshack, UNSW, Sydney, Jul 2005

The Bamboo Loveshack was our first major structure which had all the components of a small building. It is Australia's first student designed and built bamboo structure built for the Eco-Living Centre at the University of New South Wales (UNSW) Sydney. The structure is based on the original Loveshac*k* designed by Darwin based architect Simon Scully which was built by students out of steel for the past two years as a part of the winter elective at UNSW. The elective was run over 3 weeks full-time with students from varied departments of the Faculty of the Built Environment. Most of the students were working with bamboo for the first time and knew very little about this amazing grass. Our intention was to provide the students with a holistic understanding of bamboo starting from its various species, harvesting, treatment, connections and assisting them with the construction process.

The Bamboo Loveshack used the same form as the original design with some modifications to suit the site and the new material. The driving motivation was to test if the same form that was designed for steel could be used for bamboo. The material was sourced locally from northern NSW and the species of bamboo used were *Phyllostachys Bambusoides* (for the main structure), *Phyllostachys Aurea* (for decking and smaller members) & *Dendrocalamus Asper* (for foundation). All the bamboo was treated prior to beginning of the elective by dipping it in an aqueous solution of boric acid and borax.

The elective started with an introduction for students into the various species of bamboo, their potentials and limitations, our past explorations and understanding of the qualities of bamboo. Simultaneously the students were divided into teams based on the various components of the structure: foundation; floor; walls; roof and deck. Each team was responsible to design and build their part of the structure while coordinating and collaborating with the other teams. The first week was focused on design development and laboratory testing of prototype connection details with the help of an engineer John Carrick, the second week was for the fabrication of various components in the workshop and the third week for on-site construction of the structure (Figure 2).

Bolting was used as the main connection detail throughout the structure with some joints poured with quick hardening cement to increase its rigidity. The wall panels within the structure were made as various types of bamboo screens sandwiched between two layers of persplex to provide weather protection. Bi-fold timber doors at the corner of the structure provided access while opening the building towards the garden. The deck around the structure was cantilevered from the main support to create a floating effect (Figure 3).

The Bamboo Loveshack was an intense workshop run over the period of three weeks, which provided an intense learning experience for everyone involved and raised a lot of issues for us to reflect on. Through subsequent evaluations of their written journal, students demonstrated strong learning in their understanding of working with this eco-friendly material. Towards the end of the elective students presented a sense of ownership of the structure and were very proud of this shack, which was the greatest achievement of this elective. It also became a significant step forward in our own explorations with bamboo as a construction material.

Greenfield Stage Entrance Structure, Sydney, Apr 2006

The entrance to the Greenfield Ecoliving Stage was a very small project that was delivered in a short time frame and had to be simple enough to be built by volunteers. As an entrance structure the design needed to be an inviting and attractive entrance canopy to a marquee that would house the Greenfield Stage. The purpose of the stage was to spread awareness about sustainability by a series of workshops and talks and hence bamboo was the right material to create the entrance structure.

The design of the structure was based on two intersecting hyperbolic paraboloids supported on a frame structure with posts at varying heights. The resulting form resembles the flight of a bird and creates a curved and flowing effect using straight and rigid bamboo poles. The form revolved around two major constraints for the project i.e. the maximum length of available bamboo was only 4m and was on loan from the supplier for the duration of the festival. Lashing with sisal rope was used for connecting the bamboo poles because it would be easy to construct by the volunteers as well as not damage the bamboo. Treated 'Moso' imported from China by House of Bamboo in Sydney was used for the structure. Preparing drawings was difficult due to the complex form of the structure so we had made a scaled model to get the right form and effect. The model was then used to explain the structure to the volunteers and as a reference during construction process (Figure 4).

We briefed the volunteers on the design of the structure and it was built in a short time frame of just two days. The final product created a dynamic effect of a movement frozen in time. It also created interesting light and shade through the rhythmic use of bamboo.

One of the volunteers was from construction background and was really impressed with the outcome of the structure and the ease with which it could be constructed. He had learned a new skill of working with bamboo and wanted to try building one structure at his home. We were glad to have engaged at least one such person in the exploration of bamboo construction.

Peats Ridge Festival Walk-way structure, Sydney, Australia, Dec 2006

Peats Ridge Festival is a sustainability, arts and music festival held every year in the Glenworth valley at Peats Ridge, one hour drive north of Sydney. The festival is held during the New Year with approximately 8,000 people attending. The site for the festival is set in a beautiful valley surrounded by national parks, with a creek snaking through the middle creating several paddocks. The bamboo structure was to be designed so that it became the main entrance gateway and walkway to the festival area from the camping area. One of the main challenges was to make the structure of a significant scale with respect to the huge tents and marquees that were to be erected in the festival paddock.

The concept for the structure was derived from the adjacent creek and beautiful natural surrounding with a primary aim of making a structure that was simple yet dynamic, easy to construct and belonging to the place. The idea was to make the structure as an experience for the people to walk through while admiring the beauty of bamboo and the surrounding nature, rather than making a gate separating the camping area and the festival site. The entrance was to be built by volunteers and hence needed to be simple in terms of its construction method but still have a visual presence. It also had to be dismantled once the festival was finished. The design consists of curved overlapping walls made out of vertical bamboo posts of varying heights, placed at approximately 30cm apart. Three different interlocking portals of varying heights make up the entire structure with a total length of 25m and a width of 4 to 7m. The closely spaced vertical bamboo poles create a sense of enclosure screening the festival site and the overlapping adjacent walls allows for an opening, providing a glimpse into the natural surrounding and the festival site. The roof of the structure was also made of straight bamboo poles creating various interlocking hyperbolic paraboloids. Lashing was used as a method of connection as it would allow for the necessary flexibility in the organic form and would be easy to construct without any special tools. Bamboo strips were lashed on the top of the vertical bamboo posts to keep them vertical and it also acted as a beam to support the roof members.

The bamboo species used was *Phyllostachys Bambusoides* which was sourced locally from a wild patch in Glenorie. Since this was a temporary structure it was not necessary to make any concrete foundations and the bamboo posts were directly fixed in the ground. There were some last minute changes to the original design due to the available length of bamboo and some on-site challenges but the organic nature of the design accommodated these changes and in fact enhanced the beauty of the structure. One such modification was the gap in the roof which was left because of the unavailability of the required length of bamboo. While we were contemplating on the ways to resolve this issue, someone suggested that it would be full moon in a couple of days and since the structure was facing east the moon would shine right through the gap in the roof, which would act as a pause point for people walking through the structure in the evening. So the gap was left as part of the design and in the evening we did see the full moon unobstructed through this void in the roof. Brendon, a sculptor and one of the volunteers came up with an idea of incorporating bamboo wind chimes with the structure. This added another dimension of movement and sound to the frozen dynamic form of the structure which created rhythm of light and shade (Figure 5).

The structure looked completely surreal at night with all the colourful lighting and was highly appreciated by everyone who had walked through it. The owners of the site liked the structure so much that they wanted it to be retained. Hence till this date, the structure stands on the site, its condition unknown, since the entry to that part of the paddock is restricted but we are sure it will slowly deteriorate and become one with the land.

Chicken Shed Workshop, UNSW Eco-Living Centre, Sydney, Jun 2006

We had conducted a community workshop in Sydney which involved building a small shed structure to house 5-7 chickens at the Eco-Living Centre of University of New South Wales (UNSW). The purpose of this workshop was to introduce the participants to the various possibilities with bamboo as a construction material and to enable them to build with bamboo in their backyard. The participants were also involved in the concept design of the shed that used passive design and permaculture design principles. Apart from building the structure out of whole bamboo, they were also taught the skills of making bamboo strips and weaving bamboo mat which was later used as one of the walls.

The structure was approximately 1.2m wide and 2.0m long with a single sloping roof opening towards the north to capture the sunlight. The north wall had large opening to allow for the sun and the south wall was made of bamboo mat rendered with mud for insulation. The floor of the shed was made of recycled concrete with a layer of straw on the top. The structure was approximately 1.5m high to allow easy human access for cleaning purposes. For this structure we had experimented with a specific connection detail that is commonly used in the construction of temporary metal fencing. The fencing connection was essentially a metal clamp which clamped the ends of bamboo. Each member of the structure had to be selected carefully such that its ends had same diameter because the clamps were of standard size. Rubber padding was used between the clamp and bamboo where necessary to achieve a tight hold. By using such a connection we were able to reduce the number of bamboo poles significantly as compared to bolting connection and that too without compromising the strength of the structure. This was particularly possible due to the small size of the structure (Figure 6).

Although the construction of the shed was not finished due to various reasons, the participants got a hands-on experience in working with bamboo and were highly inspired to continue doing more. This particular clamping detail had some limitations because of its standard diameter and rigidity, but the good thing was that no holes were required to be drilled through the bamboo, which would help avoid its cracking. We think that a similar but more flexible clamping detail if designed specifically for bamboo construction could be a really useful connection. This could make the building of small structures out of bamboo a very quick and easy process.

Our reflections:

With every bamboo project we have learned something and advanced our knowledge. At this point we would like to reflect upon some of the learning.

- The form of the Bamboo Loveshack used the traditional post-beam construction system and was originally designed for steel. Although the connections were redesigned for bamboo, the bolting connection created pin joints which had to be stabilized by diagonal members and truss system. After the structure was finished we realized that a more integrated structural system, where all the structural elements like floor, wall and roof are not thought of separately but as part of one whole structure is required if full potential of bamboo is to be utilized.

- Since bamboo is a natural material the construction process is very different compared to other industrialized materials which are available in standard size. During the construction of Bamboo Loveshack, the foundations were laid only for the floor team to realize that it didn’t line up with their pre-fabricated floor frame in spite of all coordination on drawing board. Similar issues were faced between the floor frame and the wall frame alignment. Hence in bamboo construction a real on-site involvement is required to get a successful outcome, this is clearly visible in the works of architects like Simon Velez.

- One of the most important lessons from Bamboo Loveshack was that although bolting is a preferred joinery for large structures that are built in Colombia using Guadua, it is not suitable for other structural species which have thin walls like *Phyllostachys Bambusoides*.

- Clamping was used as a connection detail for the Chicken Shed structure to overcome the issue of cracking in bamboo due to bolting. The clamps we used were made for metal fencing joints and had standard size. We used rubber strips at the connection to accommodate the minor change in the size of bamboo but it was still difficult to find the bamboo of right size and get a strong connection. A similar kind of custom built clamp with adjustable diameter and angle would be very useful for making bamboo structures that are quick to build.

- Lashing was explored for temporary structures at the Greenfields Stage and at Peats Ridge Festival. Lashing allows for slight movement of bamboo poles in relation to each other and also retains the structural strength of bamboo as there is no need to drill a hole. But it also has its drawbacks in terms of requiring regular tightening and maintenance and is time consuming to build.

- Custom made joints like flexible clamping or other kinds may be one of the connection details that might work well with a natural, cylindrical and tapering material like bamboo. We think that a lot more experimentation is needed from our side to find a right connection detail that is strong, durable, easy to build, uses minimum level of skill and works for various species of bamboo.

- Most of our work to date has been limited to temporary structures and pavilions due to the lack of building regulations in the western world. This makes it extremely difficult to get building approvals for any habitable structure to be built out of bamboo. More work needs to be done to get some standards for bamboo construction, which has been acknowledged in many research papers.

Future projects:

Our explorations with bamboo have ranged from products and furniture items to temporary exhibition structures and small permanent sheds. Though we haven’t yet constructed our perfect dream structure, but to ignore the vast array of our previous ‘less than perfect’ structures is to miss out on a lot of creativity. It is only with these past experiences that we have a platform to celebrate what we have done so far and develop further structures.

Bamboo has the possibility to replace timber as a sustainable alternative material in many structures especially in small scale buildings and small structures. Our main interest is in using bamboo as a low-cost, ecologically and socially sustainable construction material.

Some of the projects that we are currently working on include:

- Design of a structure based on the principles of Pyllotaxis. Currently this project is at a conceptual stage but we see lot of potential with this form which will result in a structure that would be lightweight and strong.

The resulting form could be used as a temporary shelter that can be built easily in areas that have an abundant supply of bamboo or used as a permanent dwelling (Figure 7).

- Design an eco-home by combining bamboo with other environment friendly materials like mud bricks, straw bale, etc. These eco-homes could also be used as cabins for eco-tourism purposes.

- Design a clamping connection detail that is adjustable. This would make constructing temporary bamboo structures very quick and easy to assemble as well as dissemble. The connections would be made from strong material like iron so that they can easily be reused for a long time.

References:

Ranjan, M.P., Iyer, N. & Pandya, G (2004). *Bamboo and Cane Crafts of Northeast India* (2nd Ed.). The Development Commissioner of Handicrafts, Government of India, New Delhi, India. (total 344 pages)

Farrelly, David (1938). *The book of bamboo- A comprehensive guide to this remarkable plant, its uses, and its history.* Sierra Club books, San Francisco.(total 332 pages)

Villegas, Marcelo (2003) *New Bamboo- Architecture and Design,* Villegas editors, Colombia (total 207 pages)

Hidalgo-Lopez, Oscar (2003) *Bamboo- the gift of the gods*, Oscar Hidalgo-Lopez, Colombia (total 553 pages)

Janssen, J.A (1988). *Building with bamboo- A handbook*. Intermediate technology publications, Eindhoven, the Netherlands.(total 68 pages)

Velez, Simon (2000) *Grow your own house- Simon Velez and bamboo architecture,* Vitra Design Museum/ ZERI/ C.I.R.E.C.A. (total 252 pages)

DeBoer, Darrel (2003) *Bamboo Building and Culture- Applications in The U.S.* DeBoer Architects.com (total 43 pages)

"*Inssitut fur leichte Flachentragwerke*"(IL) (1985), IL-31 *Bamboo,* University of Stuttgart, Germany

Ranjan, M.P. (1991). *Ecology and Design- Lessons from the Bamboo Culture*. Keynote address at the International Bamboo Culture Forum at Oita, Japan. Retrieved on March 15, 2006 from *http://homepage.mac.com/ranjanmp/Menu22.html*

Mardjono, F (1998). *Bamboo Knowledge based Building Design Decision Support System*. Retrieved March 30, 2006 from *http://www.bwk.tue.nl/bko/research/Bamboo/Fitri.htm*

Snelson, Kennith personal webpage. Accessed on March 5, 2006 from *http://www.kennethsnelson.net/icons/struc.htm*

Fuller, B.R., Applewhite, E.J. (1979). Synergetics: Explorations in the geometry of thinking. Accessed on March 29, 2006 from *http://www.rwgrayprojects.com/synergetics/synergetics.html*

Antonio Arce-Villalobos, Oscar (1993) *Fundamentals of the design of bamboo structures,* Thesis at Eindhoven University of Technology, Eindhoven. (total 261 pages)

Figure 1 – Exhibition Stall

Figure 2 – External view of the Bamboo Loveshack

Figure 3 – Internal view of the Bamboo Loveshack

Figure 4 – Greenfields Stage Entrance

Figure 5 – Night view of Peats Ridge Walkway

Figure 6 – Connection detail for Chicken Shed

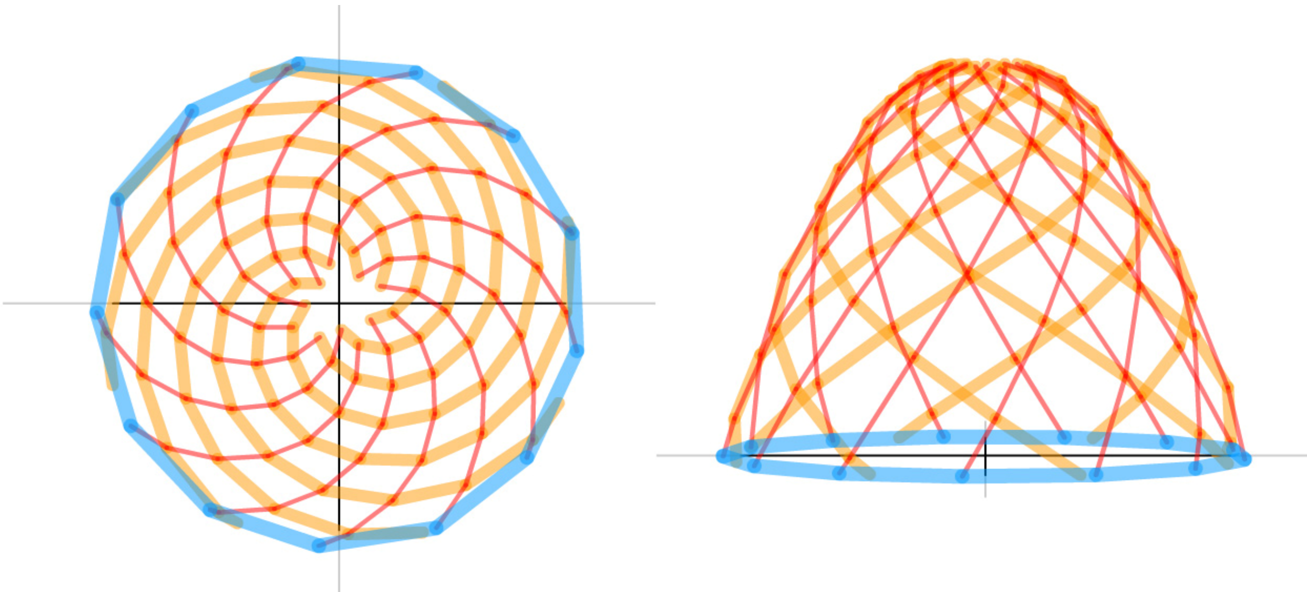


Figure 7 – Phyllotaxis Dome concept

Construction and Construction Methods: Bamboo Building Essentials

Darrel DeBoer
Architect

Megan Groth
University of Washington

Note to Committee

We have imagined this presentation as either a lecture with a significant discussion component, or as a hands-on, design session. As a lecture, we would quickly present our twelve points of building essentials – complete with case studies and specific, regional and global examples – in order to begin a dialogue with participants about what they have found to work well in their local species, ecosystem, and cultural tradition. What is the most important information about building with bamboo? And what is the most effective way to distribute this information to the greatest number of people? During this conference, we are looking to not only share the information that we have gathered from various experts around the world, but also to use this event as a starting point toward increasing awareness about bamboo building principals and skills that can help millions of people around the world.

Abstract

Bamboo buildings have been attempted everywhere that bamboo grows, but only rarely are these buildings designed for the long-term. In remote places, people partially reinvent what has already been refined after much trial and error. We will present the basic steps we have found necessary for successful structures in order to start a dialogue among experts about the elements of good bamboo building design. We would also like to discuss the best ways to properly distribute this information in the various regions represented by the participants. This is not an academic paper in the sense that it presents original research. It is instead the collected experience of hundreds of papers put into some usable form that can be easily spread around the world. In summary, these principles include:

1) Plant the hardiest species for the climate

2) Plant where there is plenty of water and sun

3) Harvest mature poles

4) Harvest when the sugar content is lowest

5) Use less-toxic treatment methods

6) Work with the bamboo once shrinkage has taken place

7) Plan on splitting

8) Don't let the bamboo touch soil or concrete

9) Give the building a good hat and boots

10) Achieve shear strength with triangles in your truss design or with shear walls

11) Build with triangles

12) Use bolted and filled joinery systems

Paper

1) Plant the hardiest species for the climate

When growing bamboo species for building, choose varieties with thicker walls, as well as a cold tolerance that relates to your area - the key is to plant a species that is capable of withstanding the coldest seasonal temperatures. Refrain from using fertilizer on the bamboo, in particular nitrogen, which leads to rapid growth and weaker poles.

The current international building code tested strength of a species from a single place and time as applicable for the entire species, regardless of growing conditions. Several builders have put forth the "unproven" idea that the density of the wood is a better measure of how soil, rainfall, care and age have all had their effect - regardless of species. Unfortunately, there are currently no grading or quality standards for bamboo poles. This means that the purchase of poles involves a great deal of faith and relationship-building between buyer and grower.

Different species are chosen for import into the U.S. because of a unique visual characteristic like striped leaves or colored culms. For builders, the most intriguing species are seen by others as "just another green bamboo." But imagine what we consider the holy grail of bamboos: in the tropical latitudes of the Himalayas, over thousands of years, plants have been forced to adapt to the rise of the mountains to very high elevations. So, the unique combination of a clumping, cold-tolerant, large diameter with strong fiber and tremendous pole production when grown in a more favorable climate might exist.

2) Plant where there is plenty of water and sun

Bamboo requires plenty of water year round, as well as an abundance of sunshine. For this reason, bamboo is seen growing wild in ravines and along the banks of rivers and in places with a Monsoon hot-season climate: tropical Southeast Asia, the temperate foothills of the Himalayas, and the tropical northern half of South America primarily.

In places where there is less rain (i.e. southern California), wastewater is a good water source. The dense feeder roots make great filters and bamboo is capable of handling and using much hotter sources of nitrogen than most plants. Moso bamboo, for example, seems not to thrive unless watered every day.

When growing bamboo in places without monsoon rains, liberal use of mulch and cardboard will both hold in the moisture and allow the plant to use less energy otherwise needed to force its roots through the heavy clay soil. Additionally, oxygen enters through the rhizomes of the bamboo, therefore it is important that the plant is able to drain well. Mulch will allow for this process to happen efficiently.

The amount of sun required varies by species and past experience is catalogued by the American Bamboo Society. It is important to know that some bamboo species are native understory plants and need to be established in partial to full shade. In general, though, growth rates are significantly faster in full sun.

3) Harvest mature poles

Bamboo reaches maturity three to six years after the shoot first emerges. At this point the fibers are strongest and there is less moisture in the culm. The beauty of planting your own bamboo is that you will know the age of your culms, and therefore when it is time to harvest. Unfortunately this is often not the case, but there are a few tell-tale signs to look for in order to determine whether or not a culm is ready to be harvested. In tropical climates, the oldest culms are the ones with the most lichen and mosses. Clean, smooth poles should be avoided as they are probably new shoots and are lacking the strong structural qualities needed for building. Some species (i.e. Genus *Phyllostachys*) have a characteristic white wax ring below the nodes that will gradually darken over time. Once it is no longer "white," the pole is in its third year. Other species acquire color slowly over time, for example *Phyllostachys nigra* and *Phyllostachys nigra* "bory" acquire their dark spots over several years. Also in the *Phyllostachys* genus, plants grow another sub-branch on the same lateral branch each year - therefore the age of the culm can be found by counting the branchlets.

4) Harvest when the sugar content is lowest

It is best to harvest bamboo when the starch content of the plant is lower and therefore less susceptible to attacks by insects (though some argue that this is due to seasonal changes in insect populations and not the starch content of the plant). There is rich regional folk lore and traditions that describe the optimal bamboo harvesting day and time. In Colombia, for example, it is widely believed that bamboo needs to be felled during the waning moon, just before sunrise. In parts of India, bamboo that is cut during the bright, new moon is believed to be less susceptible to insect attacks. The important point is to harvest when sugar is at a minimum: after the spring and fall growth spurts, and following the rainy season can make a difference.

When felling the culms, cut at the base, “over the first node located above the ground", using as narrow a cutting tool as possible to reach between culms. A battery-powered Sawzall, chain saw, machete, pointed handsaw or a hatchet are all effective. Make sure that a bowl isn’t formed by the node that will collect rain water and rot the rhizome. While bamboo is relatively resistant to pests, the reason for the concern about sugars is related to attacks by powder post beetles, *dinoderus minutus*. Termites are generally uninterested, and other insects see the bamboo more as a home than food, the beetles will drill their 1/8" diameter holes and eat until very little structure remains. The damage might not be obvious since the beetles tunnel back and forth within the fibers and only visibly emerge when they're done - at which point the thin-walled poles can be crushed with your bare hand. The advantage of choosing the thicker walled poles is that the edible portion is the pithy interior fiber, not the structural exterior material. In this case, the pole will retain its structural qualities after an insect attack.

5) Use less-toxic treatment methods

There are two main ways that treating bamboo extends the life of the pole: it makes it distasteful to insects and it changes the pH and keep the moisture levels low to keep out fungus.

When thinking about treatment methods, consider how framing lumber is treated in your area, and do the same. Since Douglas Fir is never used exposed to weather, then keep bamboo inside in order to achieve maximum longevity. In general, untreated bamboo poles have a life of 1-2 years when exposed to the elements, 3-5 years when sheltered from rain, and up to hundreds of years when used indoors. The current less toxic treatment salts remain water soluble, but the task of treatment is to get it into the interior fibers, so it can, in theory, be exposed to the rain for awhile... it's just not great practice. In particular, do not expose the interior of bamboo to the outdoors. If bamboo is split open to reveal the interior, the sugar will cause little black dots of mildew to appear as soon as the rain starts. Surprisingly, one of the most effective treatments combines the ingredients found in eyewash and laundry soap. Boric acid -- found in Visine and Dr. Pepper, and most inexpensively sold as a fertilizer or mouse poison -- has little ill effect on mammals. Combine in equal parts with borax (sold as Twenty Mule Team laundry detergent) is not good for plants, but at about the 5% concentration that won't dissolve further, it is effective against both fungi and powder-post beetles. In Bali, the vertical soak diffusion method is used where the borax mixture is poured into the pole which has had the nodes punched out, leaving only the last one. The mixture is left in the pole for nearly a week where it diffuses through the pithier interior cell walls.

Another treatment method is the Boucherie system: a form of pressure injection that must be done within 24 hours of harvest or the capillaries close. This one can be a challenge. Various experiments have been done using smoke, but with mixed reviews. Japanese companies have perfected the method but the specific details have not reached other countries. At the moment, there are good things to say about hydrogen peroxide (but it's relatively expensive) and various plant-based traditional treatments practiced locally and worthy of intense study.

6) Work with the bamboo once shrinkage has taken place

It is possible to work with fresh, green bamboo if adjustable joinery (a system that can be tightened over time as the poles shrink) is used, but it is recommended to work with dry bamboo. After harvesting the bamboo, leave the culm in the grove - upright, propped up off the ground and with the branches and leaves still attached - for a few weeks. It will continue to photosynthesize and use up the remaining sugar in the culm until the plant runs out of water. The powder-post beetles are unlikely to enter the culm during this time because they enter through the cuts (i.e. where the branch is cut off).

Moisture content varies greatly between culms (as well as between sections of the same culm) and as the bamboo dries it will shrink about 6-10% in diameter, but almost not at all along the length. A general indicator is that once the green color is gone - which might be between 6 weeks and 6 months - it may be checked to see if it is in the desired 10-15% moisture content. Air-dry the bamboo by storing it in a covered area, out of the sun, preferably vertical for good air circulation and to keep it from becoming more curved months or so after harvest.

7) Plan on splitting

When it comes to bamboo splitting, do not ask "whether," ask "when." The bamboo you are working with will split, the key is to be prepared for this and know what to do when it happens. Outside of a few species of guadua, the fiber structure of bamboo runs in one direction, the length of the pole. The only exception is at the node where the fiber turns and runs perpendicular to the exterior to fill in the middle of the pole. Unfortunately, when the pole dries, the shrinkage of about 6-10% is entirely across the grain and the node shrinks differentially from the rest of the pole, causing the pole to split. This is especially true when a heat source, like the sun, hits the pole on just one side. Fence builders in Japan have learned that completely punching out the nodes can often prevent splitting. The stress can also be relieved by making a pre-emptive cut on the bandsaw the length of the pole, then gluing it back together (just as with a curly piece of wood). Joinery that wraps all of the way around the pole can also contribute to holding the pole together. Using banding or fiber binding at crucial joints will keep the fibers together, even if it never splits. With hollow bamboos, using something as simple as a radiator hose clamp can hold the fibers together. Joints can also be wrapped with twine for a different aesthetic.

Choosing the right bamboo specie for the job is extremely important. Some of the solid bamboos are much less prone to splitting: *Phyllostachys heteroclada* 'solid stem,' *Dendrocalamus strictus*, *Otatea acuminata* 'aztecorum', and several of the *Chusquea* genus. Of the hollow bamboos, those of the *Guadua* genus are generally thicker walled and have more of a helical fiber pattern. The lower portion of the culms especially will accept a nail or screw without a pilot hole, a characteristic not found in any other bamboo.

8) Don't let the bamboo touch soil or concrete

Regardless of climate, a main objective of bamboo design is to prevent the wicking of moisture on the ground up into the bamboo. Building codes generally require eight inches between wood and soil, and at least several inches between wood and exterior concrete.

The other simultaneous need in a post is to prevent it from pulling out of the ground. A good joint puts a separator like metal between the bamboo and the foundation, while at the same time holds onto that metal vigorously. The simplest way to achieve this is to make a bridge between the cellulose (bamboo) and the damaging water (in the ground or concrete). For example, use a piece of steel rebar or angle iron cast into the footing and mortar it several nodes into the bamboo to prevent withdrawal.

9) Give the building a "good hat and boots"

This is undoubtedly the most important lesson and one that is often overlooked. The first choice is to use all bamboo *inside the structures*. This will keep the sun and rain from affecting your building. Even small rafter tails peeking out beyond the overhang are guaranteed to split and provide insect habitat in a couple of years.

In the United States, millions of board feet of our favorite framing lumber - Douglas fir - are used, but almost none on the exterior where it would quickly rot. The first thing that happens is the sun and rain dissolve the protective wax, the surface bleaches to silver, the heat from the sun on only one side of the pole causes it to expand unevenly then split, and the fibers become brittle and break.

10) Achieve shear strength with triangles in your truss design or with shear walls

Use bamboo in tension and compression, not bending (imagine the flexing of a pole). It is important to recognize that bamboo wants to bend, but it is put to best use in pure tension or compression. Structural design principles for bamboo structures are the same as any other building system: for longer spans, design trusses. This will keep the poles from acting in bending.

When designing, do not ask for the same curve in multiple poles. Tight curves especially will be more of a fight than you want. Recognize the ever-present curvature. Most bamboos naturally curve in two dimensions not three, in a direction that is related to the branches. Poles can be turned until the flat is found in order to put multiple poles in the same plane.

11) Build With Triangles.

Designing a building with a series of triangles will provide stability by making the entire structure rigid. No shear walls will be required to carry the horizontal forces down to the ground. On the other hand, to rely on the strength of the joinery to this degree means that joinery should be optimized as much as possible. Additionally, longer spans have two or three bamboos stacked in the structural equivalent of a glu-laminated wood beam.

12) Use bolted and filled joinery systems

Here is where planning ahead helps the most. If you plan a structure that is quick to assemble and relies on simple joinery that is hundreds of times stronger than traditional lashed or pinned joints, then a relatively small investment in hardware makes perfect sense.

In western cultures, we think of our favorite building materials, especially wood, as subtractive. We start with a large piece and keep making it smaller until it is right. The surface is usually made flat and of standardized shape. With bamboo, the thinking is more akin to masonry, with the shape predetermined and not easily changed. The key is to celebrate the difference and use bamboo where the shape is an asset and very visible in the finished surfaces. Design the structure in order to avoid time-consuming joinery, especially where materials must be coped and curved in order to meet the bamboo. This will allow more effort to be put into smart design rather than into laborious repetition.

Conceived by Simon Velez and Marcelo Villegas, the mortar-filled joint is a recent development in the history of bamboo buildings, and one that has made the largest impact.

Seven Concepts To Build A Bamboo Bridge

Jörg Stamm
Thailand, 29 de Abril de 2009

This article compares the basic concepts of traditional construction systems with modern and contemporary ones. It wants to analyze them in terms of raw material consumption, simplicity of techniques and structural problems. The article succeeds a conference on "Evolution of construction systems in Bamboo", presented in Spanish language in Puebla, Mexico in March 2008. But here the theme is focusing on how to apply those concepts to bridges, which are the maximum expression of load bearing structures. Obviously these examples can be used also for roof structures and are part of the basic formation of architects and master builders. Based on the important scientific publications on bamboo trusses and joinery by engineers like Prof Jules Jannssen from Eindhoven University in the Netherlands and Kaori Takeuchi at National University in Colombia, this article offers a more conceptual approach, without repeating or going into the numerical engineering. That detailed analysis has still to be carried out by a specialist.

Abstract

After two decades of modern bamboo construction, good and bad examples, we are evaluating and forging the bases for norms to include bamboo in future construction industry. To ensure uniform raw material supply we have advanced considerably in themes like sustainable harvesting, preservation, drying and joinery. To define homogeneous characteristics for the desired poles an "ICONTEC" Norm compendium is already regulating the above mentioned themes for Colombia. Although the daily reality is still far from this goal, this regulation gives an important orientation for the forestry sector, to redirect its production towards a secure market with added value, instead of the traditional uses like "throw away" formwork. But the norms also include the danger of limiting creativity by favoring simple and commonly known systems. Independently of the broad variety of joints there is also quite a variety of structural concepts, in order to gather the elements of a truss. Similar to the need for norms in quality of poles and norms for bamboo joinery, we also need a clear order for the different systems of load bearing structures.

Construction in Colombia is based on traditional post and beam concepts. At a technical and professional level there is a lack of knowledge of other methods. This article offers some concepts that are very suitable for construction with giant bamboo poles. Developing one upon another, seven different concepts are presented. Some of these structures can even compete technically and economically with constructions of industrial materials. This article presents:

- *Construction systems for bamboo in their structural essence of long and slender poles.*
- *Bamboo poles are composed to recreate their natural length and cover even bigger spans.*

- *Suitable Joints for Bamboo construction with short and straight pole segments.*
- *Traditional Truss structures that cover big spans and respond to the required loads.*
- *New structural aspects for natural fibers in contemporary architecture.*

Introduction

Several universities have been investigating how to apply modern truss systems with bamboo, basically transferring the typical models of steel frames. Other approaches have been from experienced wood builders, which transfer their knowledge of traditional wooden trusses with more or less success into the hollow and crooked bamboo culms. Both ancestors give quite good guidance for frameworks needed in houses and schools, but still fall short to provide solutions for major roof structures and bridges, as the internal forces of a truss increase exponentially to the length of the free span. A 40 meter Bridge has double the load and the cost of a bridge with only 30 meter span, although it covers only 30 % more distance. The bamboo truss does not live up to a conventional truss made from steel or wood, which has been perfected over time and is nowadays a mature result of structural evolution. So it's understandable that these engineered structures, copied into bamboo, very seldom reach the acknowledgement of a structural engineer and consequently lack the financial input of the user.

Nevertheless we are closing the gap and have investigated the load bearing behavior of bamboo poles and improved the joinery techniques like mortar grouting. This trick allows transferring the loads from one bamboo to another, by using not only by steel bolts, but also through the cement cylinder inside the hollow bamboo culm, that distributes the pressure on the thin wall towards the strong diaphragm at the nodes. On the other hand we have to develop structural concepts that enable us covering bigger spans as the normal 3 to 5 meter in traditional dwellings. Some of the concepts presented here are contemporary three-dimensional trusses, other construction systems take in mind the advantage to work with the natural culm length and use the full potential of the high tensile strength of bamboo.

Based on the conference on the "Evolucion de Estructuras en Bambu" published in Puebla, March 2008, we can list the structural concepts in a system according to its complexity.

A. Traditional Structures B. Modern Structures C. Contemporary Structures

A) – Reduces the traditional structures into woven systems or simple post and beam concepts, using fish mouth joinery or natural fibers like vines and raw hyde. Basic tool is the heap knife.

B) – the modern structures are based on traditional concepts but have a more sophisticated level in joinery techniques. Basic concepts of two dimensional trusses are copied by civil engineers. The elements are straight and relatively short sections of the culm are used. The joints are bolted and grouted with cement. Although the tools like electric drills and chizels are quite simple, a very high skilled labor is required. The raw material needs to be straight and uniform.

C) – the contemporary structures have to pay respect to principles like protection by design, but it´s geometry is three dimensional and “free of form”. It plays with curves, “shell” shapes, “hypars”, joinery is either very simple or highly engineered. The size of these buildings can be very big, due to the use of the natural fibre lengths of entire bamboo culms. The raw material can be curved, conical and crooked, short or large, depending on the object.

Methods

The construction system depends on the availability of the resource and the technical grade of the tools. These conditions and the geological situation of the riversides, together with the ingenuity of the Pontifex (Latin for bridge builder) determine which concept is to be chosen. The article name “seven concepts” explains the simple to the complex, and later discusses the advantages and disadvantages concerning their application using bamboo poles.

This article will not go further into engineering specifications or joinery details as this merits a separate discussion. Moreover this paper is a conceptual tool for the architect and master builder, to go through a variety of possibilities and analyze how to combine the structural considerations with the external factors at the chosen site. A clear distinction of structural concepts enables us to see and to determine the direction of the forces and their reactions. The quantification and exact determination of these vectors must be reviewed obviously by a structural engineer.

1. The Beam
2. The Arch
3. The Suspension Bridge
4. Cable stade Bridge and Cantilever
5. A Bridge with form active surfaces
6. The Truss
7. Space frames

The article can be seen as a guide for the planning of bamboo bridges, although its approach is merely focusing on structural concepts, not taking in mind the important and complex architectural contexts like functionality, social and aesthetic aspects. The structural concepts here proposed are not only limited to bridges, which also can be either small or big, simple walkways or for vehicles. But there are much more challenges to a bridge than to a roof truss, due to the mobile load assumptions it has to deal with. A cattle herd on a rural bridge outweighs easily a line of cars. Passengers on elevated walkways sometimes have the bad habit of leaning towards one side, for example to gain a better view to the sports event on the road below, creating unprecedented lateral forces on the handrail that can flip the bridge over its lengthwise axis. The high load assumptions of 500 kg in the norm for passenger bridges have their origin in the prevention of these disasters. These norms generate tremendous costs which the public sector has to assume, as he created them.

But a private client who just needs a personal access road over a creek to get to his property can have a look for more economic solutions. The cost of the roof is also always a discussion point, but taking in mind that the static height of a truss is almost giving the necessary roof support for free. There is no doubt that the roof will increase the life expectancy to minimum 30 to 50 years, similar to the standard of north European Wood Bridges.

And there is one warning to the urban developers: bridges shouldn't have stairs! Although there is a growing need for access ways and overpasses in cities, there is apparently no way to prevent children and adults to cross below the elevated walkway. Ramps are more comfortable to use than stairs, however they are more expensive, as their inclination should not pass 8 %.

Description

The Beam

a. The bamboo: - a tube with ring reinforcement

The bamboo tube is an excellent structural element. It is strong outside, where the buckling forces act and it is light and hollow inside, in its neutral zone. Rings act like reinforcement to prevent the tubes circular walls from the dangerous oval and interconnect the fiber bundles with each other to decrease splitting tendencies. A typical guadua supports about 2 tons of tension force and 700 kg of compression per square centimeter wall thickness. It also is flexible and quite resilient against buckling, although the engineering literature says the opposite. This paradigm is rooted in the definition of old-fashioned testing procedures where the culm was tested for flexion by pressing him laterally and deforming his tube just at a place without nodes. In its natural habitat we see a slender and very tall culm bending surprisingly strong in the winds, but rarely does it break. By evolution this culm developed a refined tissue composition and wall thickness, which in every section does respond perfectly to the challenges by wind force and the leverage created on the long pole. This property has a lot of incidence on design of structures, because we can choose if we go for the strong and heavy parts or for the light and flexible one.

In the base section we find a thick wall and thick fiber bundles surrounded by big parenchyma cells, which serve as shock absorber for the strong leverage. Further up the culm, the ratio changes from one third of fibers versus two thirds of parenchyma towards the opposite. This denser composition allows higher elasticity, but is less tolerant when it approaches the breaking point. Splits from the upper culm sections have shown in tests less fatigue than tempered steel. But the upper part is also less tolerant to cracks when shrinking of drying bamboo poles creates tensions. This is even more significant in old and mature poles whose cell walls are full of silica. The base of the culm is relatively heavy because of thick diameters and thick walls and the water retained in this tissue. But due to its tubular shape it is always lighter than a piece of solid wood of similar diameter. Wood of similar specific density (guadua= 750kg/m3 = oak) and similar cross section would have better performance in lateral forces perpendicular to the fibre, but lengthwise the bamboo tube has less buckling. Laminated bamboo lumber would compete perfectly with oak or other precious hardwoods, but with laminated softwoods our bamboo lumber is economically out of competition, due to the high percentage (3 to 10%) of glue needed to rejoin the splits. Bamboo timber - or round bamboo poles – is vulnerable to lateral pressure, especially when the tube is not grouted and permanent punctual loads are applied. This happens often when used as a beam. The rafters transfer the heavy load of the roof tiles to the horizontal bamboo beam, which squeezes over the years. This phenomenon is also typical for ageing wood, but it is far more dangerous in bamboo, due to the hollowness of the tube. It seems that the daily change in humidity causes expansion and contraction and the cell walls over the years adjust their position to each other. Therefore it is recommended to load bamboo mainly with axial forces. Load bearing joints should be grouted to enhance their resistance. Horizontal beams should be avoided, unless their lateral load is insignificant, - like in space frames. Horizontal elements like tension beams in King trusses can be doubled and precisely designed to withstand the required lateral forces by walking passengers.

Spaced columns or composed arches are apparently very strong, but should better be calculated as several individual beams. Doubling or “Sistering” of beams will not have any significant “EULER Effect”, because the contact area of bolts and dowels is very limited in round poles.

Photo 1: Four guaduas of 8 meters are joined as a “spaced column”.

Photo 2, 3, 4: This sculpture designed by Marko Brajovic in Mallorca was inspired by the DaVinci Bridges, who may have seen Marco Polo's description of the "rainbow bridge" in China. Several short bamboo beams are "woven" into a 16 meter arch. These systems are quick to install and are still used for timber extraction in Germany and Austria. The arch is quite weak due to his low static height, but this improves considerably, if the tips are extended and join as a handrail, creating triangles, enabling a relatively stable 12 meter bridge.

b. The curved Beam

The thumb rule formula for the internal moment of a beam is:

Internal Momentum = (Live Load + Dead Load) x Span^2 : by 8

If a beam gains static height its load bearing capacity enhances. The height of a beam decreases proportionally to the force of internal moments. The bottom part of a beam is under tension, whereas the superior is under compression. Imagine these forces being theoretically split in one arch under compression and one catenary line under tension. But the cohesion of the fibers in a beam does neutralize these two forces in the center where no moments are acting. This is why in the interception with another elements by tenon could be made by cutting a groove at the center of a beam without compromising its strength. The same principle is valid for a spaced column. Tension and compression are taking place in the outer perimeter and the connecting dowels. But in the center is a neutral zone, where all kinds of beams and diagonals can be interconnected without any harm.

Without this cohesion the resulting force, in either the arch or the catenary, is transferred to the side, where it creates a reaction. The arch under compression pushes into the footings of the bridgehead. The catenary pulls on the counterweights. If the catenary is hanging high the reaction is minor than in a very little slip. That is why long bridges need high towers. The same is valid for the arch: if the arch is high its resulting moment and the reaction in the footings is less.

Arches are very powerful systems if the load is well distributed. Their main weakness is to deal with unsymmetrical and punctual loads, because the line of moments leaves the “band width” and the curve arch becomes a “straight” line. Another dangerous effect is the buckling sideways, that’s why a bridge needs a certain width and diagonal lateral bracing between the arches. A good way to achieve bandwidth in both directions is the “composed curved beam”, where several lines of bamboos are gathering in a package, interconnected by hundreds of bolts and dowels.

The composed beam in photo 5 is slightly curved, following the natural curve of a bamboo stem. This project is for a bicycle bridge over a canal in Amsterdam needs 5 composed beams, with a pitch of 60cm in 12 meters. The protection by design consists in a waterproof concrete slab that also functions as the road. The slab is poured on a formwork of “PinBoo”, which are glue free bamboo boards made from splits and joined with bamboo dowels.

The same logic is valid for the internal moments of a bridge truss, which is just a curved beam in macro. Small spans can be easily handled with only with trusses. Bigger spans have to be combined with arches to maintain the truss height manageable. The static height of a metal truss should be 5% of its span, but in wood and bamboo a 10% ratio is the thumb rule.

Photo 5: Six curved lines of guadua bamboos are joined to a 12 meter composed beam. The 60 cm pitch is quite powerful, but it will cause a strong reaction in the bridgeheads. The lateral buckling will be controlled by a concrete slab. The connection of the beams with the footing is done with an articulated galvanized steel plate, that allows a reliable fixing on concrete.

The Arch

a. The roman arch and the inverted catenary

Like above mentioned there is a relation between the length, the height and the pitch of a beam. The line of the moments is not precisely similar to a perfect arch, but to a parabola or following the inverted line of an imaginary hanging chain, called a catenary. There is a practical reason to design an arch with a certain “band width”, to ensure that the line follows the internal momentum within the limits. These forces are virtually “waving” along the arch, as the life load moves from one riverside towards the other. A bridge allows the division of this arch into an upper and a lower beam, stabilizing themselves mutually with crosses or diagonals. The static height of 2,50m between the belts is enough to allow people walking on the floor beams, where as the upper one supports the roof that protects the building. There are no additional costs for the elevation of the roof, but the extended lifespan pays back your investment immediately.

The extra weight of the roof is a calculable factor and accounts from 2,5% to 25 % of the total dead weight, depending on a wide possible material choice from zinc to tiles. A proper weight of the roof is a kind of pre-tensioning of the truss and has a positive effect on oscillation and vibration caused by the live load. Heavy bridges a far more comfortable for the user, as the typical dead weight of our colonial style bamboo bridge is around 500kg/meter, which equals easily the required 500kg live load required for footbridges.

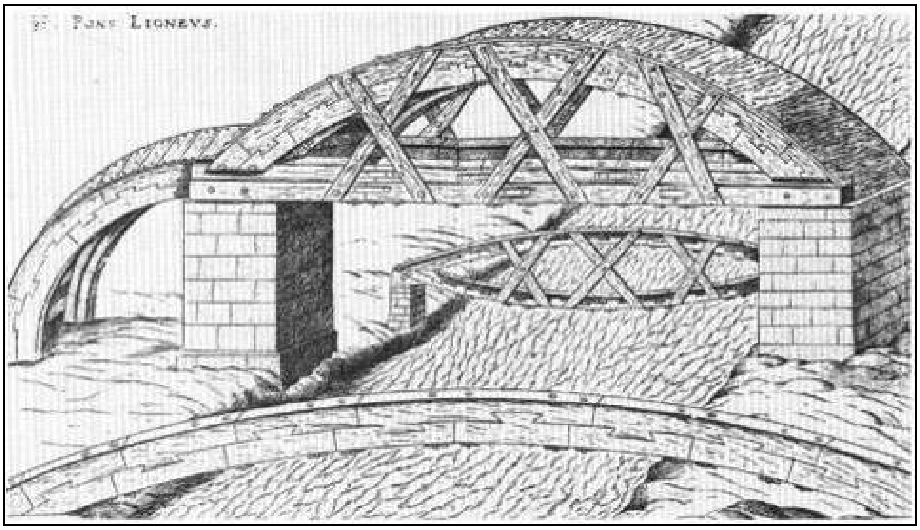


Photo 6: The formwork for the roman arches were composed with beams of short wood. The dented joints are key to neutralize the parallel shear forces of the elements. Bamboo bridges also combine short poles of 4 to 8 meters to ensure uniformity in diameters and wall thickness.

Photo 7: The Bamboo Bridge at the technical University in Pereira (UTP) was built during a one month workshop in the year 2000. The 40 meter bamboo arch stretches over a 4 lane road and has to respect a 5 meter clearance. The load test was done in a moderate progression until reaching 250kg/m2. The arch flexed only 4 cm, recovered 3,8cm, and is stable since then. The permanent deformation of 2mm is caused by the squeezed fibers at the contact zones with each other and with the thread of the steel bolts. The bridge also survived a lateral impact of a drunken truck driver that forgot to close his "bucket".

“Flat” or two dimensional trusses are a good option to enhance rigidity of arches, but it also requires additional collateral bracing between trusses. Whereas at the roof levels we can use “St. Andrews” crossbeams, at floor level I recommend an eight cm thick reinforced concrete slab, which give good comfort to passengers with animals. Collateral bracing is the first step to space frame concepts, that are discussed later.

Architect Simon Velez uses his 14 meter wide roof area to stabilize the lateral forces through three dimensional bracing, which allows maintaining a clear line by the visible distinction between of the arch with it’s suspended floor and the complex network of overhead bracing, which prevents the arch from buckling.

Photo 8: Bridge “Jenny Garzón”, Bogota 2003, designed by Simon Velez and named after the engineer who investigated the grouted bamboo joints for the ZERI pavilion in Hannover. The bridge has a 46 meter span and shows clearly the arch concept and its suspended floor level.

Suspension Bridges

The problems with buckling are a minor issue in suspension bridges and cable bridges, and only to be considered in the tower design. However wind and traffic can generate strong oscillations that not only challenge the towers, they are also uncomfortable for the user as was recently experienced at the Millennium Bridge in London.

a. The bamboo cable

The external section of a bamboo wall has excellent tensile properties and it can hold up to 2 tons/cm2. It is also very tolerant to torsion which makes it easy to twist into a cable. The upper culm sections are even stronger and more flexible, so even very fine splits can be obtained and twined into ropes, which can be preserved by melting the natural wax during heat treatment. Bamboo cables don't suffer from rust like steel cables in maritime areas, and its humidity uptake is far less than hemp or jute ropes, thus they have been used for centuries in shipping. Tropical bamboos don't have that much wax as subtropical species and they are preserved by smoking with tar. Some species are even named after there extraordinary suitability for rope (bambu tali – Gigantochloa apus) and are found all over South East Asia.

Bamboo rope bridges have been built during centuries, but nowadays the tradition is dying out, as these techniques are now limited to very remote rural areas. But they may be revived in a more technical way, like in laminating techniques as "Advance Bamboo Composites", which uses the tensile properties and may even be worked into beams with unlimited length. A similar technique in the glulam wood industry is called Paralam, but due to the easy splitting of bamboo, these advanced composite bamboo laminates (ABC) or Woven Strand Board (WSB) are much more competitive.

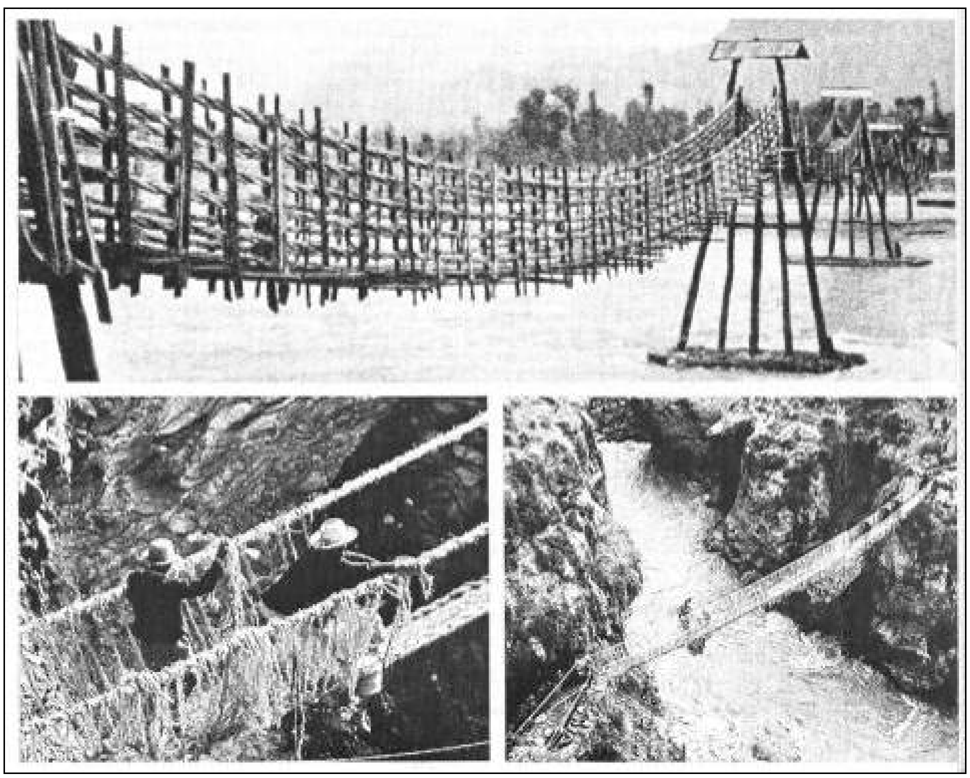


Photo 9: Bridge in Xian, China using cables of woven bamboo splits. The bamboo is a lignified giant within the grass family. In Peru grass cables have been made for thousands of years.

b. The Belt Bridge

Some Bamboos have weaker nodes than others and only distribution can generate homogeneous properties of a laminated beam. The same principle is valid for the composed beams of several poles; - the axial interconnection can be achieved with grouted rebar. The lateral stability has to be ensured by sistering and staggering of the joints as far away from each other as possible.

The tension test of grouted joinery of 12 cm guadua poles, done by Jenny Garzon in 1999, revealed astonishing data with averages between 2 and 3 tons per each grouted node. Applying a security factor of 3, it recommends 700 kg/node for axial rebar, and 900kg for perpendicular bolts (published in Hidalgo, 2003, Gift of the Gods).

The creation of a long bamboo belt bridge, similar to the Rhein - Donau Canal Bridge in Germany (photo 10) is possible, but it has to take in mind the risk of oscillations and the danger of flipping over. There are several examples of bridges in laminated beams and in the near future some laminated bamboo beams can be provided even at competitive prices. The problem of this technology has been the transport of such long elements.

But the belts do no not have to be made exclusively in laminated beams. Natural Bamboo poles can be worked into belts by staggering the poles and using steel rebar. This concept can also be used for tensile roofs over big areas. No example is known so far, but in theory the concept is very promising.

Photo 10: Belt Bridge at the bicycle trail along the Rhine-Donau Canal at the Altmühl, valley in Germany. An about 190 meters long Belt of laminated pine follows the curve of the changing momentum, while it is supported by two towers. The road is the roof which ensures protection by design over the 6 beams of 20 x 60 cm cross-section. The overall length of 190 meters had been delivered in three sections which were glued together in situ with finger joints.

Cable stade Bridge and Cantilever

Where as a suspension bridge is suspended from one long main cable, the cable stade bridges are basically two cantilevered platforms connected in the center of the span. The cables are individually suspended from the tower and can be changed or adjusted. The same principle was used by the natives in Colombia, using the tensile advantages of the natural bamboo.

a. The Páez Bridges in Tierradentro using guadua as tensile elements.

Photo 11: The former bridge of Avirama, Paez, Tierradentro, Colombia, covered a span of 40 meters. Similar Bridges are still found today but they need to be rebuilt every two or three years. Therefore a bamboo grove has been planted close to each site, so spare parts grow meanwhile the out door bridge bamboo decays. The bamboo works tension wise and the poles on each riverside form a partly cantilevered arch for the handrails.

b. The Cucuta Bridge

The archaic concept of using the entire culm in a tensile element and combine it with a arch inspired me to design a footbridge as a sculpture to contrast to a modern concrete nightmare: The fast growing town of Cucuta at the Venezuelan border had just finished a circular road distribution and needed a walkway to cross the 4 lanes. The natural material and its traditional lay out was combined with a modern industrial membrane. The towers had to withstand considerable wind forces on the tent, which were induced by a steel device on top and anchored to the footing by steel cables. The challenge was met by columns with composed columns as a pack of 6 poles forming a pyramid over 4 foundations for each tower. The tension elements are up to 25 meter long sistered culms with steel rebar in 3 grouted internodes each.

Photo 12: The arch is composed by 6 lines of guadua, stabilized by tension beams. The first “Cables” are actually columns under compression, forming a pyramidal tower, which in reality has to respond more to the loads from the membrane, than from the floor. Most of the bridge load is assumed by the arches, - according to the computer model the tension beams are actually mainly decorative.

Membrane constructions have to take in mind the wind force. The sometimes enormous tents can easily convert to sails and develop threatening forces. To avoid this threat, the membrane is tensioned into opposing curves to create an “anticlastic” surface (developed by Frei Otto from Institute for Light weight structures). The membrane is a fiberglass reinforces PVC sheet, coated with Teflon to avoid dust. This technology is still quite new and exclusive, with few professional suppliers. The bamboo bridge now has an extended life expectancy of more than 25 years and an improved reputation where formerly bamboo was considered a poor man’s timber. This change will trigger investments in the agro industry and offer a future for this environmental friendly alternative.

Photo 13: The 400 m² membrane allows sufficient weather protection for the bamboo poles. Its cables are actively involved in strengthening the tower and help to support even the floor beam at the center. Although on the photo the morning sun still hits the tower, but the bridge is quite protected by the membrane at noon. The bamboo is painted with an open poring natural oil firnis, which includes UV protection and antifungal agents.

Bridge with form active Surfaces

The anticlastic membrane can also actively integrate into structural duties and not only are the cables on the edge taken into account, but also the glass fiber reinforcement has considerable strength. Rigid screens like walls are also active surfaces, both in compression and tension aspects, but they are usually quite heavy. These concepts are usually found in huge concrete buildings like at airports and convention centers. In the case of bamboo there is a nice option to work with laminated panels (plyboo) or woven strand board panels., Dr. Ing. Rottke developed cupolas with form active screens based on bamboo panels at RWTH University in Aachen, Germany. Other examples of this concept are found in Heino Engel’s Book about Structures “Tragwerksysteme”.

a. The Bali Bridge

The Bridge at Greenschool in Bali covers a span of 22 meters and was designed by me initially on the base of composed arches. The defense against asimetric cargo was assumed by diagonal tension beams similar to the above mentioned bridge concept of the Colombian natives. The artist John Hardy and his designer Aldo Landwehr wanted to exaggerate the inclination and the length of the tips, which made a second layer of bamboo necessary to stabilize these long elements. But the resulting rhomboids were still not creating sufficient stiffness of a screen, so a third layer of sticks (traditional roof thatch called alang alang) were attached. The four screens act now as a form active surface and stabilize the form of the arch. No cables were needed at the tips.

Photo 14: The two opposing directions are shown in yellow (Dendrocalamus asper) and in black bamboo (Gigantochloa atroviolecia).

Photo 15: The 22 meter Bridge at "Greenschool" in Sibang, Bali, Indonesia. The two horns are typical ethnic architecture of the Minang Kerbau people from Sumatra and very good for natural air conditioning. The structural concept of the form active surface relies on 4 stiff screens leaning into each other, so the two horns do not require cables to assume the tension of the diagonals.

Photo 16: The two arches are composed by 3 bamboos of *Dendrocalamus asper*, interconected by steel bolts and bamboo dowels. The floor is made from the cracked poles, using bamboo dowels to join about 20 splits each into glue free Bamboo board, called "PinBoo".

Truss Bridges

The Framework of a traditional truss is flat and the elements are arranged in two dimensions that define their forces in vectors on the coordinates X and Y. A simple geometrical method of structural analysis is to visualize the forces in its direction and its size is by drawing vectors. The truss design depends also on the thickness and length of the elements at hand. Civil engineering has developed in the 18th and 19th century, when thick trunks weren't anymore available and the ingenuity of man had to solve the problems of their roofs and bridges with pole diameters that were quite similar to bamboo poles. One of my best books for inspirations is a reprint of a 100 year old handbook for master carpenters (Th. Engelhardt, Leipzig 1900), another one is IL31, Bamboo – Bambus, from Frei Otto's "Institute for Lightweight Structures" at Stuttgart University. His work also started as an investigation about what can be done with the huge amount of small diameter pine trees that resulted from the abundant reforestations during the 60's. Later he observed that pines have the same dimensions as tropical bamboos, but the light and strong bamboo poles were much more appropriate for Light weight construction and an outstanding book on structural concepts in bamboo was written by Klaus Dunkelberg and Eda Schaur.

A lot of wooden trusses have evolved for a great variety of applications during industrialization and became basic knowledge in the formation of civil engineers. Later, as steel became more common and cheaper, steel trusses evolved into their own direction. The WARREN Truss became popular due to the simplicity of tensile connection by Rivets, whereas KING Truss and HOWE were more suitable for wooden joinery, using compression joints for the main forces.

a. KING Truss

The KING Truss owes his name to the center post, like already used in medieval buildings like the 18 meter King truss documented in drawings of the wooden St. Peters Cathedral in 8th century Rome. Nobody knows if the person that baptized the truss did refer to the “Kingpost” as a central element that distributes power… or ….already hanging by his neck…. Both interpretations describe this importance: the truss receives the dead load from the center of tensile beam and transfers it through the diagonals back to the supporting walls. The floor beam has to neutralize the lateral push on the wall by its tensile strength, which is far greater than the sum of the vertical load. This push is absorbed by a joint and must respond to a sufficient parallel sheering capacity and resist the enormous compression through the use of a dense material. Oak was usually the best option as it is a very hard wood (750kg/m3) and has an excellent parallel sheering strength due to its strong radial fibers (about 8kg/cm2 in Engelhardt).

Bamboo does not have radial fibers, nor does is count on sufficient square centimeters and its hollowness does not allow to be squeezed, - apparently a terrible situation. But the cement mortar injection solves this problem and the cylinder transfers the sheer load to the next diaphragm, where fiber cells are interwoven and avoid splitting.

In most bridge cases the bamboo trusses transfer the load of the diagonal compressors directly to the bridgehead, to avoid the above mentioned squeezing of the tension beam. The reaction caused in the footings is similar to the internal momentum of a beam, because the tensile elements of the truss do not absorb any lateral forces. The floor beam’s duties are limited to support the gangway and to avoid buckling, but this trick allows us to built bamboo trusses up to 30 meters.

Photo 17: Bridge in form of a “Box”. The KING Truss of 12 meters was made in Guadua *chacoensis* en Maceio, Brazil. The style is a true copy of successful systems used in the middle ages and colonial times. Traverses double beams are hanging under the floor, which gives more internal height for the passenger. The crushed bamboo mat called “esterilla” provides the formwork, and the floor belt of the truss confines the limits of the concrete slab, which besides having good abrasive behaviour, also stabilizes against lateral buckling.

Wooden beams jointed by steel bolts generate a serious problem for the engineer as the tempered steel does not allow much bending and has a tendency to break. Wooden beams have a hard inner core and soft tissue outside, which allows bending of the bolts. That can be avoided by “Bulldog” dowels or short sections of steel tubes put around the connecting area, that help to transfer the sheer forces and the bolt is working only in his axial direction, holding the jointed beams together. This technique can’t be applied to bamboo although the problem of bending bolts is apparently even worse in round poles. On the other hand Bamboo tubes are more similar to steel tubes, as the outer perimeter of the pole is quite hard and the bolt is working under shear forces instead of bending. For bamboo joinery I recommend 12 mm bolts or threaded rods, preferably not tempered, which have a shear strength of about 2 tons, similar to the load that a 12 cm grouted guadua internodes can withstand. Many clients want to save some money on hardware materials and by two or even three calibers of bolts. This does not only confuse the worker, who does not always understand the loads acting in the particular joint he is working on, it also requires constant supply of not only one, but three types of drill bits, bolts, nuts, washers, wrenches, etc. For seaside projects the minimum requirement is hot dipped galvanized threaded rods, or even better are stainless steel threaded rods.

For minor forces you could apply also bamboo dowels, - like wooden nails have served for centuries and their lifetime expectancy is better than blacksmith iron in contact with oak.

Small bamboo bridges up to 8 meters a truss height of only 80 to 90 cm is required, which allows using a prefabricated King truss for a handrail. The prefab flooring grid of 2,35 cm width does still fit into a Container. A roof can be adjusted by introducing some poles in between the two handrails lines. Many clients don't like roofs, but outdoors bamboo does not last very long, unless it's annually painted yearly with UV protection and mold care.

Photo 18: This small King truss bridge of 6 meters has been installed at the Botanical Garden in Medellín, 2000. It has been pre-assembled and delivered by a small truck; the roof has been thatched locally. "Thermowood" has already a big market, but in Bamboo we still have to investigate to reach reliable preservation. The color is generated by a smoking treatment (pyrolisis), but the traditional Japanese technique is not easy to copy and additional borax preservation is necessary. The diagonal compressors are cut one third of the diameter into the tension beams and transmit the forces into the last nodes, which have to be grouted and its shear strength is also enhanced by two bolts. Note the slight curve of the truss: it's pitch is following the natural bending of the bamboo culm.

b. HOWE Truss

The railway bridges in America brought a lot of innovations in terms of assembly time and conceptual aspects of normed and pre-fabricated pieces for bridges to be built "by the miles". The engineers TOWN and HOWE invented two systems that can be easily applied to bamboo structures, as their elements fit in size with the wooden predecessor. Meanwhile the KING Truss is a framework of only one level, the trusses of Mr. Town and Howe had two or three layers that reduce the buckling of the relatively slim beams.

The HOWE Truss has shown excellent results in bamboo bridges of 20 to 30 meters, using segments of 5m lengths and 3m heights. This module allows us to apply the normal 6m pole for diagonals and posts without much wastage, thus optimizing the use of the previously preserved standard poles. The straight bamboo poles in a delivery are chosen for the diagonals and its tension and compression forces, because these vectors are linear. The curved bamboo poles, a gift from nature to the creative spirit, allow bending the bridge truss into a slight pitch upwards. This does not only help aesthetically, more importantly it is a pre tensioning of the structure. All trusses will sink some millimeters when entering service, meanwhile their fibers adjust to each other and against the bolts.

The natural curve of a bamboo pole is less that about 2.5 % of the length and a truss should be similar. A 30m truss should not have more than 1.5 meters pitch. Some arches require a bigger opening below, but a 5 % would be the maximum that could be achieved without intentional cuts or heat bending. Bamboos of more than 10 cm diameter are extremely difficult to bend, even with heat.

Photo 19: This 30 meter bridge in Santa Fe de Antioquia, Colombia was pre assembled completely on a lawn besides the road. The bamboo structure had a weight of 8 tons and a mobile crane simply lifted it onto the bridgeheads. The entire operation only required a two hour road block and the entire bridge project has being finished in one month.

Photo 20: The HOWE concept is a sandwich framework. The tension and compression beams mutually stabilize at the cross over in the center, where usually the worst for buckling occurs. The tension element in the middle layer is bolted in between the outer and inner layer to transfer the forces evenly. The compression beams are cut one-third into the arches and grouted to avoid squeezing. Observe how the traverses are hanging below the floor arch and how the rails under the floor form a "lost casing" with the crushed bamboo mats.

The Space Frame

The structures with vectors in the three dimensions of X, Y and Z can be called space frames and include geodesic domes structures. Its elements work in tension and compression with forces induced through punctual joints. The smallest shapes surrounded by the beams are simple platonic corpuses like tetrahedron or a pyramid. A space frame might need several levels to be determined and rigid structure.

The tetrahedron with 4 Bamboo tubes requires a reliable joint, which conducts the forces from the cortex of the tube towards is axial line. This can be achieved with cement grouting, resins, epoxy glue, sand or milled glass as the infill material. The grouting with the special cement will transfer the load reliably to one axial bolt that is connected to the spherical bowl. This point can be either simply welded or can be a multipurpose solution like the Mero bowl.

Following descriptions on this kind of conical joints, already published by Gonzalez from Costa Rica during his PhD under Prof. Janssen, several approaches have been successful. The Institute for Wooden Structures at RWTH Aachen Prof. Führer and Dr. Evelin Rottke developed with Christoph

Tönges such a conical joint, which cold handle 18 tons of tensile strength, - well the joint worked, but the screw failed. This experience motivated to look deeper into the use of these joints for bamboo Bridges in space frame manner. Another successful joint has been developed by Kool Bamboo.

Photo 21, 22: Very powerful for axial bolts are conical bambú joints and MERO sphere.

Space frame applications on Bamboo Bridges could be similar to examples in wooden engineering over the river Isar in Thalkirchen, Germany. A roadway is supported by these 6 wooden arches; the road is the roof and protects the structure from sun and rain.

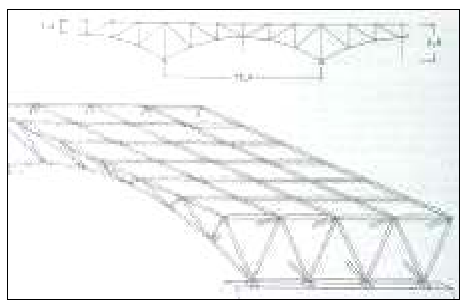


Photo 23, 24: Scheme of the wooden space frame truss over the River Isar, Germany.

a. The project of the bridge over the river Cauca in Popayan.

This Bridge will be a 30 meter space frame in bamboo, combined with 5 packs of bamboo arches (3 lines of guaduas in each) to ensure a live load capacity of 500 kg/m².

The selected guaduas have a diameter between 12 and 14cm and wall thickness of minimum 12mm. The largest elements are 2.4 meters long; the bolts (grade 4) are 18mm thick and transfer the load straight into a 12cm diameter steel sphere. Each cone will be individually examined in a previous load test, numbered and monitored digitally, to substantiate quality assurance for eventual claims.

This joinery technique is very challenging and its development, including the testing facilty, is quite expensive, but it opens the way for mass markets. The same production process for the joint can be repeated precisely, just the measures of the bamboo pole changes in length or diameter. The cost of the bamboo is quite insignificant compared to the effort on the joints and does almost not influence the cost of the entire element. The bamboo poles need to be perfectly preserved and even receive flame retardant painting. Architects may then order these units by the thousands, just with different lengths. The lay out and planning of such projects can be done already with existing software for space frames in steel. The bamboo element has still to go through official testing for construction material, but at least some prototypes are already there.

In terms of the quantity of bamboo needed per square meter of structure, this system has by far the most efficient use of bamboo and it's very versatile, but it's also the most technical one.

The maintenance or the change of one element is relatively easy, because each element has its own adjustment screw. The cost of the entire system in bamboo is higher than similar existing metal systems on the market. Natural materials need just far more knowledge on selection, preservation and quality control, than industrial processes with galvanized steel tubes. But there is definitely a market where wood and bamboo space frames find their niche. This bridge project could help open the door:

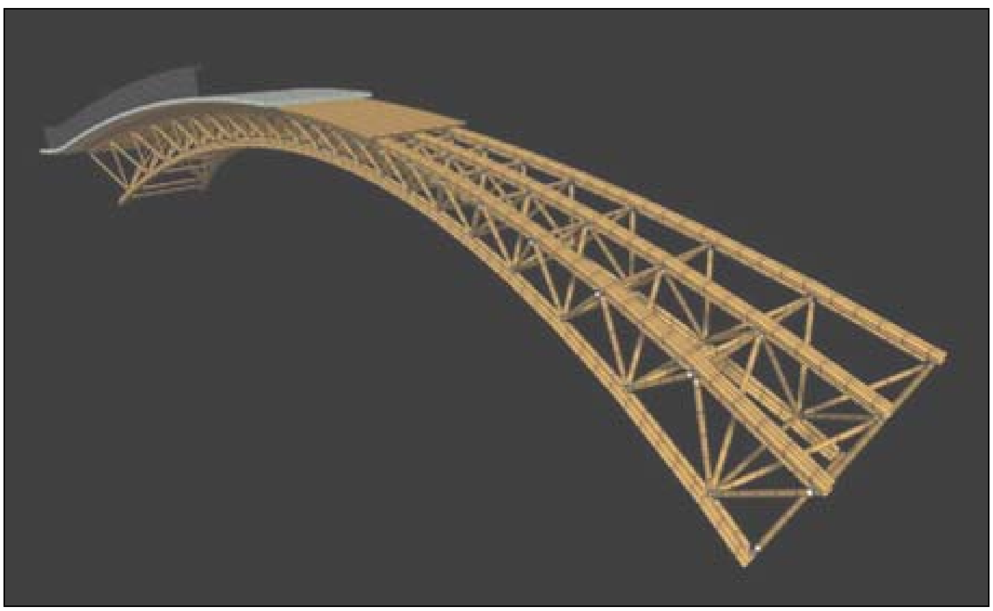


Photo 25: Render of an arched space frame bridge in bamboo. The project of a park along the river Cauca in Popayan including this 30 meter bridge is designed by Architect Valdenebro. It combines the curved space frame with five additional packs of five bamboos. The protection by design principle is the road way, which covers the structure like a roof.

Discussion

In order to compare the construction concepts we need a reference point. The cornerstones of evaluation are the “value”, usually expressed in “direct” costs. From there it is not far to compare the level of technical complexity, the need of skilled man power and special tools. Bamboo - at least in the tropical countries - is apparently a very economical raw material, but there are also cost generated through selective harvesting, transport, preservation and installation. The increase technical complexity, guaranty and expected service time is directly proportional to the increase of the cost. These factors influence considerably in the decision of the structural concept to choose.

To give an overview about the above described concepts a table is presented here. Most of the examples have been already realized physically, but the functionality, the span and the weight requirements have not been the same, so is not possible to give a comparison under the similar premises. Also the remoteness and site influences, average time and material requirements have been different, but an average is given by the author’s experiences. The table is a baseline for discussions and offers variables for the designer. The concept is graded in 1 to 7 and offers two varieties. The free span between supports or bridgeheads can be from 6 to 40 meters, the required amount of poles and their size gives the total length of bamboo needed. The life time depends on the protection by design and is generally directly proportional to the roof overhang.

The overall goal of the table is to compare the efficiency in the use of bamboo poles under considerations of certain span and load assumptions. The load bearing capacity of bamboo depends a lot on the applied structural concept. Some use the bamboo pole merely by flexion (the beam), some apply the forces perfectly in line with the axis (space frame). In between both extremes we find transitions of different grades, compromising on one hand more poles, on the other more skills.

Qualification of Labor and their related cost are understood as simple workers (W) and skilled carpenters (C), but the required construction time is obviously depending a lot on the span and the site remoteness, etc. The complexity is graded from traditionally simple, to complex and engineered. A few of the outlined 7 concepts have not been worked yet in bamboo, but do exist in wood, which enables us to assume the technical viability.

The logical sequence starts by definition of the concept and its varieties. Than each example is represented by the name of a real existing bridge, most of them have even Autocad plans. Some structural analysis and scaled models are available for future deeper analysis. The span and its width of the bridge allow a certain amount of passengers (a live load of 6 persons per square meter would be 450 kg/m2), which is here assumed with 60% of its official load bearing capacity (4 persons per square meter with 75 kg sum 300kg). The amount of bamboo (handrail included) at the bridge section is shown in relation to the span and the load. The life time of the bridge plays an important role in the bamboo consumption over the years and should justify the investment. The cost is in direct relation to the technical complexity and its need for skilled workers. The final figure should reveal the overall bamboo needed per person and span. This table is just a discussion proposal, based on the experience of the author and has to be checked on other structures.

Table 1: Evaluation of 7 concepts, taking in mind material efficiency, load capacity and life time.

	Concept	Varieties	Example	Span/ load	Bambo ml /span	Life Time	Labor	Pole need/ Pers/ year
1.	**Beam**	a. natural bamboo pole, straight	3 pole packs pure flection	Up to 6 m 1 pers /ml	6 x 6m = 6/ml sp	2 years, no roof	1 day / 2W very simple	36/6/2 = 3 ml/pers/yr
		b. spaced beam, spaced column	2x 4poles spaced	Up to 8m, 4 pers/ml	10 x 8m = 10/ml sp	3 years, board roof	1 day/2W + 1C, simple	80/32/3 = 0,8 ml/pers/y
2.	**Arch**	a. false Arch, woven Arch	Mallorca, Da Vinci	Up to12m 2 pers/ml	20 x 6m = 6/ml sp	2 years, no roof	1 day/ 3W + 1C, tradition	120/24/2 = 2,5 ml/pers/y
		b. roman Arch, composes Arch	In project for Amsterdam	12 x 4,5m 200 pers.	5x6x12m = 30/ml	30 years, road roof	4 weeks/ 2W +2C, simple	480/200/30 = 0,1 ml/per/y
3.	**Suspension**	a. bamboo Cable	Xian, Bali, Peru	≤ 30 x 1,2 m. 60 pers	8x3x30m in slivers?	2 years, no roof	4 weeks ? 10W+ 4C tra	720/60/2 = 6 ml/pers/yr
		b. tensile poles in a long Belt. WSB	Rhein Donau	≤ 30 x 1,3 m. 30 pers	12x8x6m = 18/ml ?	20 years, road roof	8W+ 4C ? engineered	600/30/20 = 1 ml/pers/y
4.	**Cable stade**	a. entire poles as “cables”	Paez	≤36 x 0,6 m. 20 pers	40 poles of 20m.	2 years, no roof	simple, traditional	800/20/2 = 40 ml/pers/yr
		b. Cantilever	Cucuta	≤30 x 3 m 400 pers	40x2x30 m = 80/ml	30 years, membrane	complex, engineered	2400/400/30 =0,2 ml/ps/yr
5.	**Form active**	a. stiff shapes, shells	Bali	≤20x2,5m 200 pers	30x2x22 m = 60/ml	30 years, grass roof	simple, traditional	1320/200/30 =0,2 ml/ps/yr
		b. anticlastic membranes	Partially in Cucuta	Supports center	Towers and floor	30 years, membrane	Complex, engineered	No design yet
6.	**Truss**	a. King Truss	Maceio	≤10x2,5m 100 perso	24x2x14 m= 48/ml.	30 years, tile roof	simple, engineered	672/100/30 =0,2 ml/ps/yr
		b. Howe Truss	Antioquia	≤30x 33m 400 pers	56x2x34 m=56/ml.	30 years, tile roof	Complex, engineered	1800/400/30 =0,15ml/ps/y
7.	**Space frame**	a. space frames with arches	Popayan?	≤ 30 x 3m 400 pers	(25+10) x31m	30 years, road roof	Complex, engineered	1100/400/30 =0.08 ml/p/y
		b. tensegrity Bucky Fuller	?	≤ 30 x 2m 100 pers	50 poles of 6 m	3 years, no roof	Complex, engineered	

According to the hypothetical assumptions of a life time of 30 years and quite high live load capacity, the table shows some astonishing results. Basically all covered bridges need only between 0,1 and 0,2 meter of bamboo per passenger and per year, where as the non protected bridges consume between 2,5 and even up to 40 meters, resulting ten to twenty times more than the engineered bridges.

But it is not the only angle to compare advantages and disadvantages. Each Bridge site already determines a lot of factors, like the soil consistency of the riverbanks, the maximum level of flooding over the past decades, the proximity and the best access to the next roads to get in construction materials, tools or even a crane. If there is no access to a narrow valley, there might be the possibility to install a cable that allows the lifting of the trusses. Other sites require a “false” bridge platform to assemble the truss or to avoid tools falling into the river or the cars on the road below.

Also the average size and the mechanical properties of the chosen bamboo species influence the design. The client might have challenging ideas about functionality or may impose aesthetic preferences.

Some bridges need an official construction permit from city authorities including structural analysis and signed plans by a registered engineer. Building supervisors leave little margin for change or improvisation and are very uncomfortable with unfamiliar building materials. But everybody, client and builder, are identifying themselves with their Bamboo Bridge, so there is always a deal for creative solutions.

Photo 26: The deformation caused by load tests with 55-gallon oil drums (about 200 liters) is registered by a topographer. Later the date is compared with the structural analysis by engineering software. Over the years we have closed in on the gap between these two approaches. Latest tests have confirmed the deformations and recovery predicted by the computer programs. Now we are generally quite close to 0.015 % of the span at tested live loads of 220 kg/m2 (= one barrel/m2). This covers about 50% of the most national norm requirement between 450 - 500 kg/m2. Test on full loads have never performed, as these extremes requirements are for extremely rare situations. Unnecessary extreme testing would eventually cause micro damage in the structure and reduce its overall lifetime. This testing politic has been internationally accepted, even by the German authorities responsible for the structural revision of the Zeri pavilion. 6 load tests have been performed up to now on real existing structures and the data should be compiled and evaluated sooner or later in a professional investigation in order to compare the data between computer simulations and real structures.

.Conclusions

- It does not make sense to compete between concepts, as each one has different advantages that respond to a variety of challenges that can occur in the project. There can also be a combination of concepts. This is needed on one hand to avoid buckling of arches by asymmetrical or punctual loads. On the other hand the arch can be an additional defense line for a truss, just in case one element or a joint fails, due to an accident or lack of maintenance.

- Protection by design using roof and tall footings pay in about 10 times more efficient raw material use, although labor and skill requirements are more challenging.

- Straight bamboo does not exist in nature, and it is a waste of time to ask for a container load of straight and uniform poles. But you can ask for a range of specification like almost straight, or slightly curved, strongly curved, bottom, middle or top section, certain density of mature poles, certain diameters (at the base) and length up to 12 meters. The quality of the selection is up to the provider, but you have a choice. In Colombia and Indonesia there are already about a dozen companies, dedicated to produce good quality and quantity of preserved bamboo poles with those specifications. Most of them have been trained by the author.

- Nature does not limit itself to the straight line of a drawing board. So let's design curves according to the natural bending of bamboo. Curved lines are beautiful, but some architects don't like the triangles. But the diagonal bracing is essential for a truss and can be integrated as lateral confinement, also as ornaments: a lot of common users of a bridge do not understand the crossings of a handrail support and think its decoration.

- Most of the above mentioned construction systems in bamboo are already mature and successfully used for years. They have been refined in terms of simplicity, use of power tools and time efficiency, so there is a base for scheduling their production. Others are still in experimental stage and the first projects are starting soon. The experienced bamboo builder knows his material and will meet the challenges. What we don't know are the costs, but what does it matter to work hard when it comes to discover new horizons.

About the Author

Jorg Stamm has designed and built dozens of houses, schools, community halls and bridges in Bamboo. The variety of construction systems experienced in 15 years since meeting guadua in Colombia stretch from simple post and beam to complex frame works in several layers. He developed a prefabrication method that works with previously selected, preserved and dried poles and brings the actually construction time to a quarter of the commonly used time. The Truss construction itself is usually done on the ground over a pre - established matrix that was planned and drawn in Computer Added Design programs (AutoCad). The matrix follows the 1:25 drawings and the pinpoints important positions with stakes. The assembly is precise to the centimeter and even 40 meter trusses can be screwed together without dangerous scaffolding and complicated leveling. The resulting truss is very light, as a dry bamboo pole usually weighs only about 20kg, and can be positioned by hand or by crane quite easily into its definite position. The structure is quite identical to the planning, which allows structural analysis based on the same CAD drawings.

Also the preparation of the bamboo poles, their grading, the preservation and drying has been systematically organized. The bamboo goes through this process within two months, before stored properly in a warehouse. This process allows controlling quality and costs. The client can order the necessary poles by the meter like every other modern construction material and cut down construction time. This method converted bamboo construction into a green alternative which is economically competitive and fits into the existing commercial habits of delivery against deadlines.

Due to this achievement he has realized jobs in Europe, America, Africa and Asia with different bamboo species. The ongoing apprenticeship is reflected on one hand in the new techniques applied to fit the diversity of sizes, diameters and consistencies. On the other hand he widened the horizons by meeting impressive ethnic architecture mainly in Indonesia, with its great treasure of styles and functional forms.

The invitation to Bali, by the former Jewelry Designer John Hardy, to built “Greenschool” in Bamboo, was of great importance. Inspired by the potential and the challenge to build exclusively with natural materials like Bamboo, Stones, Mud and Grass he combined these traditional resources with the interesting roof forms. This led to the discovery that these curves are not only creating beautiful light effects, but they are very functional as “form active” structures and useful by their effect on creating draft and natural air conditioning. The design of a 2000 m2 roof for a new factory building was inspired by the silhouette of three volcanoes on the horizon at the background of JH Company. The tree cones of the factory building resemble these volcanoes, including the magma chamber and the crater, which became the skylight over a spiraling internal tower.

Working with more than a dozen local species with different sizes and properties, the design team looked for the options, experimenting with a variety of construction concepts and the possibility to work even with the longest available poles of 20 meters. To avoid unnecessary cuts a 20 preservation tank was built. The long, light, strong and elastic poles offered a surprising quantity of unexpected applications, which were later refined and systemized.

The author did join as a technical advisor some of the investigations on bamboo at the Technical University of Pereira, where selective harvesting, preservation and kiln drying were under his duty. He also wrote a technical booklet on bamboo bridge building, edited by the GTZ-UTP Project.

Important inspiration has been the already mentioned book “Bambus-Bamboo”, IL 31, from Klaus Dunkelberg y Eda Schauer, Frei Otto’s Institute for light weight structures at the University of Stuttgart in Germany. Another important work is Oscar Hidalgo’s “Gift of the Gods”, a Bible in terms of the gathering of a wide array investigations on Bamboo all over the world. Prof. Dr. Walter Liese’s book on “Anatomy of Bamboo Culm” allowed a deep insight into the microscopic world of the structural composition on cellular level.

Photo References

Photos: 3, 6, 10, 11, 23, 24 scanned from: Informationsdienst Holz, Germany, see bibliography

Photo 9: scanned form : IL31 , Stuttgart, see bibliography

Photo 11: scanned from : Guadua, Marcelo Villegas, see bibliography

Photo 14: John Hardy, Bali, courtesy

Render: Arq. Eladio Valdenebro, Popayan, courtesy

The other photos are from the author.

Bibliografía

Dunkelberg, K: Bambus als Baustoff, Institute for Light weight structues. IL 31, Stuttgart 1987.
Engel Heino: Tragsysteme - Structure Systems, ISBN 978-3-7757-1876-9, Germany 1997.
Engelhardt, Th. 1900: Biblioteca Uni Hannover, Reprint ISBN 3-88746-019-7, Hannover 1982.
Frühwald, A.: Holz-Rohstoff der Zukunft, Informationsdienst Holz, Alemania, 1997.
Hidalgo, L. Oscar: Bamboo - The Gift of the gods. ISBN 958-33-4298-x, Bogotá, 2003.
Janssen, J.A: Designing and Building with Bamboo. Inbar Techn. Rep. No 20. Beijing 2000.
Liese, W: The Anatomy of Bamboo Culms. Inbar, ISBN 81-86247 -26-2, Beijing 1998.
Liese, W: Bamboo Preservation Compendium. Inbar, ISBN 81-901808-0-0, Beijing 2003.
Londoño, X.: Characterizatión of the anatómy of *guadua angustifolia* culms, Bamboo Science and Culture, Vol. 16. American Bamboo Society, 2002.
Riaño, Londoño: Plant growth and biomass distribution on *Guadua angustifolia*. Bamboo Science and Culture, Vol. 16. ABS, 2002.
Takeuchi, C: Studies on the structural behavior of Guadua angustifolia. Conference paper at Int. Bamboo Symposium at Guayaquil, 2000.
Vélez, S.: Grow Your own House, ZERI-VITRA, 2000.
Villegas, M.: Bambusa guadua, Villegas editores, 1996.
Wegener, G.: Ökobilanzen, Informationsdienst Holz, Alemania, 1997.

A Tale of Two Bridges
A Proposal for the International World Bamboo Congress 2009, Bangkok

Mark Emery

It was the best of times, it was the worst of times……

Abstract

This proposal is a subjective portrayal of the construction process of two bamboo bridges that I have helped construct over the past two years. A tale of Two Bridges wishes to reveal the art of Bamboo Bridge building in motion from the perspective of the builder. With the aid of a High Definition video camera I wish to share a personal account, through the ups and downs, of the construction of two bridges.

The two bamboo bridges under analysis include the 30m pedestrian over-pass in the City of Cúcuta, Colombia, and the 30 meter entrance bridge at the Soneva Kiri Resort on Koh Kood island, Thailand. These two bamboo bridges, designed by carpenter Joerg Stamm, modernize indigenous bridge building concepts through the use of well selected, preserved, large diameter bamboo, and utilize modern joinery to maximize load bearing potential. Both bridges were born from a similar conceptual design base although express very different aesthetic outcomes and utilize different structural systems. At a glance one can note this difference between the two bridges; one with a modern anticlastic tent membrane, the other utilizing local ¨sago palm thatching and small bamboo rafters for roof protection. Both Bridges express the clients desire for a representative building that reflects their company's identity

Bending and Joining

The secondary discussion of this proposal will be examining the joinery techniques and explain in laments terms how to unite single bamboo culms to form long complex elements that create structural beams and arches. Herein we examine the differences of working with the different bamboo species endemic to each location; Guadua angustifolia, and Dendrocalamus asper, and explain from the perspective of the builder what it is like working with, and combining these flexible materials with rigid mortar and steel to assemble massive trusses. Through trial and error, discoveries are made and new techniques are born from the workers input to improve process.

Above- Bridge Cúcuta, Colombia with membrane tarp protecting a symmetrical structure. Below- Model of Bridge at Koh Kood, Thailand currently under construction, to be completed in june 2009. Asymmetrical bridge design with the tension elements radiating from the double footing, whilst at the other end, these apparently similar elements only support the roof structure.

Bending Bamboo. On the left shows huge diameter of the dendrocalumus culm, on the right the smaller but very strong Guadua.

Communication

Communication on the worksite breeds new vocabulary between the workers. To differentiate structural members new descriptive terminology is born: *5-pack, triangular 3-pack, 3-flat-pack, star-pack, and ray beam,* quickly catch on as work site slang to describe the coupling of bamboo poles. These names are used to replace engineering terms such *arch, column, and tension beam.*

Communication from designer to constructor is different in Bamboo buildings as opposed to a conventional building that relies on regularity of the material. A bamboo building maybe only having several fixed reference points for construction from which other points between may vary. AutoCAD is an invaluable tool for the designer, however sometimes with an irregular building material such as bamboo, precise measurements, angle of unions and even where to connect the elements are not apparent until construction. This is why we always explain a design on the worksite with a physical model using round bamboo skewers. This way even the language barrier is surpassed, and an instant understanding of the finished structure is clearly understood by the whole working team.

Construction Drawing of the 30m bamboo Bridge at Soneva Kiri Resort, Koh Kood, Thailand. Shpwn are the "double footing" on the left, and lettered are the "Ray beams" A-L. Above the construction details shows the coupled bamboo elements- Triangular 3-pack, 5-pack, Triangular 6-pack.

The Team Storey

The strong bond between workers created over a 3-month construction period is the parallel storey that is often forgotten in construction. The "team storey" or the personal account of what it is like to build with bamboo is very important, especially for us, the designers of bamboo structures. If you have never made a bamboo dowel with a machete, carved a fish mouth with a chainsaw, or carried a 10 meter bamboo pole on your shoulder, it is even more important for you to listen to the workers say, as their storeys help us to develop a better understanding of bamboo and how to design with it.

Left- Team Koh Kood, Thailand. Right- Giant truss lying damaged on scaffolding after a failed lifting attempt. Photo shows Primary Double footings, and distorted arch's after damage.

With the aid of my HD camera I would like to share the experience of building the bridge on Koh Kood island, Thailand. The mental and emotional process of building a bamboo bridge is unique. Not only is a bridge the pure expression of structural form, it is a dynamic human experience to unite landmass, and the satisfaction of the first crossing from end to end is an incomparable emotion. Without team collaboration, this process would not be possible, and the bridge would simply not exist.

This proposal includes a 10-minute video reel sharing this emotional experience, and explains the crucial steps in mechanical lifting of a bamboo truss, featuring the National example from Koh Kood, Thailand. This dramatic video footage reveals the do's and don'ts of lifting a 7 ton bamboo truss, but more importantly would like to share the emotion and drama experienced in "A Tale of Two Bridges".

About the Author

Mark Emery graduated from the Faculty of Built Environment at the University of New South Wales Landscape Architecture program in 2006. Mark has worked extensively throughout South America, learning the art of bamboo architecture under the supervision of German carpenter and personal mentor, Joerg Stamm. In 2008 Mark established his own design multi-disciplinary practice aligned with an uncompromising philosophy for truthful architecture using sustainable material. His practice, Bambooroo, named after the strongest woody plant on the planet, and as a synonym with the national symbol of Australia the Kangaroo, seeks providing comfortable living with elegant design solutions, whilst exploiting the use of our most precious natural material, Bamboo.

Bamboo as a Material for Housing and Buildings – Indian Experience

Dr.Shailesh Kr.Agrawal
Executive Director, Building Materials & Technology Promotion Council,
Ministry of Housing & Urban Poverty Alleviation, Government of India

Background

Wood has been used for centuries as a common material in construction of buildings and other structures. Similarly, bamboo has also a long and well established tradition for being used as a construction material throughout the tropical and sub-tropical regions of the world.

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 has 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 has 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.

Main characteristic features, which make bamboo as a potential building material, are its high tensile strength and very good weight to strength ratio. The strength-weight ratio of bamboo also supports its use as a highly resilient material against forces created by high velocity winds and earthquakes. 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. The 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. The commonly used species in construction are Bambusa balcooa, Bambusa bambos, Bambusa tulda, Dendrocalamus giganteous, Dendrocalamus hamiltonii, Dendrocalamus asper, etc.

Bamboo, a highly versatile resource and widely available, is being used as an engineering material for construction of houses and other buildings. A number of small and medium sized demonstration structures have already been constructed during past few years. These have shown very good performance in different climates. In order to propagate use of bamboo in housing and building construction for wider application, awareness and confidence building amongst professionals and householders is required. This calls for organized actions on prototyping, demonstration, standardization aimed at improving acceptance levels and promoting appropriate construction practices.

World-wide availability of Bamboo
(Number of bamboo species and coverage by country, In Asia)

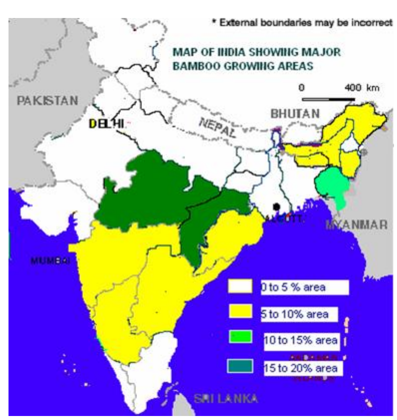
Country/area	Number of species	Area (million hectares)
Bangladesh	33	0.6
China	300	2.9 (only ‘Moso’)
India	136	9.6
Indonesia	35	0.1
Japan	95	0.12
Malaysia	44	0.3
Myanmar	90	2.2
Papua new guinea	26	N/A
Philippines	55	N/A
Sri lanka	14	N/A
Taiwan	40	0.18
Thailand	60	0.81

Over twenty million tones of bamboo are harvested each year, with almost three fifths of it in India and China. An estimated 25 million people all over the world depend on or use bamboo materials. The table above indicates the distribution of bamboo in Asia. It is also serves to highlight the potential dominance of India with its vast resources and reserves of bamboo in future economic activity and trade.

In India, 28% of area and 66% of growing stock of bamboo in NE region and 20% of area and 12% of growing stock in MP & Chattisgarh.

Availability of Bamboo in India

S No.	State/region	Area %	Growing stock %
1	North East	28.0	66
2	Madhya Pradesh	20.3	12
3	Maharashtra	9.9	5
4	Orissa	8.7	7
5	Andhra Pradesh	7.4	2
6	Karnataka	5.5	3
7	Others	20.2	5



The housing and building construction industry is one of the largest consumers for natural mineral resources and forests. It is increasingly realised that innovative building materials and construction technologies which offer potential for environmental protection, employment generation, economy in construction and energy conservation need to be encouraged as best options to meet the rising demand of housing. Whole of north-east is prone to earthquakes and falls under Seismic Zone V. BMTPC lays emphasis on promoting design and construction of disaster resistant technologies for housing. Construction techniques using bamboo as main material have been found very suitable for earthquake resistant housing. With the constant rise in the cost of traditional building materials and with the poor affordability of large segments of our population the cost of an adequate house is increasingly going beyond the affordable limits of more than 30-35% of our population lying in the lower income segments. This calls for wide spread technology dissemination of cost effective building materials and construction techniques.

Bamboo as a Building and Construction Material

Bamboo is structurally stronger than steel. At the same time, it is light-weight, easily workable, and has vibration damping and heat insulation properties. Structurally, bamboo can find application in three main types of structures: scaffolding, housing, and roads.

Scaffolding

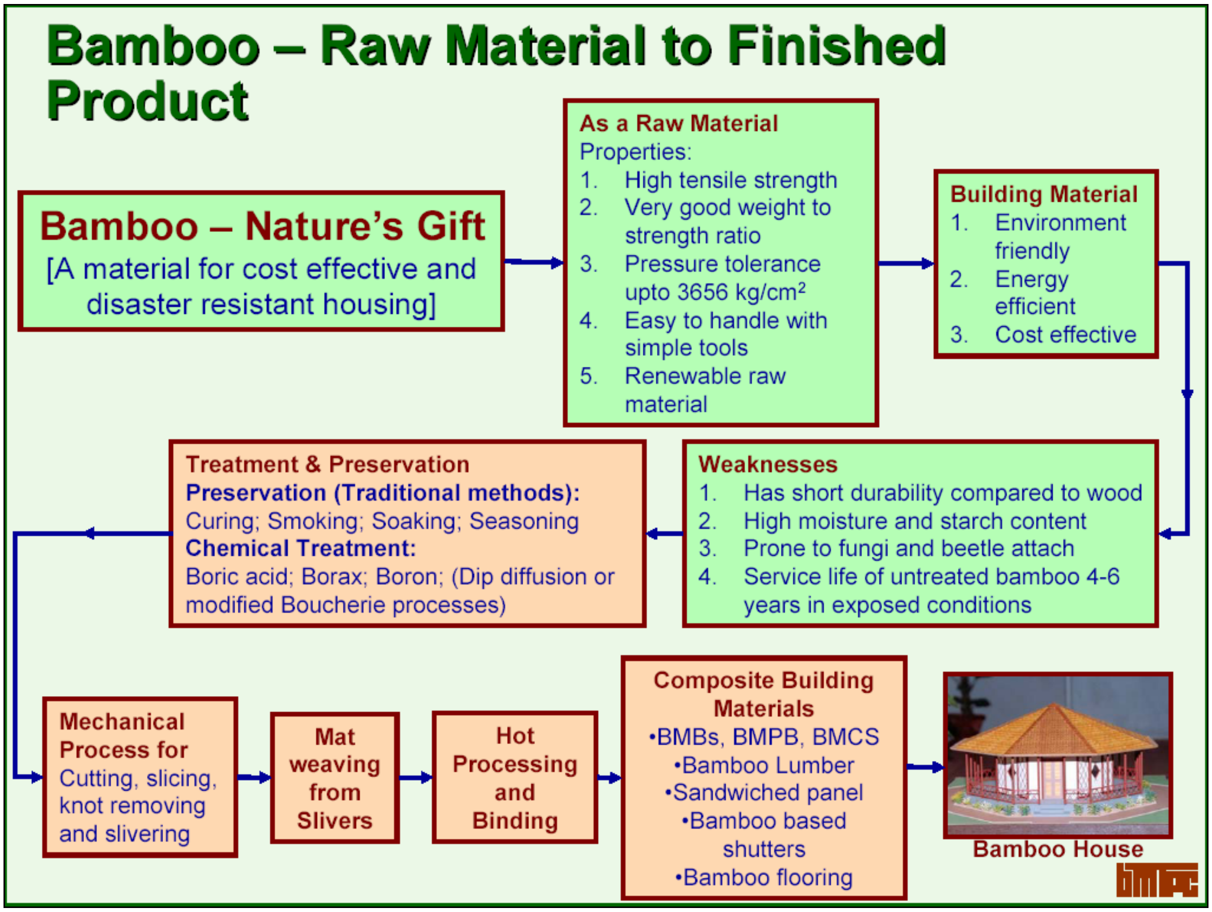
Bamboo is being used for scaffolding in most of the countries where it grows. In fact, despite construction becoming high-rise, bamboo has continued to hold advantages over other materials such as steel, which has entered the scaffolding market recently. Steel scaffolding is available as an industrial product of standardized dimensions that make it quick to erect and dismantle. Moreover, steel can be used at least 50 times more than bamboo, which can be used five to ten times at most depending upon the load of the construction. In this respect, bamboo scaffolding needs some technical upgrading.

However, bamboo is a preferred scaffolding material because its flexibility in the variety of lengths that it can be cut into, the lower investments that contractors need to make in the scaffolding stocks (bamboo costs just 6 per cent of the price of steel for similar quantity of scaffolding) and the ease with which it can be set up and dismantled. It is the preferred scaffolding option even in developed countries such as Hong Kong and continues to be used for the majority of high-rise buildings in these countries

In India too the usage of bamboo for the purpose of scaffolding is on the higher side. There is virtually no value addition on the raw bamboo used for scaffolding purposes.

Bamboo – a Housing material

In a structural application, bamboo rounds are used to create roof support systems. These systems include a prefabricated triangular truss comprising units eight metres long. A truss can be carried by four people, and deflects only 2.5 cm along its entire length. It is covered with bamboo boards, lath and plaster to create a waterproof roof. This system utilises bamboo rafters with bamboo boards, which are plastered on both sides, and fired clay tiles are used to waterproof.



Floor:

Bamboo flooring and bamboo board are newly developed interior designing material made using modern scientific methods from superior quality bamboo. Bamboo flooring is an attractive alternative to wood or laminate flooring.Bamboo with a wall thickness of culm of at least 11 mm is suitable for making floorboards. The process of making bamboo strip flooring consists of the following steps:

- Hollow bamboo of a minimum thickness of 11 mm is sliced into strips.
- These strips are milled to a thickness of 7 mm. They are then boiled to remove the starch and treated for anti-moth, anti-mildew, etc.
- The strips are then dried and carbonised (if required).
- The dried strips are now milled to 5 mm thickness.
- These strips are now glued and laminated into solid boards under high pressure, which are then milled into standard strip flooring profiles.

The machinery and equipment required for manufacturing bamboo flooring can be imported from Taiwan, though some is available locally as well.

Floors can be made out of flattened bamboo, woven bamboo mats or split bamboo.

As reinforcement:

There are four categories in which the use of bamboo has been made:

1. Bamboo fibres in cement mortar for roofing sheets
2. Split bamboo as reinforcing bars in concrete
3. Bamboo as a form work for concrete
4. Bamboo as a soil reinforcement

For Roofing:

Bamboo Mat Corrugated Roofing Sheet has been developed by BMTPC in close collaboration with Indian Plywood Research and Training Institute (IPIRTI) Bangalore, India. It is made from woven bamboo mats.

For Walls:

Woven bamboo mats are used to make walls in countries such as Bangladesh and India. Vertical whole or halved culms and flattened bamboo strips are also used for making walls. Walls can be made with bamboo as a minor component and mud as a major one.

For Doors and windows:

Bamboo can be fashioned artistically to make doors and windows.

BMTPC's Initiatives in Promotion of Bamboo in Housing & Buildings

The Building Materials & Technology Promotion Council (BMTPC) under the Ministry of Housing & Urban Poverty Alleviation, Govt. of India is actively involved in development of bamboo based technologies and to promote these technologies in the North-Eastern Region including other bamboo growing areas, by encouraging commercial production of bamboo based products, construction of demonstration houses and setting up of Bamboo Mat Production Centres for processing of bamboo, etc.

Bamboo Mat Corrugated Roofing Sheets

The BMTPC in collaboration with Indian Plywood Industries Research & Training Institute (IPIRTI), Bangalore, have developed a technology for manufacturing of Bamboo Mat Corrugated Sheet (BMCS) which is durable, strong, water-proof, and decay-insect-fire resistant. The commercial production has been started at Byrnihat, Meghalaya. The product has been accepted by the consumers and is becoming increasing popular as a roofing option in the north east part of the country. It is estimated that in full capacity this unit will generate livelihood for nearly 7000 women/men (through mat weaving) in rural regions where bamboo is abundantly grown.

Bamboo Mat Corrugated Ridge Cap

BMTPC in collaboration with IPIRTI, Bangalore, has also developed a technology for manufacturing of Bamboo Mat Corrugated Ridge Cap for roofing. The Technology is ready for commercialization.

Construction of Demonstration Structures

BMTPC has constructed 24 demonstration structures in Mizoram, Tripura, Nagaland and Meghalaya using bamboo based technologies. These include Houses, OPD buildings, Library buildings, Picnic huts, Schools, etc. The cost of construction using conventional technologies in these areas is around Rs. 800/- per sq ft. This is considerably reduced using bamboo based technologies and the cost of construction achieved is Rs.315 to Rs.622 per sq.ft. for different types of structures. The specifications used are:

(a) Treated bamboo columns and beams,
(b) Ferrocement walls on bamboo grid reinforcement,
(c) Treated bamboo trusses, rafters and purlins,
(d) Bamboo mat board in wooden frames for door shutters,
(e) Bamboo Mat Corrugated Roofing Sheets,
(f) IPS flooring, etc.

Development of Technology for Construction of Two Storey Bamboo Housing System

A technology for construction of two storey bamboo housing system has been developed and a demonstration house has been constructed at the campus of IPIRTI Bangalore. At each stage of house construction various elements were tested and models of such elements were made before the actual construction was carried out.

Design and Development of Pre-fabricated Modular Housing System

BMTPC has undertaken Design and Development of pre-fabricated modular housing system using bamboo and bamboo based composites in collaboration with IPIRTI, Bangloare. A model design of pre-fab double walled bamboo composite house attached bath and kitchen having size 20’ x 24’ x 8’ was developed. This system will enable application of bamboo composite building materials in pre-fabricated houses. These types of houses can be constructed quite quickly for immediate and long term rehabilitation for post disaster relief.

Bamboo Mat Production Centres

BMTPC alongwith Cane & Bamboo Technology Centre (CBTC) in cooperation with State Governments, is establishing Bamboo Mat Production Centres in the States of Assam, Tripura, Mizoram, Meghalaya and Kerala. The main objectives of Bamboo Mat Production Centres are to provide uninterrupted supply of bamboo mats to the manufacturing units of bamboo based building components for increasing the productivity, quality, to provide training in mat production process and to create employment opportunities.

The Council has established such Bamboo Mat Production Centres in Tripura, Mizoram, Meghalaya and Kerala.

BMTPC and CBTC are also providing training on bamboo mat production to the artisans from each Bamboo Mat Production Centres. The production capacity of each production centre will be 300 mat per day. It is estimated that the each Centre will be able to produce the mat at the rate of Rs.35 per mat and would be able to sell at the rate of Rs.45 per mat. This provides employment generation of nearly 150 women/men per day i.e. 45,000 women/men days per year per Centre. Besides the above, the Centres can also generate income by supplying bamboo sticks made out of bamboo waste, to the artisans for making handicraft items. The mats produced by Bamboo Mat Production Centres are likely to utilized by various manufacturers who are producing Bamboo Mat Corrugated Roofing Sheets and Bamboo Mat Boards.

Bamboo – More Than An Alternative

Bamboo has so far not been regarded as a substitute for wood. An analytical look at the applications for which wood is being used and the usage of bamboo indicates that it is possible to use bamboo for all the applications for which wood is being used. The usage of bamboo has in fact been established conclusively for categories that consume larger volumes of wood, namely, paper pulp, plywood, construction and furniture.

There are preconceived notions about the technical capability of bamboo. These have hindered the adoption of bamboo as a wood substitute. The wood industry is not able to visualize bamboo as a process-friendly material that can peeled. It also considers bamboo to be susceptible to fire, water and termites.

The Bamboo, if used efficiently, shall lead to the following in the interest of the nation and masses:

- *Enterprise Development*
- *Training for skill upgradation*
- *Employment generation*
- *Conservation of forest timber*
- *Bulk utilization of bamboo*