BAMBOO POLES FOR SPATIAL AND LIGHT STRUCTURES

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Abstract

This document is a summary of a research project that we made during 2003/2004 in Colombia. The paper informs about the natural resource bamboo and its mechanical properties. After showing that this material is appropriate to be used as a pole in spatial and light structures, we explain our own proposal on how to join these poles of bamboo in a three-dimensional way. Finally, some possible applications will be presented.

Why Bamboo ?

Bamboo "The giant grass" is a fascinating material. It grows mainly in the tropical and temperate climates of Asia, Africa and Latin America. There are a lot of different species. Some bamboos are so small and soft that you can even eat them. But other ones have really strong fibres and reach a height of up to 20m with a diameter up to 16 cm in less than one year. [LIE85]
The history of using culms of bamboo goes back to prehistoric times**.** Beside handcrafts or furniture, one of the oldest applications of this natural material is in the field of construction. People of different cultures always used bamboo for housing constructions, bridges, ships or scaffolding on the building site. Even one of the first airplanes was made of bamboo. [HID03]
Presently, the interest in bamboo construction is increasing. The Colombian architect Simon Velez for example became famous with the design of the beautiful bamboo pavilion for the EXPO2000 in Hannover, Germany. [VEL00]


bamboo species "guadua" fig.1


historical bamboo bridge fig.2

Especially for spatial and light structures, there are mainly two reasons to study, to use and to develop techniques with bamboo.

1. ECOLOGICAL VALUE: In view of our responsibility to the environment we need to look for sustainable alternatives for the materials in modern constructions. Bamboo is a very fast growing natural resource and from a bamboo area, ripe culms can be harvested each year. Bamboo can be used as well as a reforestation plant and it offers a great service to nature. [GIR99]
The processing and use of bamboo does not produce any ecological waste. And in comparison to other materials, very little energy is needed on its way from the place where it grows to its application on the construction. [JAN00]

2. GOOD MECHANICAL PROPERTIES: For engineering aspects, bamboo has a lot of advantages making it fit to use for spatial structures. Firstly, it is a very light material. That leads to a low weight of the structure itself, which is good for any kind of dynamic influence**.** Furthermore, the bamboo fibres have an impressive resistance. Especially the compression and the tensile strength are very high. The tubular form of bamboo culms is the reason for its good ratio between the cross section and the moment of inertia that means in case of compression forces you can work out a favourable slenderness. That is why bamboo is perfect for spatial structures where mostly axial forces arise.
Finally, putting the mass of bamboo into relation with the maximum force and its transmission path, we get a really interesting value, which can compete with steel but being much cheaper. [IL85] [HID03]

Building with Bamboo in Colombia

Like with all materials and especially with natural grown resources, it is important to handle bamboo well, to apply the design and the calculations on its special properties

Actually Colombia is besides Asia one of the places with the most bamboo building activities. There are a lot of research projects working on different themes and more and more architects who are using bamboo. [ARB01]
The most used species is called *Guadua angustifulia Kunth* which grows mainly in the Colombian coffee-zone of the Andes. It has an average external diameter of 12cm with a wall thickness of 1.5cm. It reaches a height of more then 10 meters in only 6 months and gets mature after 3 years. [LON92].
Especially the fact that a lot of light and strong bamboo constructions suffered little damage during the 1999 earthquake in the coffee-zone made many people get interested in building again with bamboo. Today you find a lot of new housing projects (bahareque), constructions up to three floors, or even bridges with a span length over 40m. [HID03]

bamboo bridge, popayan colombia, fig.3
Jörg Stamm, 1997

bamboo pavilion, manizales colombia, fig.4
arch. Simon Velez, 1999

Although today there still is not an official preselection or building code for bamboo, these constructions can teach us a lot. All the field of knowledge and activities in the use of bamboo is still mainly based on experience and some investigation. This document can only give a short summary of the main properties and some recommendations in the use of bamboo.

First of all, the selection of bamboo is an important point. After choosing the right species, you have to make sure that the bamboo you will use is older than three years and that it got well dried to a moisture content of less then 25%, because the use of "young and wet" culms for structural elements can produce crushing or cracks.
Furthermore, bamboo culms grow slightly conical and not all of the rods are exactly straight, that means you have to choose the best ones for your project before starting the construction. [HID03]

One of the first things for the design of a bamboo structure is, that it has "good boots and a big hat" like Simon Velez says. You always have to keep the bamboo itself free from moisture, rain or direct sun radiation. Humid background can cause putrification or loss of resistance. Direct influence of sun leads to a change of colour such us a whitening of the surface. Bamboo also needs treatments against decay fungi, insects, termites and borers. [VEL00]

Bamboo offers the best resistance to tensile forces. But it is important to know that not all the parts of the cross section work the same way. The external fibres resist a lot more than the internal ones. Some material tests of the external fibres even reported values close to the values of steel while the internal ones only resist 30% of that. In that case the whole culm of bamboo offers only an average resistance, which still is a lot higher then the resistance of wood.

Bamboo behaves really well under compressing forces. The internodes reforce the culm every 20cm, the tubular shape of bamboo offers a good moment of inertia and the fibres work at a high resistance.

But you have to be careful with the weak shear strength of bamboo. It is not recommended to put high forces perpendicular to the fibres. It can easily slice. Therefore you always have to pay attention on how you design the joints. And bending tests, for example, always cracked under shear forces.

Additionally to the calculations of the loading capacity it is often necessary to check the deformations and displacements as well, because bamboo has a low modulus of Elasticity.

Mechanical Properties of *Guadua angustifolia Kunth*

The right use of the values for the mechanical properties is very important in the construction with bamboo. In fact, there are only few publications about the resistance and there is still no building code regulating constructions in terms of the mechanical properties of bamboo.
Comparing the literature and publications about that topic often shows a variety of different values for resistance and some published researchs indicate very high values for the mechanical properties but giving insufficient background information about the species, age and moisture content.
As well as Bamboo-Space, most projects working with bamboo have to define their own limits for the mechanical properties depending on minimum values in comparing serious investigations, own experiences and own investigations.

The following table presents some important publications of mechanical properties of the often used Colombian bamboo species *Guadua angustifolia Kunth*. You find as well the average values of the five percent lower boundary that we recommend for each kind of strength.

author / year	specifications	compression strength (N/mm^2)	tensile strength (N/mm^2)	bending strength (N/mm^2)	shear strength (N/mm^2)	modulus of elasticity (N/mm^2)
Martin, Mateus, Hidalgo 1981, Bogotá [MAT81]	age 3-5 years density 0.8g/cm³ moisture ≤ 30 %	62 (max) 49 (ave) 35 (min) 28 (lp)	200 (max) external fibre 70 (max) internal fibre			12000 ($E_{0,max}$) 6000 ($E_{0,05}$)
Garcia, Martinez 1992, Pereira [GAR92]	age 4-5 years density 0.7g/cm³ moisture ≤ 30 % *guadua Macana*	38 (ave) 34 (min) 14 (perm)		30 (ave) 17 (min) 6 (perm)	3.8 (ave) 2.3 (min) 1.1 (perm)	3000 (ave) 2500 ($E_{0,05}$)
Trujillo, Lopez AIS - FOREC 2000, Medellin [LOP00]	age 3-5 years density 0.7g/cm³ moisture ≤ 30 %	65 (max) 44 (ave) 28 (min) 14 (perm)	74 (max) 54 (ave) 35 (min) 26 (perm)	calculated 15 (perm)	8 (max) 6 (ave) 4,3 (min) 1,1 (perm)	12000 ($E_{0,mean}$) 6000 ($E_{0,05}$)
Lindemann FMPA , Stuttgart, 1999 [LIN00]	complete λ=10 culms, λ=56 air dry, λ=86	56 (ave) 39 (ave) 27 (ave)	calculated 95 (ave)	74 (ave)	4,3 (ave) 1,1 (lp)	18000 ($E_{0,mean}$)
Janssen 2000, Eindhoven [JAN00]	density 0.6g/cm³ moisture „air dry“	56 (max) 7,8 (perm)		84 (max) 12 (perm)	12 (max) 1,8 (perm)	20000 ($E_{0,max}$) 10000 ($E_{0,05}$)
average of minimum values by bamboo-space		**~30 (min)**	**~50 (min)**	**~30 (min)**	**~4 (min)**	**~6000 ($E_{0,05}$)**

Table 1, mechanical properties of *Guadua angustifolia Kunth*

(max) - maximum rupture strength, ultimate stress
(min) - minimum rupture strength, ultimate stress (five percent lower boundary)
(ave) - average rupture strength, ultimate stress
(perm) - permitted strength, allowable stress - recommended by the author of the test
(lp) - resistance on the limit of proportional deformation

Other species of bamboo

Among the large variety of bamboo species, there are still many with similar mechanical properties as *Guadua angustifolia Kunth* which are appropriate to use for construction as well. Oscar Hidalgo presents in his book for example the following species which you find mostly in Asia:
Ph.bambusoides, Ph. nigra var., Ph. pubescen, Ph. Lithophila, Dendracalamus latiflorus, B. stenostachya, B. vulgaris var. vittata .... [HID03]

Bamboo for spatial and light structures - a competition

The structural elements of spatial and lightweight constructions are actually mainly built of steel, wood or new and expensive materials because they should be light and strong. Exactly, this is what bamboo culms offer. Also, they are cheap, ecological and naturally made for axial forces.

The following example compares commercial cross-section of steel, wood and bamboo in terms of their allowable stress under compressing forces. The calculations are based on the EUROCODE 3 for steel and the EUROCODE 5 for wood and bamboo. The cross-section of the poles with a length of 2.5 m is chosen in a way that the weight of all the three is the same.

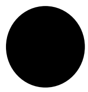
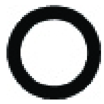
Compression force on rods of 2.5m, euler c. 2	Wood EC5 S10/MS10	Bamboo EC5 *Guadua angustifolia kunth*	Steel EC3 S235
Density kg / m³	550	700	7800
M.of Elasticity N/mm²	7400	6000	210000
f_c N/mm²	21	30	235
cross-section	 D=9cm	 D=12cm d=9cm	 D=5.1cm d=4.5cm
Area A cm²	63.6	49.5	4.4
Inertia I cm⁴	322.1	695.8	12.7
Slenderness λ	111.1	66.7	147.2
Weight kg	**8.7**	**8.7**	**8.7**
Force, allowable KN	**15.1**	**25.6**	**27.6**
BIC $\frac{g}{N*m}$	0.23	0.14	0.13
Prize per meter € Colombia / Germany	2 / 5	1 / 3	4 / 8
ECOCOSTO $\frac{MJ/m^3}{N/mm^2}$ [JAN00]	80	30	1500

Table 2, comparison of materials

The example shows that bamboo easily can compete with steel or wood. Based on the chosen cross-sections, bamboo can even resist more forces than wood and is in the same rank as steel.
Of course you can increase the cross-section of wood or steel to get a higher resistance, but the weight will increase automatically as well. That is why the value of the BIC-factor is so interesting. The BIC-factor puts the mass into relation with the force and its transmission path. In this case, bamboo is nearly as efficient as steel. [IL85]

But the most competitive properties of bamboo are the costs. The ECOCOST, that mainly means the amount of needed energy for processing bamboo is even less than for wood. [JAN00]
Further bamboo is a lot cheaper than wood or steel and it does not matter if you buy it in Colombia or if you have to import it to Germany for example. Bamboo remains the cheapest of the three.

Finally, there are some good arguments to use culms of bamboo for spatial and light structures. And although bamboo does not grow everywhere, you can bring and use it almost everywhere.

Existing joints for bamboo constructions

Making joints in bamboo always has been difficult because it is hollow, has nodes and resists only a little shear stress. A lot or traditional joints suffer from weakness or deformation. Many joints can not take advantage of the strength of the culm itself and a special problem is to design a joint for tensile forces. A culm of guadua resists for example a tensile strength of more or less 100 KN, but there still does not exist any joint which is able to transmit that force from one bamboo to the next.
Timber and steel became proper building materials only after the problem joint had been solved. Bamboo has to tread the similar path. After explaining some traditional and modern techniques for joining bamboo, a new proposal of the Bamboo-Space Research Project project will be presented.

Actual joints


fig. 5


fig.6


fig.7


fig.8

The traditional way to connect bamboo is based on handmade techniques which use cables or wood sticks like figure 5 shows. These joints are cheap and a lot of people from rural zones still know how to make it. The disadvantage is the little resistance of these joints which are only useful for small projects.

Today, the most common joint is to fill the culms close to the joint with mortar and to put a vertical or parallel bolt to connect with the next bamboo culm. Figure 6 gives an example how the German carpenter Jörg Stamm uses vertical bolts for his joints. [STA01] An example of a parallel bolt is presented in figure 7, which is a joint designed by Simon Velez. [VEL00]
The investigation of the Colombian Jenny Garcon worked out some recommendations for these kind of joints. A parallel bolt can be used up to 7 KN on tensile strength for each node filled with mortar and vertical bolts resist until 10KN for each filled node. [GAR96]
Figure 8 presents a joint with only one vertical bolt and without mortar. Colombian students built some trusses with this technique and recommend bringing in max. forces of 10 KN on this joint. [GUT02]
This "mortar and bolt technique" offers a better resistance then traditional joints but it always depends on how much culms are filled with mortar. That means that the construction can get heavy. Further, it is quiet a lot of work on the building site to fill all the joints with mortar and to put the bolts.

Alternative joints


fig. 9


fig.10


fig.11


fig.12

David Trujillo, Figure 9, worked with 12 small bolts putting them through a steel ring vertical to the bamboo. He got an average of max. resistance of 70 KN for tensile strength. To avoid deformations of more than 0,5 cm he is recommending to use max. loads of 20 KN. [TRU00]
Figure 10 is a joint detail of a construction by Shoei Yoh. He used two big vertical bolts to connect them with another steel tube which goes from inside the bamboo to a sphere. [YOH89]

The German student Christoph Tönges made a study of a technique which consist in putting a conical element into the end of the culm and to fix the thinner end with a ring in a way that the cone resists on tensile forces. A cone of mortar with a ring of steel is showed in figure 11 and an example of a metallic cone with a ring of fiber glass is given in figure 12. [TON03]

New proposal for joints

The joints currently used for bamboo are relatively heavy and complicated because of the use of mortar or do not resist high forces. But to be able to use bamboo for spatial and light structures it is important to resolve the problem of a joint which does not bring much weight to the structure and which works under high forces to take advantage of the high resistance of the bamboo fibers.

Looking for a new technique, we became inspired by some of the alternative joints for bamboo and by some techniques which are already used in steel constructions. The joint should be light, strong and appropriate for temporary constructions, which have to be easy to assemble and disassemble. [HEY01]

The following pictures present the proposal of the Bamboo-Space Research Project.

fig.13

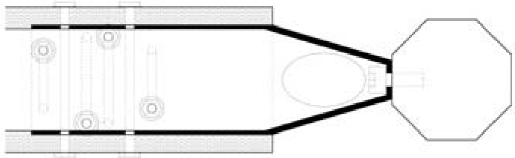


fig.14

The joint is made of two elements. Firstly, there is a thin steel tube with a diameter of 9 cm and a length of 30 cm. After perforating the inner fibres of the bamboo to make sure that the tube fits, the tube is inserted 20 cm into the bamboo culm where it receives 12 vertical bolts to transmit the forces to the bamboo fibers. One end of the tube is reduced to a conical form and offers two eliptical openings, which allow attaching from inside another larger bolt to the conical tip.
The second element is a three-dimensional sphere such as used in steel constructions which receives this bolt and the conical part of the tubes permits connecting a couple of bamboos to only one sphere.

Figure 13 is a photo of one of the first prototypes of the special tube, the bolt, its key and finally the culm of bamboo. A more technical section is presented in figure 14 where you can see how the vertical bolts connect the bamboo with the steel tube and how the sphere receives its bolt.

fig.15

fig.16

fig.17

We made the first prototype with the bamboo *Guadua angustifolia Kunth* and figure 15 shows how this joint looks when it is assembled. Figure 16 gives an idea of the sphere. The photo belongs to the products of the MERO Company, but of course it is possible to use other products or to make some new proposals. A rendering of a complete joint based on this technique is presented in figure 17.

The material tests with this joint and the bamboo *Guadua angustifolia Kunth* that we made at the "Universidad Nacional de Colombia, Sede Medellin" have demonstrated max. resistances up to 85 KN for tensil strength. Based on the calculations by civil engineer R. Laude we can recommend using this joint with *Guadua angustifolia Kunth* for tensile or compression forces up to 30 KN.
This value finally corresponds to what the material itself resists on compression forces. (25KN, table 2)

Additionally, this is one of the first joints permitting the use of bamboo in spatial structures and the system is perfect for temporary structures.

Applications

Based on the presented joint, poles of bamboo could become almost universal elements for spatial and light structures like triangular trusses, double layer space structures, geodesic domes or tensegrity structures. In the following constructions bamboo could be used instead of steel or wood.

Arch. Brader fig.18
wood structure

Technikon fig.19
steel framework

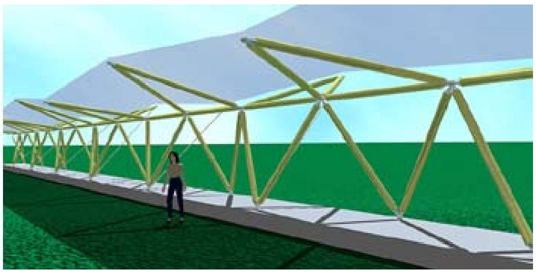
Cenotec fig.20
steel trusses

Arch. Shoei Yoh fig.21
bamboo dome

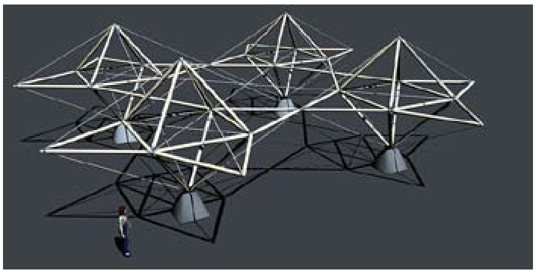
Poles of bamboo are especially appropriate for big and light roof constructions. We recommend using straight culms of bamboo between 1m-4 m and to prefabricate the joints. On the building site, you just would have to connect them to the spheres. The finish material for the roof could be made of a textile membrane or aluminum panels to maintain the whole structure light.

Finally, here are some of the first designs of the Bamboo-Space Research Project using bamboo, the described joint and textile membranes.

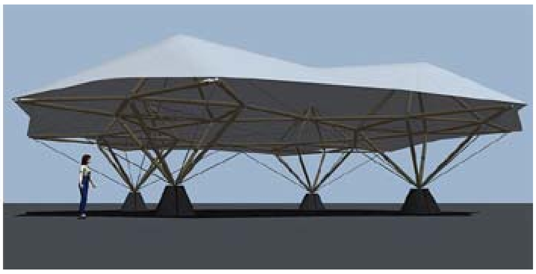
Arch. T.Obermann fig.22
pavilion as study and party area



Arch. T.Obermann fig.23
repetitive module for sun protection

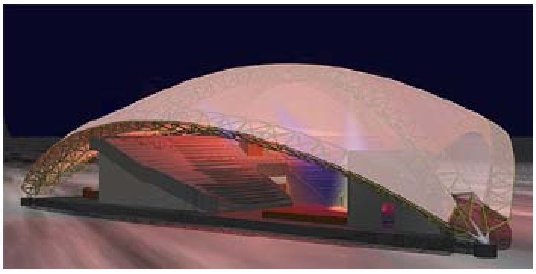


Arch. T.Obermann fig.22
tensegrity structure for multi using space



Arch. T.Obermann fig.23
the same structure covered by a textile membrane

Arch. T.Obermann fig.22
triangular trusses composing a dome



Arch. T.Obermann fig.23
the same dome covered and used as theatre

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Internet recommendations

Sociedad Colombiana de Bambu : http://www.guadua.org

Bamboo Research - RHTW Aachen: http://bambus.rwth-aachen.de/de/index.html

International Network for Bamboo and Rattan : http://www.inbar.int/

Bamboo Research - Jules. J. Janssen: http://www.bwk.tue.nl/bko/research/Bamboo/

Bamboo Research - Bamboo Space: http://www.bamboo-space.info