

# CONTENTS

**ABSTRACT**

**WHY BAMBOO?**

**BIOLOGICAL ATTRIBUTES**

**CUTTING + PROCESSING**

**BAMBOO CONNECTIONS**

**BAMBOO CONNECTIONS MODEL**

# ABSTRACT

This investigation will look into the construction with bamboo in architecture. It will determine the potential building scale that bamboo is capable of producing.

One of the fastest growing floras on earth, bamboo grows in warm climates and can be found in Asia, North and South America, and Africa. There are also a variety of bamboos that are found in the world. When bamboo is grown to its greatest strength and has reached its lowest sap level, it is harvested for construction applications. Harvesting bamboo in cycles is also required. Methods of growing bamboo can affect its future shape as well. Bamboo also needs to be treated to prevent rotting insect infestation.

When constructing with bamboo it is important to know its structural properties. First, the longitudinal growing fibers and the rounded profile make bamboo not easy to brace as well as difficulty in detailing. The smooth exterior surface and hollow adds to difficulty as well.

There are basically two general categories for bamboo connections: high-technology and low-technology connections. High-tech connections involved industrial parts (nuts and bolts), while low-tech such as bamboo-related material, is affordable to be made and does not require skilled labor. Examples of low-technology connections are friction-tight rope connections (lashing ties, cords and ropes), plug-in connections, and interlocking connections. Examples of high-technology connections are woodcore connections, transportation armature/screw connections, Induo-anchor connections, and steel pin connections. (show examples of all the diff varieties).



*Bamboo connection in metal by Shoei Yoh<sup>1</sup>*

# WHY BAMBOO?

Why choose bamboo to build with? What is so great about it? One reason is its abundance location around the world. Bamboo plants can be found almost worldwide. In all continents natively, with the exception of Europe and Antarctica, Bamboo can be found from latitudes of 51° North to 47° South, and 14,000 feet above sea level. The highest altitude has been found in the equatorial Andes. Bamboo has been found to grow in also dry habitats, though the optimum location for bamboo growth is in humid regions of forests and lowland tropical jungles. There are about 1100 bamboo species in the world (Villegas 22).



*Hanging bridge in Columbia, South America<sup>2</sup>*

Since bamboo's fast and easy growing capabilities, it is inexpensive and anyone can grow it. Due to its stiffness, it is easy to have just bamboo as the only material to support a structure, thus requiring less materials and building costs. Since there is no bark to decorticate, there is no waste involved with cultivating the bamboo. It can be cut down simply with a machete (Oliver 118). No man-made surface is as soft as the polished exterior of a bamboo cane (Vitra Design 237). This is due to the wax and silicon excretion on the outside.



*Housing in New Guinea, 25 meters high<sup>3</sup>*

Bamboo has some disadvantages as well. First, is bamboo's round profile. Due to the round profile, it is difficult to create strong, tight perpendicular connections between two bamboo members. The direction of the fibers grows in longitudinal direction, which makes it not suitable for load carrying in cross direction (no cross fibers). Since bamboo is a natural product, members will vary in diameter and length, and there is no standardization to the material. (Rottke 2) Bamboo's materiality does not act like wood; therefore it is not be treated like wood. This means you cannot use nails and screws due to the danger of splintering (Vitra Design 109). Even with these limitations for creating bamboo connections, there are connections that can still be made.

# BIOLOGICAL ATTRIBUTES

Bamboo does not belong to the tree category, but rather to grass. The reason is bamboo belongs to the Poaceae (or Gramineae) family (the grass family) and Bambusoideae subfamily (Villegas 22). Bamboo is then divided into two groups: the herbaceous bamboo (Olyreae) and woody bamboos (Bambuseae) (22).

Bamboo is characterized of having rhizomes, “the shoot system that grows underground and is divided into internodes and nodes like the shoots above ground (Vitra Design 157). Herbaceous bamboo has little-developed rhizomes and culms (canes or stems) that are lignified (rigid) slightly. Woody bamboo has strong and well-developed rhizomes with lignified culms (Villegas 23). Clum in bamboo is basically a cylindrical shell, divided by intersecting diaphragms at the nodes (Xiao 7).

The structural characteristics of bamboo is it a vertical-fiber oriented growing material with high strength along its fibers and low strength intersecting its fibers (Xiao 7). It is a composite material, with long and aligned cellulose fibers found in a ligneous matrix (7). A bamboo cane, unlike a tree, has 50 percent mass due to its hollow center (which is then only 45 percent fiber (Vitra Design 159).

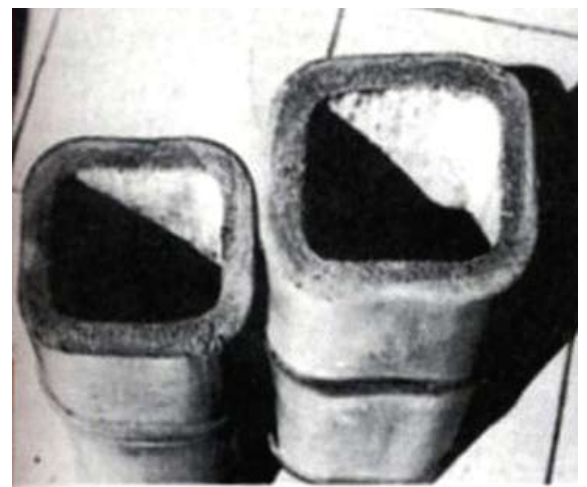
Bamboo has the idea structure: tapering toward the top and with a stiffened interior (Vitra Design 205)

Square bamboo is created by having a square sheath over the bamboo sprout for it to grow into. This allows more contact areas for joints (Vitra Design 237).

Many other factors that go into the mechanical properties of bamboo are age of the cane when harvested, moisture content, and diameter/wall thickness (Vitra Design 237).



*Sectional cut of bamboo cane with roots, lengthwise<sup>4</sup>*



*Square bamboo using square sheath over sprouts which will grow inside them the desired shape<sup>5</sup>*

# Guadua Angustifolia

Guadua angustifolia is the most common and best used bamboo type in the world. It is naturally found in South America in the countries of Colombia, Ecuador, and Venezuela (Villegas 27). Though through globalization, it can be found in Central America, Caribbean countries, Asia, North America and Europe (27). Having ideal strength/weight ratio, it exceeds the strength of many woods and is compared to strength/weight ratio of steel and high-tech fibers (Villegas 34). Test examination results of the load capacity of Guadua done by the Otto-Graf-Institut are as follow (238):

#### Pressure tests:

Resistance to pressure $f_{c,0}$	56 N/mm <sup>2</sup>
Resistance to pressure $E_{c,0}$	18,400 N/mm <sup>2</sup>

#### 4-Point bending tests (DIN EN 408):

Mean flectional resistance $f_m$	74 N/mm <sup>2</sup>
Mean flectional resistance $f_m$ Given ideal drying and/ Or ideal moisture content	100 N/mm <sup>2</sup>
Moduel $E_m$	17,900 N.mm <sup>2</sup>

#### Connection tests:

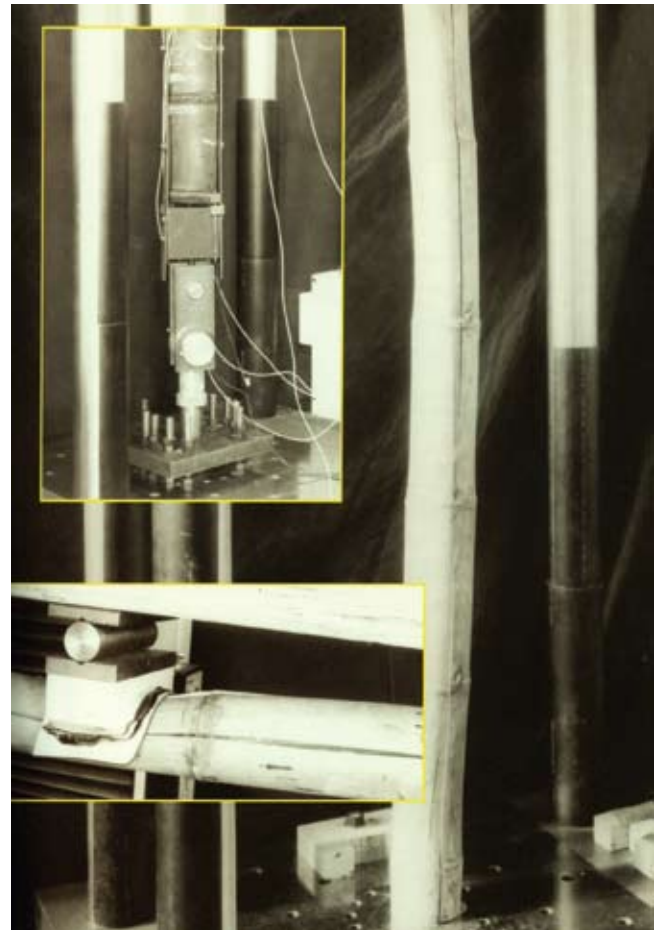
Mean tensile bearing load of conectors tested	140 KN
--------------------------------------------------	--------

As a result, Guadua Angustifolia can be used for heavy land and can be used as an alternative to timber structure (Vitra Design 238). The maximum load-bearing capacity reached during testing of the Guadua and still showed a load-bearing capacity of 1/3-1/2 of its maximum capacity (238). Though Guadua Angustifolia has some parameters:

- +Guadua Angustifolia with cross-section fineness  $r/t$  of  $3 < r/t < 5.5$
- +Testing hall without air conditioning
- +10-15% moisture content in the bamboo (238).



Guadua Angustifolia<sup>6</sup>



Bamboo load-bearing tests<sup>7</sup>

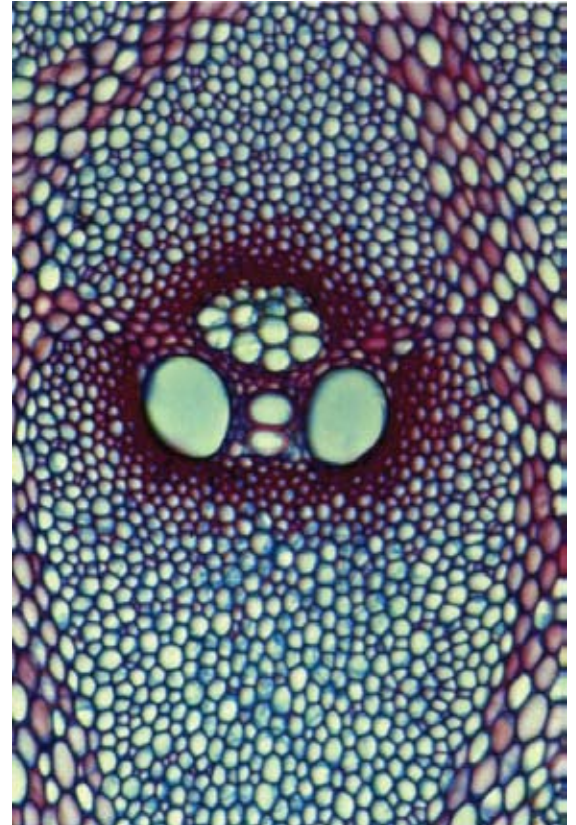
*G. angustifolia* are faster growing and a higher productivity compared to trees. Having a growth cycle of a third of a tree, can be cultivated after 5 to 6 years of growth, and if done properly can have an infinite production. With a maximum diameter of 25 cm ( $\approx 10$  in) and average of 9-13 cm (3.5-5 in), the *G. angustifolia*'s daily growth of 21 cm ( $\approx 8$  in) with a maximum height of 15-30 meters ( $\approx 49$ -98 feet) (Villegas 30).

## Environmental Advantages

The guadua has numerous environmental advantages. It conserves the soil, limits erosion, manages the flows of streams and rivers, supplies organic material, and a CO<sub>2</sub> sink. Studies have shown its stabilization of carbon dioxide of its first six years of growth from new sowings is 54 metric tons/hectare (860.22 bushels/acre) (Villegas 32).

## Fiber Quality

The reason *Guadua angustifolia* is one of the best bamboo species is its strong fibers. Its structural content is a relatively high percentage of fiber and silica in the exterior cell layer that give the strong properties of its culm (hollow stems)(Villegas 33).



Microscopic view of the vascular sheath of *Guadua angustifolia* (100x)<sup>8</sup>



Various types of *phyllostachys* bamboo<sup>9</sup>

# CUTTING + PROCESSING

Guadua needs to be cultivated and used for construction no less than three years old stalks and no more than five years old; this is because of its optimum strength.

It is then set out to dry for around two to three months, to evaporate 90 percent of its natural moisture content. Fungus and insect repellent is important to implement in the bamboo.

Methods used are submerged in water, coating with lime slurry, heating, or smoking. When heating the bamboo, it “sweats” out the pyrolytic acids, which evaporate and through this treats the bamboo (Vitra Design 163).



*If bamboo is cut exactly above the end of a partition does it retain its moisture after harvesting and can thus produce new shoots<sup>10</sup>*



*Drying bamboo poles<sup>11</sup>*



*Oven used for smoke-imregnating bamboo poles<sup>12</sup>*

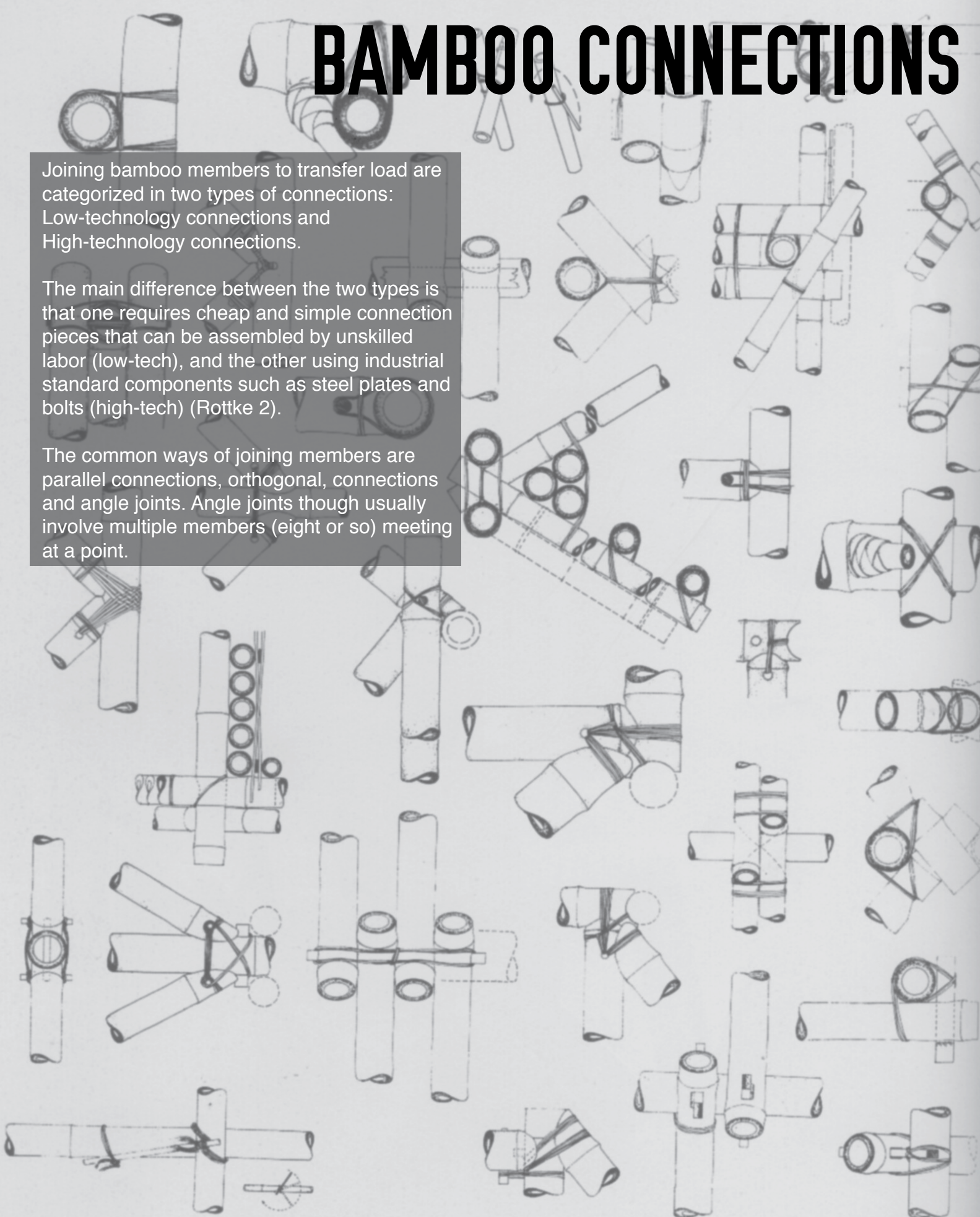


# BAMBOO CONNECTIONS

Joining bamboo members to transfer load are categorized in two types of connections: Low-technology connections and High-technology connections.

The main difference between the two types is that one requires cheap and simple connection pieces that can be assembled by unskilled labor (low-tech), and the other using industrial standard components such as steel plates and bolts (high-tech) (Rottke 2).

The common ways of joining members are parallel connections, orthogonal, connections and angle joints. Angle joints though usually involve multiple members (eight or so) meeting at a point.



# Low-Technology Connections

## Friction Tight-Rope

One of the simplest ways of connecting bamboo pieces is friction tight-rope connection. Natural materials usually used involve ropes and cords of bamboo rinds, bast (vascular tissue of a plant), raffia palm trees fibers, coconut fibers, rattan (stem) of a palm, and sago palm fibers. Bamboo strips can be used as well, needing they be green strips that are pre-soaked (Rottke 3). With factory made connectors, zinc-coated iron wires and even plastic rope can be used as well (3).

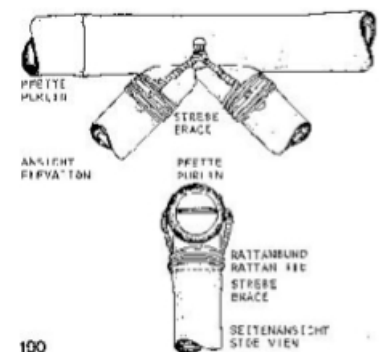
Lashing can have variations of complexity as well. With joining members cut appropriately to fit snug to each other, the bamboo pieces can be lashed together with pre-drilled holes in each of them and the rope tied through them.

## Wedge Connection

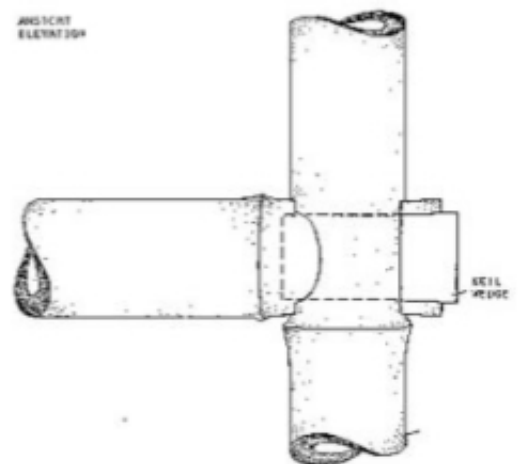
Driving a wedge at the connection of two bamboo members is a simple way of connecting bamboo. The horizontal member end needs to be rounded in order to fit and not move around at the connection. On the opposite end of the vertical member a wedge (possibly mad of wood) is driven through and ends on the other side, inside the horizontal member. Due to the possibility of the wedge shrinking, additional structural supports are needed with lashing or bolts (Rottke 12).



Fine handwork rattan connection <sup>15</sup>



Lashing tie with connection of a purlin and two braces with three drill holes <sup>16</sup>



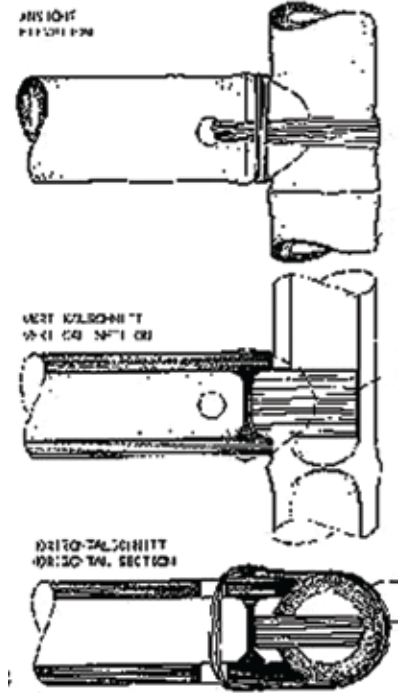
Interlocking connections with wedge <sup>17</sup>

### Inner Plug Connection

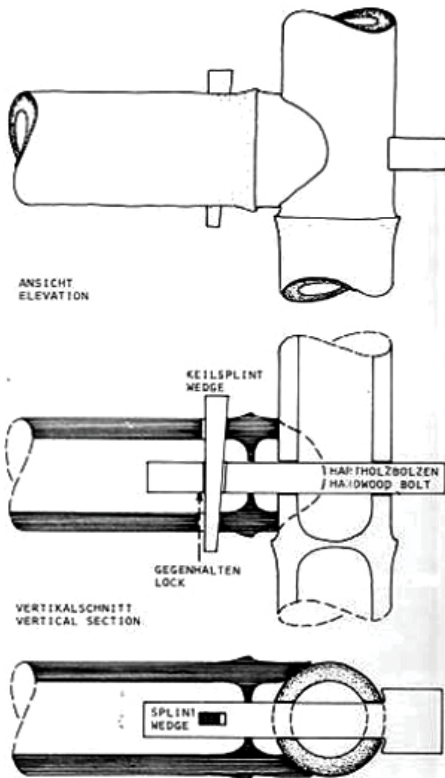
Like the wedge connection, the bamboo pieces are appropriately cut and between the two pieces is a plug (possibly a wood block). Additional connection is required with the fastening of a rope which will prevent unplugging and also the plug helps the beam from slipping (Rottke 10).

### Plugin/Bolt Connection

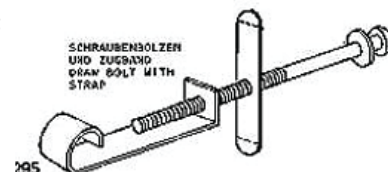
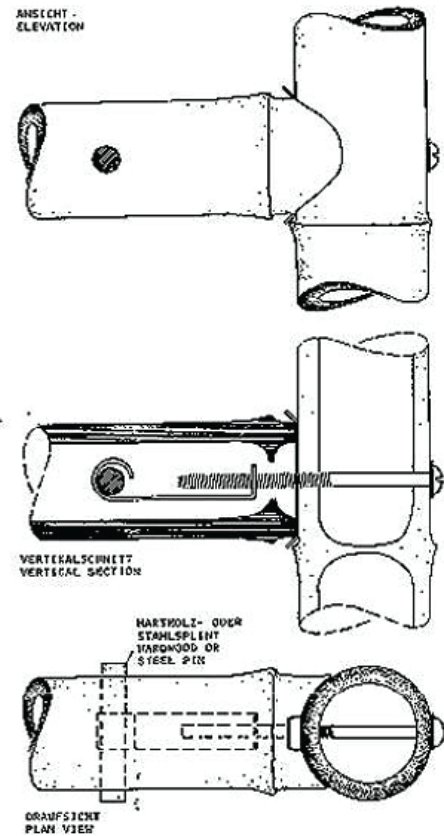
Plugin connections are similar in connections in wood with mortise and tenon, and are considered seldom used in bamboo structures. It used with rope connection sometimes as well. To be installed not too close to edge of bamboo, due to chances of the plug breaking out and the bamboo splitting (Rottke 10).



Inner plug connection <sup>18</sup>



Plugin connection <sup>19</sup>



Connection with steel clamp <sup>20</sup>

# High Technology Connection

## Interlocking Connections

Interlocking connections are not necessarily a high-tech connection, but that it involves using industrialized additional components.

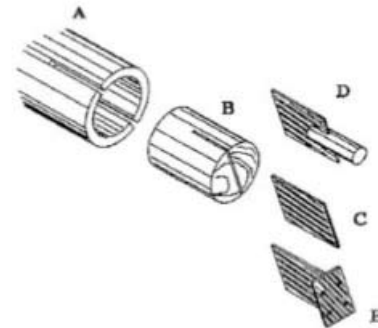
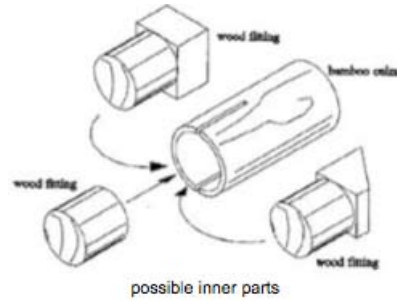
Interlocking connections involve members gluing or shedding that are in/around bamboo members. An example of interlocking connection is woodcore connection. This involves applying a wood piece in the inner surface of the bamboo and gluing it. Also for this work, two slots need to in the bamboo to prevent cracking when the wood in being lodged in the bamboo.

The wood-fitting member can be extended out as well and act as a joining member to a steel plate. The wood can be glued to the plate with epoxy resin and portland cement. Multiple steel plates then can be welded together. Another connection for interlocking is into a centered steelbox element with multiple bamboo members joined (Rottke 14).

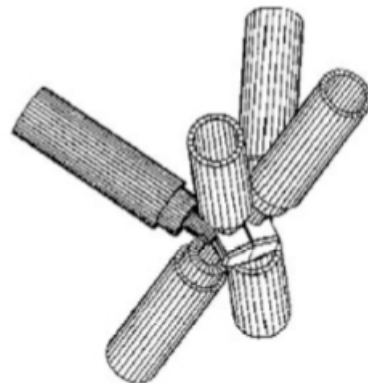
## Bamboo-Tec

An innovative invention by Bruno Huber is Bamboo-Tec. Bamboo naturally grows with a slight bend, so the diameters of the cane vary and sometimes a little oval. It is thicker though at the knots and if you try to screw or wedge, the transfer of its high strength will not be done. With Bamboo-Tec, there is no worry about it. It eliminates the weak points in the bamboo canes (Rottke 15).

How it is done is by having the bamboo cut at certain lengths, and having both ends capped that have artificial resin connected to it. The caps can be made of synthetic, steel or aluminium. The bamboo ends under the caps have circular grooves and there are circular notches on the inside of the cap. This results in a strong friction connections between the cap and bamboo. The caps can also be welded to other metal parts (if the caps are made of steel) (Rottke 15).



Woodcore connection systems <sup>21</sup>



Space truss, with center steel box element <sup>22</sup>

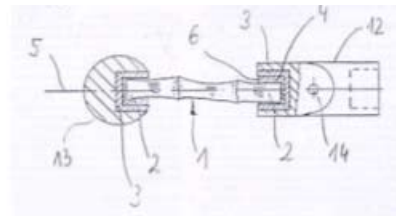
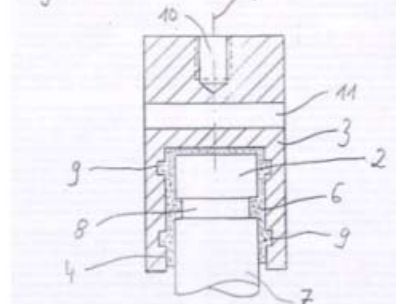


Fig. 2



- 1 single strunt
- 2 free end
- 3 connectionelement
- 4 bore
- 5 struntaxis
- 6 adhesive
- 8 notches
- 9 notches
- 10 threadbore
- 11 crossbore
- 12 jointelement
- 13 sphere
- 14 rotationaxis

Bambu-Tec® connection <sup>22</sup>

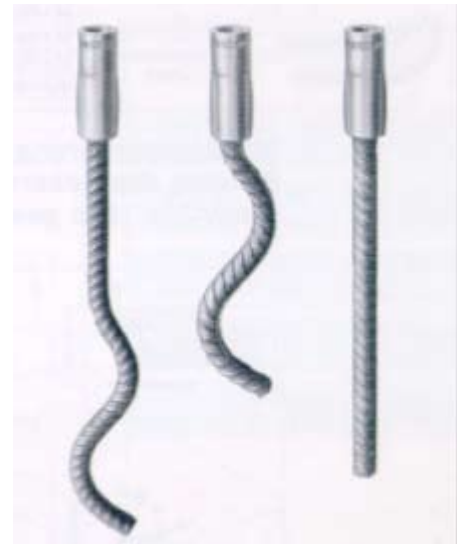
bamboo cut at certain lengths, and having both ends capped that have artificial resin connected to it. The caps can be made of synthetic, steel or aluminium. The bamboo ends under the caps have circular grooves and there are circular notches on the inside of the cap. This results in a strong friction connection between the cap and bamboo. The caps can also be welded to other metal parts (if the caps are made of steel) (Rottke 15).

### Transportation armature

Transportation armature involves pressed concrete in the connection and depends on the concrete/bamboo connection, specifically the concrete's (fillingmass) compressive strength. Another factor involves the armature's thread diameter, the tractive direction (axial, slant-wise, athwart) and the joint design. An advantage of this method is that they can be installed as soon as received on site without the prolonged prefabrication of the dowels (Rottke 16).

Reinforced Continuity Screw Connection System.

The continuity screw connection uses the sleeve stick and connection stick to shed with the bamboo and achieve an interlocking connection. With an adapter (which has a right/left outer thread) for the double sided sleeve connection. The same advantage with the transportation armature, the continuity screw connection is able to with quick installation (Rottke 17).



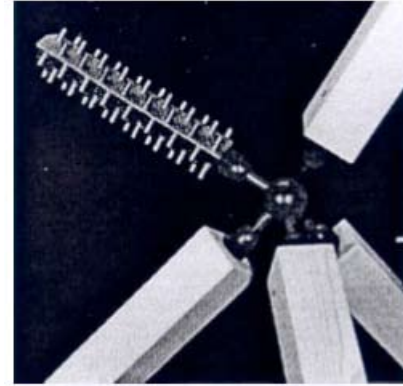
Transportation armature <sup>24</sup>



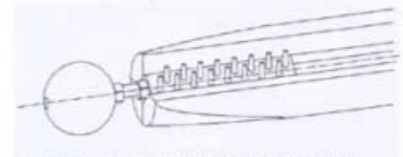
Armature connection via adapter <sup>26</sup>

### Induo-anchor Technique

For bamboo members with large diameters, induo-anchor technique can be used to transfer 100% of the load of the cane cross section. The anchor is a cast-iron core with teeth connectors on its sides. The induo-anchor can easily be shedded with a bamboo and used with concrete or artificial resin. The advantage for this is its simple manufacturing with a threaded bar and two counter nuts, and steel ball with threadbores are used as jointpoints. The disadvantage is though its high cost (Rottke17).



Induo-knot® construction <sup>27</sup>



Gewindestangen-Anschluß mit Kontermutter (Isometrie)  
Induo-knot® thread rod construction detail <sup>28</sup>

### Pan-knot Space Truss

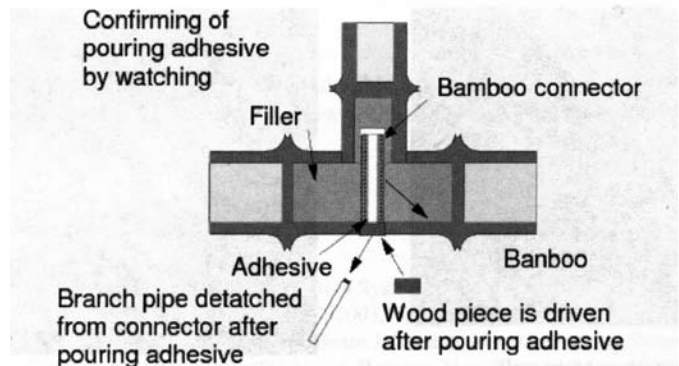
With small bamboo canes (diameter up to 3.5 inches) can transfer the maximal tensile force of about 50% (if threaded bars are glued/sheded in the ends of the bamboo canes). The pan space truss only consists of two components: a ball knot and a bamboo cane with shedded thread rod. If dealing with compressive forces, application of a headplate where compressive forces exert the maximum force (Rottke 18).



Pan-knot connection <sup>29</sup>

### S-Type Connector

A method to join round bamboo canes is with an s-type connection. Considered as an eco-friendly technology, it uses a bamboo connector that is drilled between two perpendicular members (Xiao 197).



S-type connector <sup>30</sup>



*Geodesic bamboo dome Fukuoka, Japan<sup>91</sup>*

# BAMBOO CONNECTION MODEL

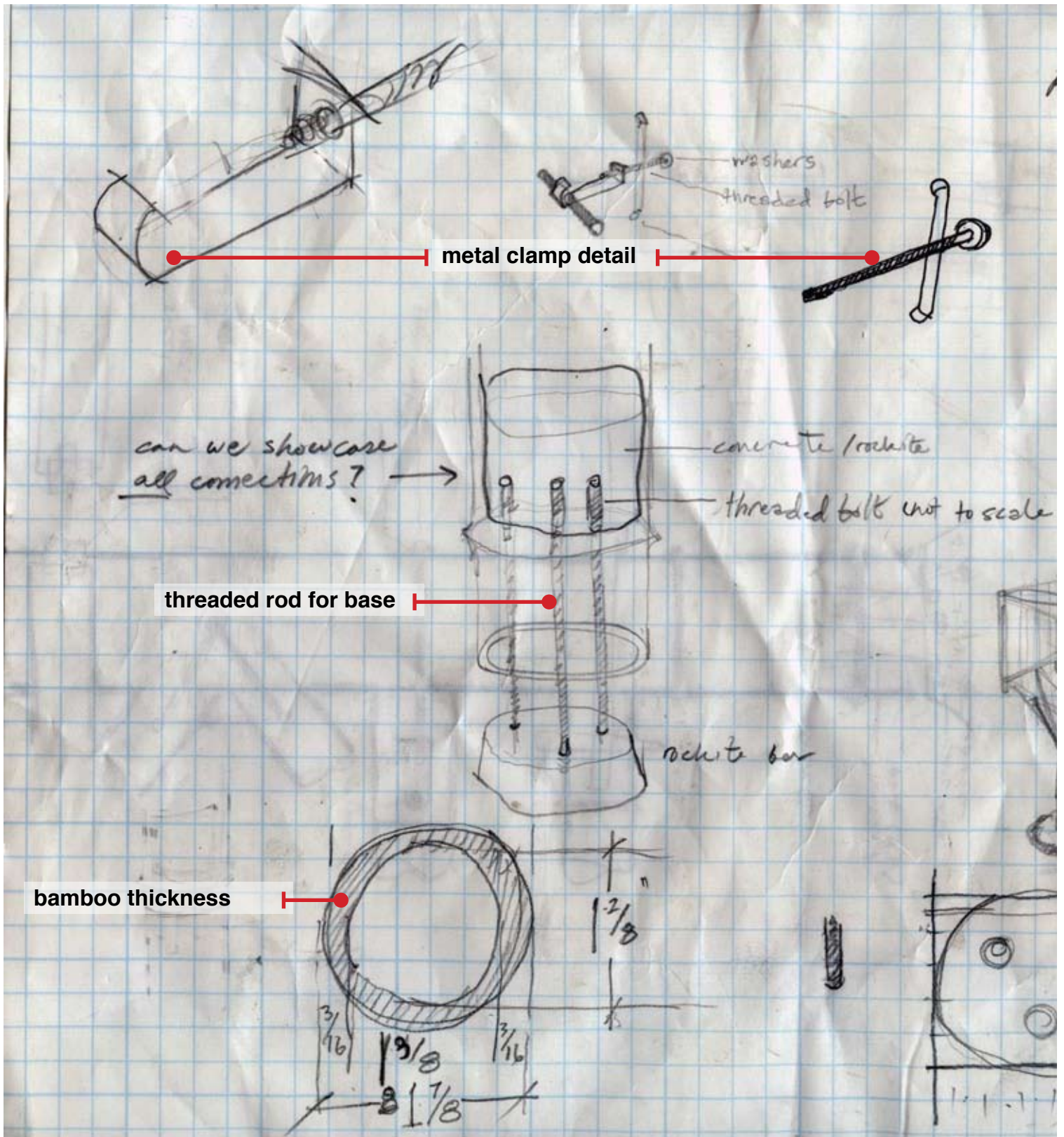
To further investigate bamboo connections, a model was built. It was an investigation of not only low-technique and high-technique connections, but different connections between bamboo.

Then connections were bamboo with concrete (rockite), steel, and wood.

Proceeding is the step by step construction.



# Model Sketches



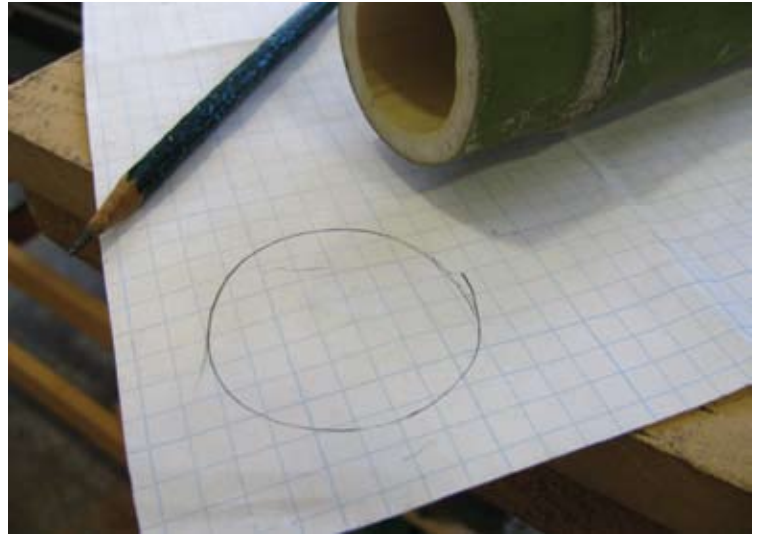
These are cuts made for the pieces: the long vertical piece with the horizontal beams.



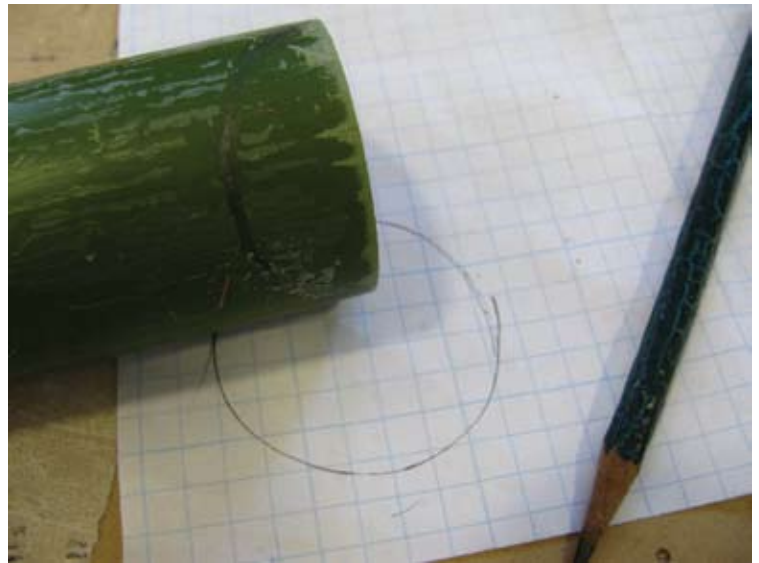
Detail of the cuts for the finish edges. Done with bandsaw and sander.



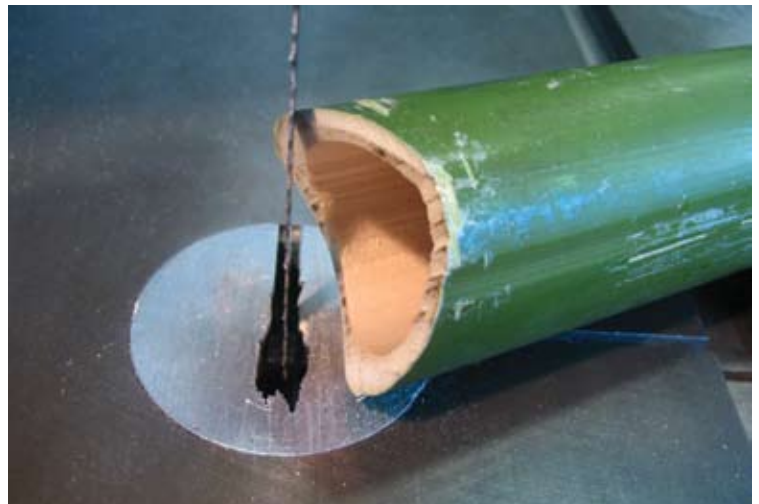
The cuts are made by first tracing the vertical piece on the paper.



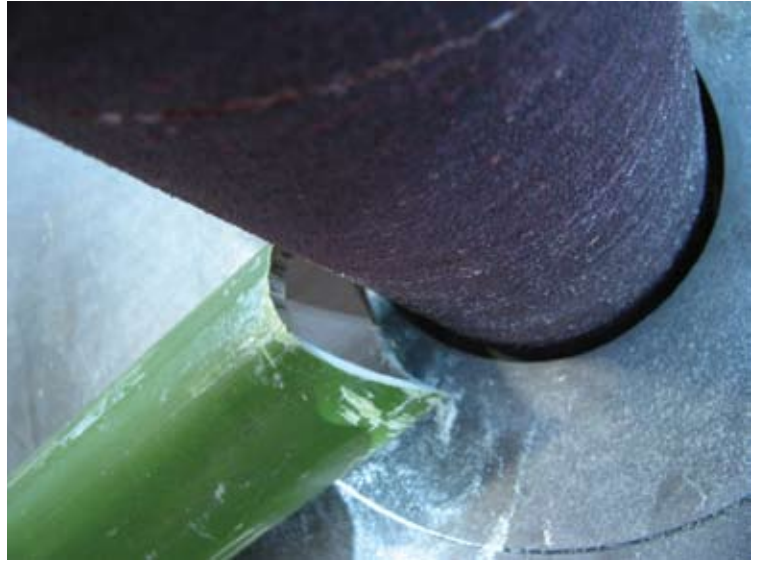
Then the cut pieces are put over half the circle and is ready to cut on the bandsaw.



Following the cut on the bandsaw as shown.



Pieces are sanded on the circular grinder.



Good cut.



The steel clamp was cut into shape on the metal bandsaw.



The piece was bent into shape with a hammer.



The metal piece was then drilled with 1/4" bit for a 1/4" screw.



Once the metal clamp was shaped and drilled, a 3/8" pin was cut to go through the bamboo and catch the clamp. The screw went in the hole, not being too loose or tight. The screw was able to catch the metal clamp slightly.



The hole in the main bamboo to receive the screw from the clamp is as seen. With a 1/4" drill bit for a 1/4" screw.



Result is as follows:  
The extra plate between the bamboo and clamp was not necessary and was taken out.



The wood pin joinery was made by making a wedge shape via the bandsaw. Both pieces are tapered, but only in one direction to make it easier. The horizontal piece with the hole for the key piece has a slightly thicker end piece to prevent from moving in and out of the bamboo and is curved to fit the profile of the bamboo.



The cut for the wood piece is as shown.



Wood pieces in the bamboo are as shown. The part where the wood connects is hidden in the bamboo.



For the twine connection, the process for cutting as previous, but an addition of angled-curved cuts are incorporated to make the desired 45° connection.



Pieces joined as shown.



The twine connection is as follows:  
Putting the bamboo at 45° and then drilling a hole through it to put the twine through and wrap it multiple times.

Putting a hole through the vertical bamboo for the twine kept the pieces stationed. One piece is tied through both holes, then the second one as follows.



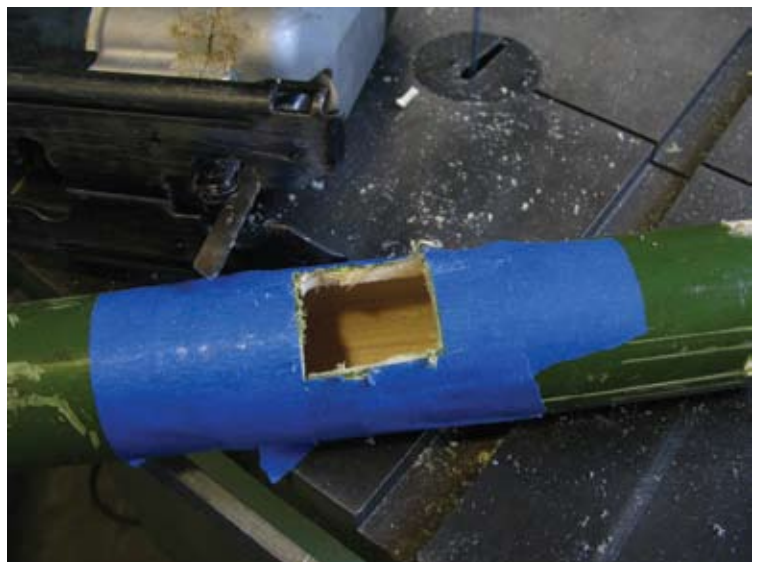
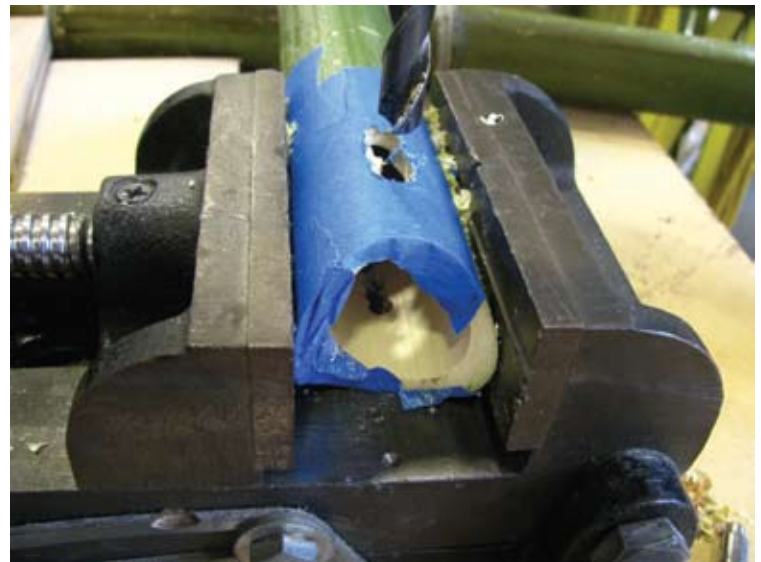
The second one is as follows:  
The tying continued along between the angled pieces as well.



For the cuts to reveal the connections in the bamboo, a test was done using a dremel. The results created undesirable burned edges.



The reveals were then done by cutting through the hole with a drill press and cleaning the corners with an utility knife. Then sanded to have a smooth edge.



A cut at the bottom for the reveal of the rockite with the threaded rods.



The threaded rods cut for the connection between the bamboo and rockite base.



Formwork for the base:  
Using foamcore with cutouts for the metal sleeves, which will hold the threaded rods, secured with a nut at the bottom.

The chipboard that surrounds the bottom of the sleeves is to create a 1/4" gap for the nut to be at the bottom holds the threaded rod.



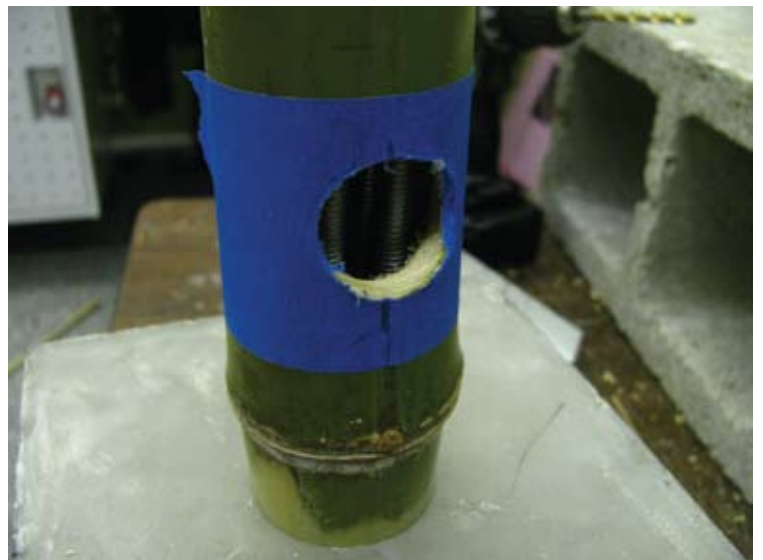
Poured the rockite in the formwork as we wait for it to cure. Notice the gap left in the middle for the cavity for the nuts.



At the bottom of the base of the bamboo, a 15/64" bit drilled for the 1/4" threaded rod. The holes are drilled through the bottom knot so the rods through the bamboo will set in the rockite in the bamboo.



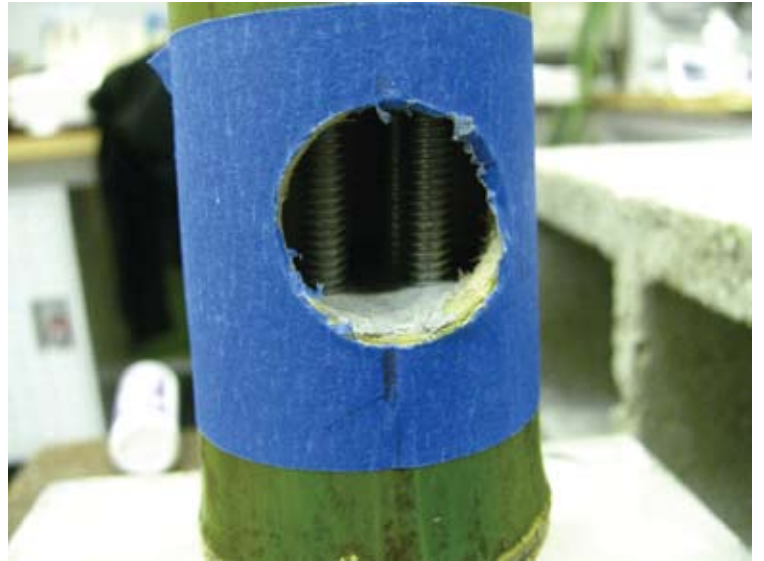
The rods through the bamboo are seen through the reveal.



The rockite was then poured at he bottom of the base through the reveal. This normally would be done with a smaller hole and covered with a plug.



Rockite curing with threaded rods as shown.



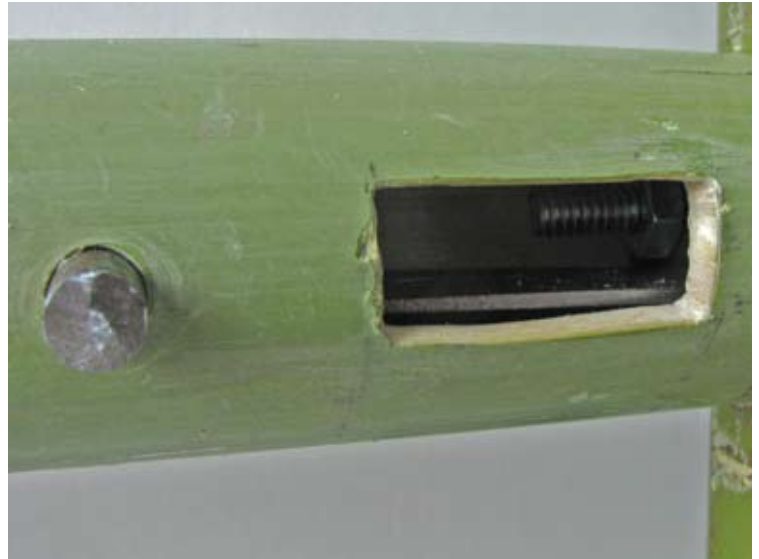
Completed model.



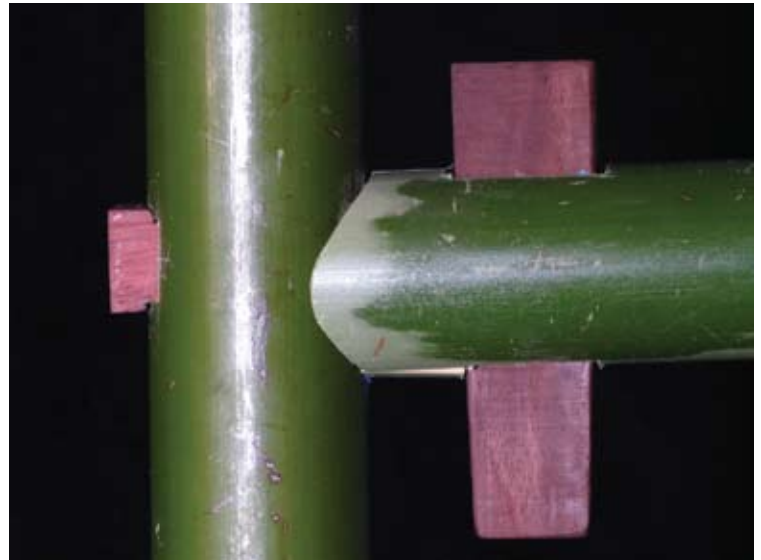
The connection with the steel clamp on the unexposed side is clean. The washer on the end is bent to conform to the shape of the bamboo. The pin is maintained in place with the pressure of the tight hole as well as the perpendicular force of the clamp on it.



The actuality of getting the clamp in was not a realistic method. The nut on the end of the screw was set at a distance from the end, and the clamp was put in through the reveal. The pin was then put into place for the clamp to make the tight connection. Note: the clamp should be put in and will be tightened on the screw head with a screwdriver.



The wood connection was a tight connection, with the wedge shape for both pieces of wood. There was a secure connection with the bamboo the wood pieces comes in contact with.



The reveal in the bamboo does not show much of the connection as I had wished.



The twine connection was the most difficult of the three connections. Reason was as looping through the holes, the connection did not get tighter. But once enough iterations, it starting holding better. The original lashing patten was just through the holes. As construction progressed, the angled bamboo pieces were still not tight in place. Orthogonal tying was then needed. Note: choice of  $45^\circ$  was not the best choice for angle connection. Lower degrees ( $30^\circ$  or so) is an ideal connection.



Final reveal of threaded rods cast in the rockite in the bamboo base.



Pouring the rockite in the formwork as it cures.  
Notice the gap left in the middle for the cavity  
for the nuts.



View of completed model.





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## Images

- cover: Vegesack, Alexander and Mateo Kries. Grow Your Own Home. Vitra Design Museum: C.I.R.E.C.A., 2000, 88.*
- infold: Vegesack, 110.*
- infold: Vegesack, 75.*
- 1 *Vegesack, 108.*
- 2 *Vegesack, 142.*
- 3 *Vegesack, 140.*
- 4 *Vegesack, 204.*
- 5 *Vegesack, 237.*
- 6 *Villegas, 29.*
- 7 *Vegesack, 239.*
- 8 *Villegas, 32.*
- 9 *Vegesack, 158.*
- 10 *Vegesack, 165.*
- 11 *Vegesack, 170.*
- 12 *Vegesack, 168.*
- 13 *Vegesack, 114.*
- 14 *Vegesack, 118.*
- 15 *Rottke, Evelin. Bamboo Connections: Construction with Bamboo. 6 June. 2003. RTH Aachen. 28 Oct 2009.*  
*<<http://bambus.rwthachen.de/eng/PDF0Files/Bamboo%20Connections.pdf>>, 7.*
- 16 *Rottke, 7.*
- 17 *Rottke, 12.*
- 18 *Rottke, 11.*
- 19 *Rottke, 10.*
- 20 *Rottke, 13.*
- 21 *Rottke, 14.*
- 22 *Rottke, 15.*
- 23 *Rottke, 16.*
- 24 *Rottke, 16.*
- 25 *Rottke, 17.*
- 26 *Rottke, 17.*
- 27 *Rottke, 18.*
- 28 *Rottke, 18.*
- 29 *Rottke, 18.*
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- 31 *Vegesack, 230.*
- back cover: Prototype of the ZERI pavilion in Colombia, Simón Vélez. Vegesack, 81.*

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