BAMBOO IN ARCHITECTURE AND CONSTRUCTION: PROPERTIES, PROTECTION AND PROCESSING

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Abstract

The paper is structured in five sections. After the introduction, I present the main properties of the bamboo, its physical and mechanical properties. Next, I explain the principal methods used to protect the bamboo elements: protection by design and protection by treatment. In the third section, I illustrate different manners of processing the bamboo canes, such as splitting, flattening, straightening or curving. In the fourth section, I exemplify the concrete utility of bamboo in bamboo products that can be standardized, like bamboo boards and composite materials. Finally, I briefly present the main methods used to connect the bamboo elements.

Key words: *bamboo properties, bamboo treatment, processing the bamboo, bamboo connections*

INTRODUCTION

Bamboo, a primarily vernacular building material, is used in most cases by poor people, mainly in those countries where the material is available. In China, the bamboo is regarded as "the friend of the poor", while in India it is called "the poor man's timber", being one of the basic components of the vernacular, low-cost houses, used in low-tech methods.

1. BAMBOO PROPERTIES

The bamboo is a woody grass that belongs to the sub-family of bambusoideae in the family of poaceae. Worldwide, there are more than 1250 species. These species grow in areas with humid-tropical, subtropical and temperate climate in Asia, Africa, Latin America, Australia, New Zeeland and the Pacific Ocean, with temperatures varying from -28°C to 50°C, at altitudes between the sea level and 4000 m (Himalayas), in the jungle, on the mountain slopes, but also at farms and on plantations. The main producers of bamboo are China, India, Thailand, the Philippines, Indonesia, Costa Rica and Kenya.
Bamboo is the fastest growing plant, some species rise steadily with almost 1m per day till they reach the full height. In India, the sprouts grow faster in the monsoon season. Bamboo does not need to be cultivated. Moreover, it can be harvested every 3-5 years. By contrast, the wood used in construction needs to be at least 10 years old and, for some wood species, even longer. In the case of bamboo, after the mature culms are harvested, no deforestation occurs because of the many shoots left behind, this fact being a gain both for the economy and the microclimatic protection. Bamboo conserves the soil humidity and, thanks to its rhizomes and the foliage, it prevents the soil erosion and retains the rainwater. Compared to a tree, bamboo generates 30% more oxygen. Bamboo is also a consumer of

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nitrogen, phosphorus and heavy metals. Thus, it reduces the pollution caused by the sewerage from factories, livestock farms and sewage farms. It is one of the first plants that grew after the explosion of the atomic bomb in Nagasaki and Hiroshima.

Image 1. Bamboo forest

Bamboo height varies between 30 cm and 30 m and its diameter between 1 cm and 30 cm. The highest is Dendrocalamusgiganteus, reaching up to 42 m in height and 30 cm in diameter.

Image 2: Clumping bamboo

Bamboo falls into one of the following categories, according to its root structure: clumpers (sympodial) or runners (monopodial). Usually, clumping bamboo is located in the tropical climates, while running bamboo belongs to the temperate zones or grows in the tropical mountains, at high altitude.

Image 3: Running bamboo

Image 4: Different types of bamboo culms

The culm (Image 4) has a tubular section except at the nodes, where the branches and leaves sprout (Image 5).The distance between two consecutive nodes differs from species to species and even on the same culm. Unlike the wood, bamboo culms contain only longitudinal fibers which bend into the diaphragm at the nodes.

Image 5: Culm vertical section

Image 6: Bamboo sprouts

Each sprout contains all the nodes and diaphragms of the mature plant, squeezed inside it (Figure 6), and its diameter matches that of the full size culm.

As the stem rises higher, its diameter and the wall width decrease, while its resistance increases. Bamboo culms have greater flexibility than wood. This may be seen in some areas where the culm is bending under the snow weight, until it touches the ground, but without breaking (Image 7).

Image 7: Bamboo forest after the snow

The uses of bamboo are many – Anna Lewington (1990), in her book "Plants for people", counts more than 1000 products made of bamboo – the examples include constructions (posts, studs, trusses, arches, rafters, purlins, roof coverings, exterior sidings, shutters, ladders, railings, walls, floors, scaffolds, as reinforcements for walls and foundations, water pipes, UV and waterproof roofing sheet, door and window frames), interior design and furniture (paneling, parquet, decorative ceilings, venetian blinds, floor lamps, mats, chairs armchairs, tables etc.), urban design (sculptures, kiosks, gates, fences, pergolas, trellises, shade structures for garden etc.), playground, sport equipment (fishing rods, skateboards, surfboards), in the paper industry (for paper pulp), for weapons (arrows, swords), for arts and crafts, toys, musical instruments, textiles (the bamboo fiber has antibacterial and hypoallergenic properties), in medicine, for hygiene products (from bamboo pulp), cosmetics and as food for people (beer, wine, vinegar, bamboo shoots) and animals. But its uses also depend on the plant age, the bamboo being used for food at 7-14 days, for baskets at 6-9 months, for boards and laminates at 2-3 years and in construction at 3-6 years.

1.1. Physical properties

The moisture content (MC) of the stem is influenced by the species and the age of the plant, the season and cutting-down time. Moreover, the MC is increasing at the base of the culm and in the nighttime. Green bamboo may have up to 100 – 150 % moisture. When the MC falls under 15%, its physical and mechanical properties increase and the risk of mould decreases.

The weight per volume or specific gravity (which varies from 500 kg/m^3 to 900 kg/m^3) influences the mechanical properties of bamboo. It increases toward the periphery and along the stem, from bottom to top and varies among species.

In a culm cross section (Image 8), two areas differentiate: one dark zone, placed at the periphery, with a high fiber density and another one, close to the center, with a low fiber density. The inner zone comprises 70% of the culm wall while the outer only 30%. The percent of the dark ring area in the culm cross section increases with the height of the stem.

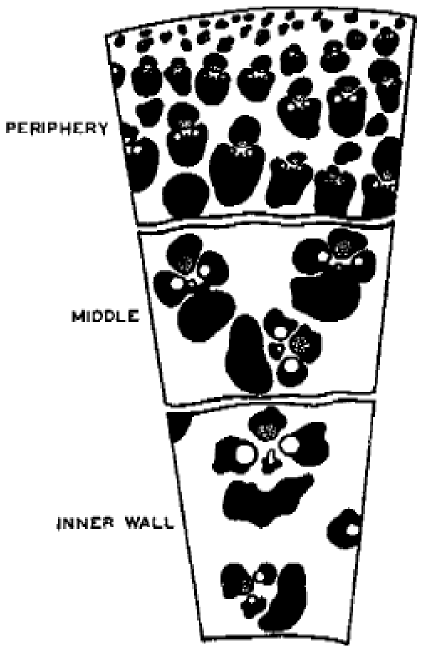

Image 8: Cross section of the wall of a culm

1.2. Mechanical properties

Its mechanical properties vary with the species, habitat, age, moisture content, the period of harvest, diameter and wall width. For a bamboo culm, the value of modulus of elasticity (MOE) increases from base to top. In the nodes area, MOE is reduced up to 40%. The compression strength goes up from the base to the top of the culm. It also increases with the age of the plant and decreases with a raise in the MC. The compression strength, parallel to the cane axis, of portions without nodes is smaller (with c 8%) than those with nodes and the compression strength perpendicular to the fiber is higher (c 45%) in portions with nodes, thus the forces perpendicular to the culm axis should be located in the nodes. The shear strength is the weakest aspect of the bamboo culm. The shear strength decreases as the thickness of the culm wall increases and it shows higher value (c 50%) in the nodes compared to the segments without nodes. The shear is related to the presence of holes in the cane and holes cannot be avoided as they are necessary in joining two or more elements. The bending strength decreases from base to top. If the span of the element is to be twice the length of an internode, the node should be positioned at mid span. The bending strength depends on the moisture content (MC). In dry bamboo, the MC is about 12%, while in green bamboo the MC is about 80%. Consequently, the ultimate bending stress for dry bamboo canes is 1.5 times the stress for green bamboo. The tensile strength is three times higher than compression strength and the tensile strength of the outer part almost triples that of the inner area, the strongest fibers being set on the edge. The nodes diminish the tensile strength of a cane. The value of a culm tensile strength decreases after 5-6 years. Tensile strength is important in designing trusses with lashed joints and when the bamboo is used as concrete reinforcement.

1.3. Technical properties

The behavior in earthquakes and hurricanes

Because of the joint type, used in bamboo structures, when earthquakes or hurricanes occur, about 85 percent of the energy is absorbed, causing a deformation of the joints, and the rest of 15 percent inflicts elastic bending on the elements. Another advantage of bamboo is the absorption of energy in the joints. Indeed, on April 1991, 20 bamboo houses built in Costa Rica for the National Bamboo Foundation survived a 7.5 magnitude earthquake, measured on Richter scale.

The burning behavior

According to DIN 4102 (Burning behavior of building materials), bamboo is categorized as being flammable but hardly combustible. A bamboo culm filled with water resist to a temperature up to 400°C.

2. METHODS FOR PROTECTION

The durability of the material is related to the age of the culm, the species to which it belongs, the time when it was harvested, the type of applied treatment, the position of the element and its maintenance. The bamboo preservation and a proper design increase the life span of bamboo elements. In Colombia, some bamboo constructions have attained a life span of 100 years.

2.1. Protection by design

Jayanetti and Follett (2008) underlines four basic principles of protection by design:

i. Keeping the bamboo dry

This involves designing large eaves with proper gutters that protect the bamboo elements from rain and direct sunlight.

ii. Keeping the bamboo out of the ground contact.

The second principle may be achieved by setting the bamboo poles and walls on a brick or concrete base / plinth wall.

iii. Ensuring good air circulation

iv. Ensuring good visibility

One way to meet these two recommendations is to let the bamboo element exposed so it can be checked and ventilated. Moreover, the ends of the culms have to be plugged to avoid insect penetration.

2.2. Protection by treatment: methods of preservation

The lifespan of an untreated culm is 1-2 years - when positioned in open air and on the soil – and 5 years when the element is covered and elevated above the ground level.
Untreated, bamboo is prone to insects (borer, termite, beetle), fungi and other natural or chemical damaging factors. The degree of insect attack is related to the moisture and starch content of the plant. Also, the risk of mould decreases as the humidity of the culm is reduced. With a MC of 15%, the risk of mould is kept to a minimum. The process of preservation should be planned before the harvest begins. For the species Guadua Angustifolia, the harvest is to take place one week before the full-moon because, at that time, the moisture content is limited. The branches and leaves should be left in place in order to allow the evaporation of the capillary water. Also, the culms have to be cut down before the rising of the sun, to avoid the absorption of nutrients which feed the insects. Nevertheless, some Indians from Latin

America have chosen the afternoon period for harvesting - this is the time when the humidity is low and the nutrients have already reached the leaves.

The chemical treatment of bamboo is difficult as the plant is more resistant to chemical penetration than wood, due to its anatomy. Choosing one technique of preservation or another depends upon where and how the bamboo element will be used.

2.3. Drying the bamboo

One traditional practice of drying the culm is to cut it and fix it vertically within the clump until it dries. Attention should be given to horizontally stacked culms which have to be placed on a rack in order to prevent bending. Also, they need to be placed inside a shaded and ventilated space.
When the elements are dried in a kiln, up to a temperature of 150 degree Celsius, the structure of the material is modified, gaining some resistance to insect attack. But this method is only for split bamboo as whole culms may crack. Air drying is thus a better option for round culms, which need about 6-12 weeks – the period varies with the MC amount and the wall thickness.

2.4. Soaking in water

In Asia (Indonesia, Vietnam, Bangladesh etc.), water immersion is an old way used by the locals to treat bamboo. The newly harvested whole culms or split bamboo elements are immersed in water (streams and ponds are also accepted) for a period of 4-12 weeks while the water soluble substances (starch and sugar) are lost. This method protects bamboo from borers, but not from fungi and termite.

2.5. Sap displacement method

The sap displacement takes place slowly, when the green bamboo element (whole or split culm) is placed vertically in a preservative solution to a depth of 30-60 cm.

2.6. Boiling

Another way to eliminate unwanted substances is by introducing the culms into a large container and boiling them for 15-60 minutes.

2.7. Borax treatment

Holes are drilled in the culm diaphragms, and then the culm is immersed into a basin or positioned vertically and filled with borax. Another way is to drill holes in the internodes (the holes should not be positioned on the same line) and fill it with borax.

2.8. Hot and cold treatment

This technique is applied to dried bamboo elements. The method consists in immersing the bamboo into a solution of fuel oil and coal-tar or creosote oil (to a 1:1 ratio) and heating the container until the boiling process starts (about 4 hours). A percent of 1% dieldrin may be added to the solution for protecting bamboo against termites. After boiling, the elements are allowed to cool down for 24 hours.

3. PROCESSING THE CULMS

3.1. Splitting the bamboo

By hand, using different tools

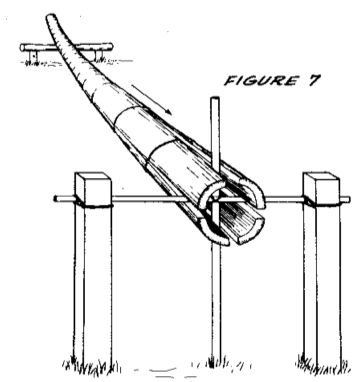

Image 9: Criss-cross bar of wood

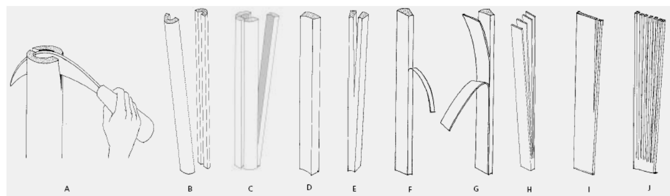

Image 10: The process of splitting the bamboo manually

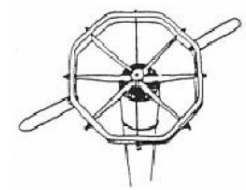

Image 11: The use of the knife frame

- With criss-cross bars of wood or iron (Image 9)

The bars are fastened to several posts fixed in the ground. One of the culm ends is slightly split with an axe, and then positioned on the criss-cross bars. Finally, the cane is pushed or dragged manually in order to split it into four pieces.

- Using the Dao (Image 10)

Dao has a rounded wooden handle and a curved thick metal blade that is sharp only on the concave side.

- Using the knife frame

Mechanical splitting

Image 12: Mechanical splitting of a bamboo culm

Flattening bamboo canes

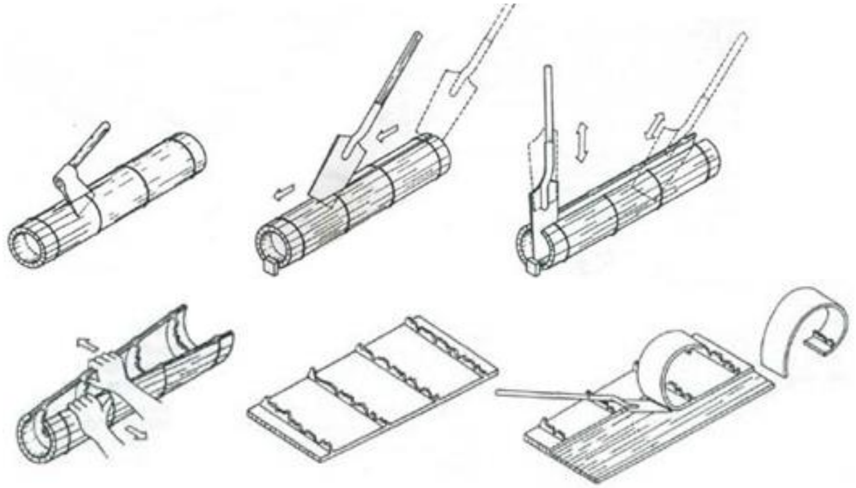

Image 13: Flattening bamboo canes

After taking off the nodes, the culm wall is cut longitudinally, splitting it several times, along its circumference, then the cane is opened and flattened, the inner layer, prone to insect attack, being also removed (Image 13).

Straightening bamboo poles

In India, the base of a newly cut bamboo cane is fastened to a tree branch, high above the ground, then a heavy weight is hanged on the opposite end of the culm and left in place for several months.

3.2. Deforming the bamboo

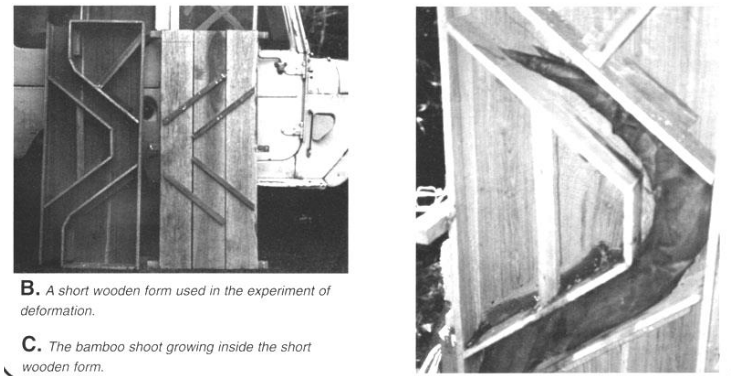

Image 14: Deforming bamboo shoots

Due to its elasticity, the green bamboo can be curved using a propane torch. The cane segment to be deformed is heated slowly with the torch until the bamboo is able to change shape easily without breaking.

Oscar Hidalgo Lopez (2003), architect and professor at Facultad de Artes, Universidad Nacional de Colombia, found a way to produce curved bamboo culms with a predetermined radius. A mould, designed according to the required arc shape, is set over the bamboo shoot. While the plant develops, its culm inherits the curve of the form.

Moreover, using square section moulds, set over the shoots, the culm cross section assumes the shape of the mould (Image 15).


Image 15: Producing square section bamboo culms

Surface transformation

- Bleaching

The bamboo is immersed in a solution of hydrogen peroxide

- Dyeing

After removing the waxy surface, the bamboo element is bleached, and then the desired color is applied. Finally, a solution of vinegar is used for maintaining the element color.
In order to change the color of the cane to green, it may be treated with copper sulfate. Further, this method is used to increase the culm resistance to mould. To give the bamboo a brown color, the canes are peeled, treated with hydrochlorid acid and baked in a kiln.

4. BAMBOO PRODUCTS

Since the bamboo canes have a tubular shape and differ from each other in terms of wall diameter, thickness and position of the nodes along the culm, there is no possibility to process them like timber, so they cannot be standardized. The composite materials and bamboo boards are the only products which are to conform to standards, codes and regulations. Composite materials are made by cutting or splitting the culm into veneer, strips, fibers or particles and then reassembling them by various methods in combination with other materials or substances. The adhesives usually used for wood are not suited to bamboo composite boards. The latter is manufactured using UF (urea-formaldehyde) and PF (phenol-formaldehyde).

- Natural Fibre Thermoset Composite (NFTC) - DUROSAM®

This material was created in 1994 by company AB COMPOSITES –India as a substitute for conventional wood, ply-wood, asbestos and aluminum. It was used for doors, windows, panels, floorings and prefabricated units (shelters for high and low altitude, toilets). The composite is water and corrosion resistant, fire retardant, UV and termite resistant and has a low thermal and electrical conductivity.

- Bamboo Mat Board (BMB)

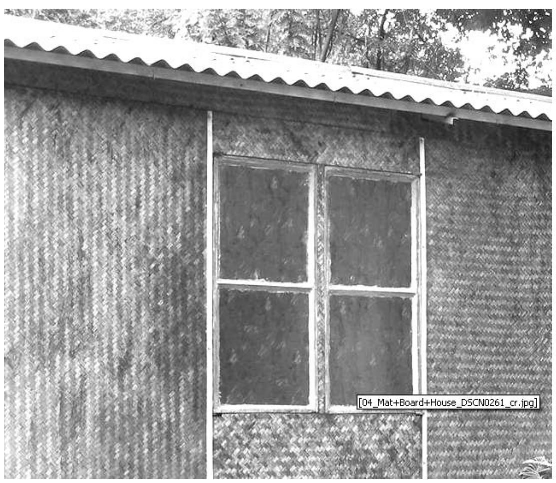

Image 16: The modular bamboo mat board house atIPIRTI

The product (Image 16), developed by IPIRTI – India, is made from bamboo mats which are weaved by hand or using mechanical devices – in a perpendicular or "herringbone" pattern – and then immersed into a PF resin solution to which they added an eco-friendly preservative. After drying to 8% humidity, the 2-7 layers (the number of layers depends on the desired thickness) are piled and hot-pressed. Finally the boards are cut to match the required size. This product is used for furniture, doors, partitions and ceilings.

- Bamboo mat plywood (BMP)

The material is a Chinese product which resembles to the Indian BMB. The outer face may be overlaid. Used for furniture, wall panels or shutters.

- Bamboo plywood panel(BPP)or bamboo curtain plywood or bamboo ply panels

The bamboo canes of desired length are cut into thin and long pieces, rubbing the nodes and taking off the external and internal layers, resulting in slivers of 0.5-0.8 mm thickness and 20-30 mm width. The slivers are used to weave mats which are dried till they reach 10-12% moisture content then immersed into a glue solution. The glued mats are dried again to 10-15% MC. A multi-layer structure (commonly three layers of mats), with alternating vertical and horizontal mats/curtains is created and hot-pressed. Finally another bamboo mat, veneer or PF resin impregnated Kraft paper is overlaid. It may be used for concrete form work.

- Bamboo veneer

In China, culms of Phyllostuchyspubescens are cut, processed and dried. Then, surface modifications (like bleaching, dyeing etc.) are applied in order to make them suitable for decoration.

- Flattened Bamboo board

Image 17: Flattened bamboo board

Image 18: Bamboo mat corrugated sheet

The boards (Image 17), obtained by flattened bamboo canes and finished with clear acrylic, can be used indoor or outdoor, for wall or ceiling paneling.

- Bamboo Mat Corrugated Sheets (BMCS)

The product was developed as an eco- friendly, energy efficient and cost effective roofing sheet, by Building Materials & Technology Promotion Council (BMTPC) and Indian Plywood Industries Research & Training Institute (IPIRTI). In order to obtain this composite, bamboo slivers are hand woven and transformed into mats by rural people, then the mats are soaked, coated, assembled and pressed under specified temperature and pressure. The product is resistant to water, fire, decay, termites and insects.

- Laminated bamboo beams

GluBam (Image 19) is a structural beam made from laminated bamboo veneers. It is the invention of Yan Xiao, professor of civil engineering at the University of Southern California. The beams can be cut like ordinary timber. Yan Xiao used it for schools and homes construction across China and to build a bridge in Hunan province.

Image 19: GluBam

image 20: Various sections of laminated bamboo beams

- Reconstructed bamboo timber

Image 21: Reconstructed bamboo timber

- Strand woven parquet

Strands from a specific type of bamboo are heated to eliminate all sugars and insects. Then, it is dried, glued, baled, pressed, and baked in furnaces until it hardens. Finally, the pieces are cut to make parquet flooring planks, which are stronger than ordinary bamboo parquet.

- Bamboo - Jute Composite

Manufactured by AB COMPOSITES, India, this material is used for corrugated roofing sheet, for doors, windows, furniture, panels, floorings and prefabricated units. The product, with a standard size of 2400x1200x 2.5mm, has a low thermal conductivity (0.020 mw/cm), withstands in 200 km/hrs wind pressure and has water absorption of max. 5.0%. Also, the material is light and it is corrosion and UV resistant, eco-friendly and bio-degradable, having a minimum 30 years life period without maintenance.

- Bamboo mat - wood veneer composites (BMVC)

The product is developed by IPIRTI (Indian Plywood Industries Research &Training Institute), a research institute in the field of composites. The board is environmentally sustainable and superior to Bamboo Mat Board (BMB). The composite consist of bamboo mats (woven in a herringbone pattern with 0.6 mm thickness slivers and coated with resin) and veneers. The board thickness varies between 4 mm to 25 mm.

- Bamboo particle boards

Bamboo particle board is obtained from bamboo wastes which are mixed with other cementing materials.

- MDF Bamboo veneer

The board has an MDF core and the outer surface is of bamboo.

- Bamboo wallpaper

Bamboo strips are glued to a fabric in order to be used as wallpaper.

5. BAMBOO CONNECTIONS

5.1. Traditional connections

When used in construction, a certain bamboo type is recommended, namely that with a big mass per volume, dried and harvested when of 5 years old. If the span is about 3.60 m, the bamboo elements have usually the following dimensions: 70 – 100 mm diameter and 6 – 12 mm wall width.

In order to obtain an optimum result, some design principles are suggested:

- The joints should be created in the node area
- Allow a distance between the joint and the end of the cane
- Reduce the number of holes. If not possible, position the hole near the node or fill the drilled cane segment with cement and use bolts for fastening the elements. Also, the holes must have a circular shape
- Avoid splitting: put galvanized wire round the culms, mostly at the ends of the canes

Because the bamboo culm has a tubular shape and splits easily, the mortise and tenon joints, specific to wood, are rare. Traditional wood connections use nails frequently but pre-drilling is required in order to avoid cracking, with bamboo canes.

Image 22: Connections using bamboo strips

5.1.1. Lashed joints

The canes are connected with lashes made of bamboo strips, coconut palm fiber, rattan, jute or hemp rope, zinc coated iron wire and plastic cords, which permit the relative movement of the elements, while still keeping them in place. If the lashes are green when used, the ties become stronger as they dry out. Common ropes wear down faster than the cords made of twisted bamboo fiber.

The ropes may also be inserted in holes while tied around the elements.

5.1.2. Connections in "fish mouth"

These are used only when elements fall perpendicular to one another.

Image 23: Connections in "fish mouth"

5.1.3. Connections with two wedges and rope

The wedges prevent the horizontal movement of the canes while the ropes stop their displacement.

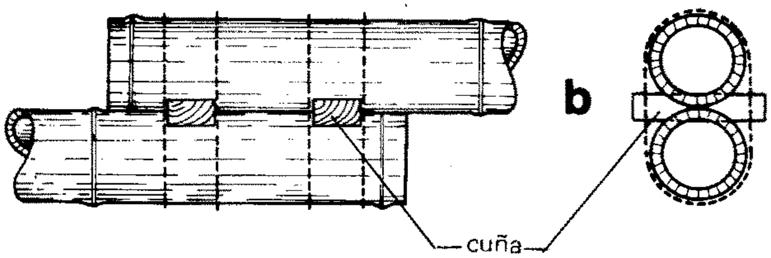

Image 24 : Connecting two horizontal elements

5.1.4. Double post

Image 25: Double post

One post is supporting the beam and a second one the roof (Image 25). No holes are needed and this is its advantage, as the drilling weakens the culm resistance. Moreover, it is easy to replace or fix the faulty post.

Another solution is to use a cleat instead of a second post. The cleat supports the beam and is fastened with rope to the pole. In this case, there is no drilling to weaken the cane.

5.2. Modern connections

5.2.1. Wood core connections

Wood core connections are helpful in joining the bamboo canes with wooden elements. A wood cylinder is partly inserted into the cane and glued to it. In order to avoid splitting, two channels are cut at the end of the cane, before the wooden core is inserted.

5.2.2. Wood core connections and steel plates

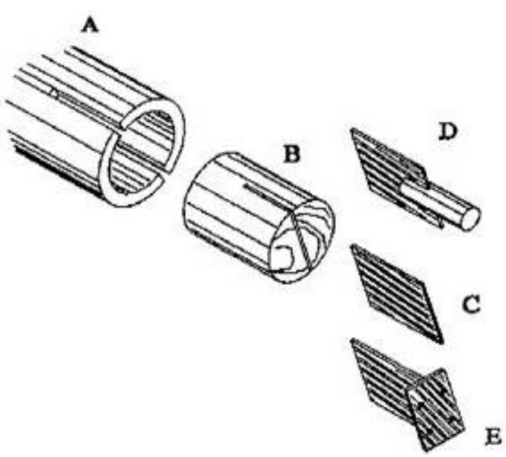

Image 26: Wood core insertion and steel plates

Further, a steel plate may be inserted into a slot of the wood cylinder and glued to it. The end of the steel element is then welded or connected to another metallic component. This type of wooden core and steel plate termination is useful in truss assembling.

5.2.3. Multi-culm beams

When the bamboo culms are to support big loads, the canes are bundled up with a steel band. Again here, wood cylinders with metallic insertions are fixed to the ends of the canes.

5.2.4. Connections with thread rods and mortar injections

After assembling the elements with thread rods, the canes are filled with mortar.

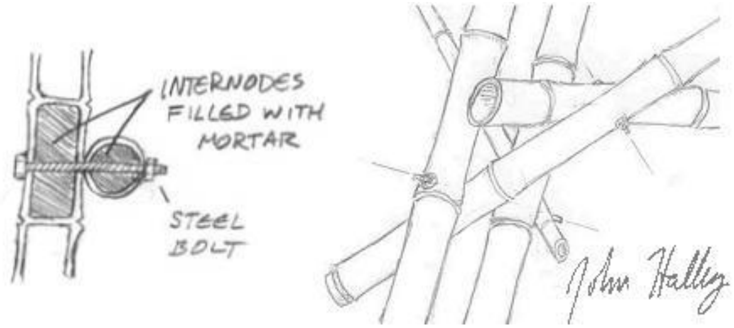

Image 27 :Connections with thread rods and mortar injections

5.2.5. Connections with steel plate or thread rods, bolts and mortar injection

- Connection with thread rod and mortar injection

For fastening a pole and a beam, a metallic rod is inserted into the vertical pole – after drilling two or three diaphragms – and mortar is injected afterwards. Then, the horizontal culm is drilled and fixed to the rod. The adjacent beam internode is filled with mortar, too.

- Connection with steel plate, bolts and mortar injection

Two or three holes are pre-drilled into the vertical cane and bolts are inserted perpendicular to its axis. Then mortar is injected inside and the beam is positioned at the top end of the pole, fastened with a steel plate. The steel strap is screwed to the bolts. Finally, the beam internode is filled with mortar.

5.3. Fixing the bamboo poles to a concrete base or foundation

- The connection between the elements and the concrete foundation is carried out through a metallic profile (Image 28).

Image 28: Fixing the canes to the foundation with a metalic profile

Illustration source

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