Building with Bamboo

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I

The Technology of Bamboo Building

1

Historical Examples

Types of Bamboo

The word "bamboo" was introduced by Carl von Linné in 1753. Bamboo is a grass plant like rice, corn and sugar cane. Different to these, the lignin of its tissues becomes after some years a structure as hard as wood, but more flexible and light. Bamboos, in their wild form, grow on all of the continents except Europe, from 51° north to 47° south. There are tropical and subtropical bamboos that thrive in different ecological niches, from cloud forests with humidity levels above 90% like the *Guadua angustifolia* in the Chocó Department of Colombia, to semi-arid zones of India (*Dendrocalamus strictus*). The majority of species are found in warm zones with humidity levels of over 80%, in tropical cloud forests, and in clayey and humid soils; for this reason they are often found near water. A few grow in dry climates or over 4,000 m above sea level. In China and Japan there are also species that can survive temperatures below zero degrees. Approximately 1,200 species exist, of which there are 750 in Asia and 450 in America. Of these last, the greatest diversity is found in Brazil (Hidalgo, 2003). It is estimated that 37 million hectares are covered with bamboo forests: 6 million in China, 9 million in India, 10 million in ten countries of Latin America and the majority in Southeast Asia (Lobovikov et al., 2007). Since antiquity, bamboo has been a construction material used to build basic habitats to complex structures; it has formed part of a set of elements that were an essential part of cultural development in Asia and America. In tropical zones, the bamboos most commonly used in construction are the *Bambusa*, *Chusquea*, *Dendrocalamus*, *Gigantochloa* and *Guadua*. Those of the group *Phyllostachys* prefer temperate zones.

The following is a list of the bamboos most commonly used in construction. Their characteristics are briefly mentioned, with the proviso that data can vary depending on local conditions. More information on the species can be found in Farelly (1938), Young and Haun (1961) and McClure (1966).

Bambusa

- *Bambusa balcoa*
  Height: 12 – 20 m. Diameter: 8 – 15 cm.
  Origin: India.
  Note: internode thickness of up to 3 cm.
- *Bambusa disimulator*
  Height: 12 m. Diameter: 6 cm.
  Origin: Southern China.
  Note: fine and very hard internode.
- *Bambusa edilis*
  Height: 20 m. Diameter: 16 cm.
  Origin: China.
- *Bambusa polymorpha*
  Height: 27 m. Diameter: 15 cm.
  Origin: China, Bengal, Burma.
- *Bambusa stenostachya*
  Height: 22 m. Diameter: 15 cm.
  Origin: China.
- *Bumbusa vulgaris*
  Height: 18 m. Diameter: 10 cm.
  Origin: Asia, Americas.
  Note: high starch content.
- *Bambusa bambos (L.) Voss*
  Height: 30 m. Diameter: 15 – 18 cm.
  Origin: Southeast Asia.
  Note: thick shell.
- *Bambusa nepalensis*
  Height: 20 m. Diameter: 10 cm.
- *Bambusa oldhami Munro* ("Green bamboo")
  Height: 6 – 12 m. Diameter: 3 – 12 cm.
  Origin: Taiwan.
  Note: strong green colour, short internodes.
- *Bambusa vulgaris, Schrader ex Wendland*
  Height: 6 – 15 m. Diameter: 5 – 10 cm.
  Origin: Southern China.
- *Bambusa vulgaris, Schrader ex Wendland, var. striata*
  Origin: Southeast Asia.
  Note: mutation of *Bambusa vulgaris* with yellow-gold colour and green stripes.

Chusquea

- *Chusquea culeou*
  Height: 6 m. Diameter: 4 cm.
  Origin: Chile.
  Note: It grows in the southernmost zones of the planet, and has a very strong culm.
- *Chusquea culeou Desvaux* ("coligüe", "colihue" or "culeú" in Chile)
  Height: 4 – 6 m. Diameter: 2 – 4 cm.
  Origin: Central America, South America.
  Note: solid stalk, yellow colour.
- *Chusquea quila Kunth* ("quila" in Chile)
  Origin: Chile.
  Note: solid stalk.

Dendrocalamus

A group of bamboos with many varieties; they grow very tall and are important for construction.

- *Dendrocalamus balcoa (Bambusa balcoa)*
  Height: 20 m. Diameter: 20 cm.
  Origin: Southeast Asia and India.
- *Dendrocalamus giganteus* ("Giant bamboo")
  One of the largest bamboos, it has a diameter of 30 cm or more. It grows up to 20 cm per day and reaches a height of more than 30 m. The species is originally from India, Burma, Sri Lanka and Thailand, and is used for large structures, for furniture and for the production of paper.
- *Dendrocalamus asper* ("Bucket bamboo" in Brazil)
  Resistant to below-zero temperatures. It does not grow as much as *Dendrocalamus giganteus*; reaches a height of 25 m and has a diameter of 20 cm. Its stalk is very hard and cracks less than *D. giganteus* while drying. Excellent for construction.
- *Dendrocalamus latiflorus*
  Height: 20 m. Diameter: 20 cm.
  Origin: Taiwan, Southern China.
  Note: internodes of up to 70 cm; very thick stalk (more than 2.5 cm).

Gigantochloa

- *Gigantochloa apus*
  Height: 16 m. Diameter: 10 cm.
  Origin: Malaysia and Indonesia.
- *Gigantochloa atroviolacea* ("Black bamboo")
  Height: 13 m. Diameter: 8 cm.
  Origin: Malaysia and Indonesia.
- *Gigantochloa levis*
  Height: 16 m. Diameter: 10 – 15 cm.
  Origin: Phillipines.

Guadua

The guadua is a type endemic to South America. Its name was given by Karl Sigismund Kunth in 1822, who took it from the term "guadua" used by the indigenous peoples of Colombia and Ecuador. The forests of guadua are called "guaduales" (*2.4*).

- *Guadua angustifolia Kunth*
  The guadua most commonly used in construction; it has a diameter between 9 cm and 12 cm, exceptionally can reach up to 21 cm. Its daily growth can be 12 cm per day, and after 3 months it reaches 80% to 90% of its definitive height, which can be between 15 m and 30 m high.
  Among its varieties are *bicolor Londoño* and *nigra Londoño*, which have variations of form according to the climate: "onion" with internodes that are long and efficient in tension; "club" with internodes more closely spaced and efficient in compression; "castle", which is less efficient in compression and more suitable for the elaboration of planks; and "goitred", characterised by its irregular stalks.
- *Guadua aculeata*
  Height: 25 m. Diameter: 12 cm.
  Origin: Mexico to Panama.
- *Guadua chacoensis* ("tacuaruzú")
  Height: 20 m. Diameter: 8 – 12 cm.
  Origin: northern Argentina and Bolivian tropics.
- *Guadua paniculata Munro* ("pretty")
  Height: 10 m. Diameter: 3 cm.
  Origin: Bolivian tropic.
  Note: the upper part is solid, while the lower has small openings.
- *Guadua superba Huber* ("tacuarembó")
  Height: 20 m. Diameter: 9 – 12 cm.
  Origin: Bolivian tropics.
  Note: cracks easily.

Phyllostachys

The bamboos of this group grow in temperate zones and have the characteristic of forming nodes in zigzag or other irregular forms. Is originally from China, nevertheless many species were cultivated in Japan, the Americas and Europe.

- *Phyllostachys aurea* (*2.7*)
  Height: 5 m. Diameter: 2 cm.
  Origin: China and Japan.
- *Phyllostachys bambusoides*
  Height: 22 m. Diameter: 14 cm.
  Origin: Japan.
- *Phyllostachys nigra, var. henonis*
  Height: 16 m. Diameter: 9 cm.
  Origin: China, introduced into Japan and the United States.
- *Phyllostachys pubescens* ("Moso", "Mao Zhu")
  Height: 21 m. Diameter: 17 cm.
  Origen: China, introduced into Japan and the United States.
- *Phyllostachys vivax*
  Height: 21 m. Diameter: 12 cm.
  Origin: China.

Positive Environmental Effects

Biomass Production

Bamboo is a rapid-growth natural resource that can produce much more dry biomass per hectare per year than eucalyptus. The production of bamboo biomass depends on many factors and therefore varies significantly. According to Liese and Düking (2009), the production of dry aerial biomass from *Bambusa bambos* in Southern India reaches 47 tonnes per hectare per year if it has been cultivated, while that of *Chusquea culeou* of Central Chile reaches only 10.5 tonnes per hectare per year. According to Riaño et al. (2002), starting from new cultivation, the *Guadua angustifolia* in Cauca Valley, Colombia, produces approximately 100 tonnes per hectare in six years.
According to Cruz Ríos (2009), the production in one plantation of *Guadua angustifolia* reached up to 594.2 tonnes per hectare in seven years.

Reduction of Soil Erosion

Bamboo has a dense network of roots that anchors earth and helps to lessen erosion due to rain and flooding.

Water Retention

One hectare of *Guadua angustifolia* can retain over 30,000 liters of water (Sabogal, 1979).

Regulation of Hydraulic Flow

Retaining water in its stem, bamboo conserves water in the rainy season, using it later in the dry season.

Temperature Reduction

Thanks to their leaves, bamboo forests reduce air temperature through water evaporation.

Sequestering of CO_2

Plants that assimilate CO_2 for photosynthesis, storing it in their biomass, make an important contribution to the global climate. Because of its rapid growth, bamboo can take in more CO_2 than a tree. The *Guadua angustifolia Kunth* takes in 54 tonnes of CO_2 per hectare during its first six years of growth (Londoño, 2003). This might be a relevant fact for international greenhouse gas emission allowance trading. However, this fact is only valid if the bamboo plant that has sequestered the CO_2 is transformed into products with long life spans.
According to Cruz Ríos (2009), the absorption of carbon at one plantation of *Guadua angustifolia* is 149.9 tonnes per hectare in the first seven years, which is an average of 21.41 tonnes of carbon per year per hectare, and a natural growth of *Guadua angustifolia*, with a density of 5755 plants per hectare, has absorbed a total of 132.6 tonnes of carbon. After six years, the bamboo stock stabilises the quantity of carbon absorption, due to the fact that this is totally vegetative development. "Being a plant that self-regenerates, bamboo has, with adequate management and harvest, a permanent CO_2 absorption, which does not happen with other species. The guadua is planted only once and with good management converts into a permanent plantation." (Cruz Ríos, 2009)

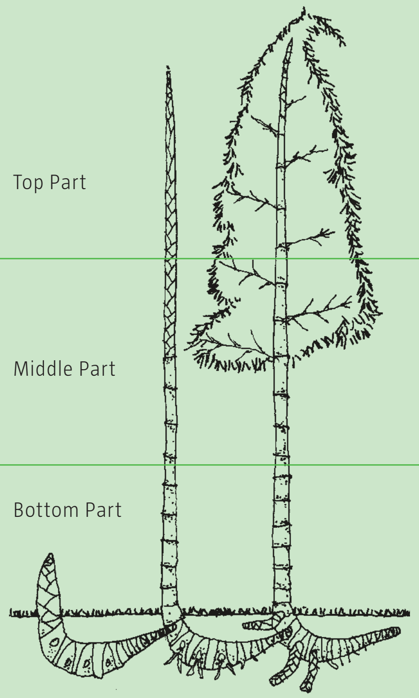
Primary Energy

According to Janssen (1981), the production of bamboo uses 300 MJ/m^3, compared with 600 MJ/m^3 for wood.

Different Uses

The use depends on the type of bamboo, its age and the part of the plant. Figure *1.1* describes the uses for the bamboo *Guadua angustifolia Kunth*.

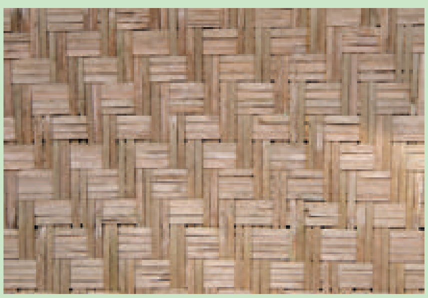
Due to its favourable mechanical characteristics, great flexibility, rapid growth, low weight and low cost, bamboo is a construction material with many applications. It is estimated that one billion people live in houses constructed from bamboo (Liese and Düking, 2009); for example, in Bangla Desh over 70% and in Guayaquil, Ecuador, 50% of the population uses it in construction. In seismic zones bamboo construction is preferred due to its lightness and flexibility. In humid tropical zones bamboo is used in construction since it is a local, cheap and easily handled material; furthermore in these areas it allows walls with low thermic mass.



	USES ACCORDING TO THE PLANT SECTION	DESCRIPTION	HEIGHT	LENGTH
Leader	Returns to the earth as organic material	Apical part of the plant	20 m	1.20 – 2 m
Stick	Structural straps for roofs, and guides for transitory cultivations	Part of the stalk with the smallest section	18 m	3 m
Top				
Middle	In structures such as roof purlins, scaffolding, structural columns for greenhouses Elaboration of planks, slender columns and beams	Because of its diameter, it is the most marketable part of the upper stalk Part of the stalk most used, for its diameter	15 m 11 m	4 m 8 m
Bottom	Columns in civil works, greenhouses and fences	In this part, the stalk has the greatest diameter. It is the most resistant part of the plant	3 m	3 m
Rhizome	Sculptures, furniture and children's toys	Network of underground stalks	2m	2 m
USES ACCORDING TO AGE	**30 days Food** **1 year Basketwork**	**2 years Planks, Strips, Laths**	**3 to 4 years Civil Structures, Floors, Laminates**	

1.1

The ideal use of large bamboos like *Guadua angustifolia* depends on their age. In their first days, bamboo hearts are used as human food; between six and 12 months, strips extracted from the external zone of the cane are ideal for making fabrics (*1.2* and *1.3*); at two years the canes are better for making plank boards (see Chapter 7, "Canes, Planks, Strips, Laths and Belts") and normally between three and five years the stalks are ideal for use in construction.



1.2

1.3

1.4

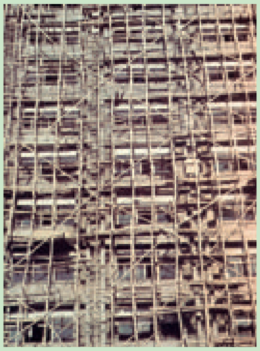
1.5

The majority of traditional houses in the rural zones of warm humid climates where bamboo grows, are constructed of this material. Figures *1.4* and *1.5* show examples from Indonesia and India. Due to walls of bamboo planks there is sufficient air circulation.

A typical use of bamboo canes is in the construction of scaffolding. In Asia these are found with heights of more than 40 storeys (Matthews 1985) (*1.6*). New is the use of bamboo strips of 1 × 1 cm parallelly forming a structural beam of 12 cm in diameter, composed of approximately 100 laths secured with leather; see p. 86 f.

Another common use in regions where bamboo grows is for crafts and everyday objects (*1.7* to *1.10*), musical instruments (*1.11* to *1.13* and *1.19*) and furniture (*1.14* to *1.16*). New is the experimental use in vehicles like bicycles, cars and buses: figure *1.17* shows the design of a bamboo buggy by Jörg Stamm; Julio César Toro has designed and built a rural bus for 20 people (*1.18*). To make the body, the floor and the railings, he used 40 lineal meters of guadua and for the roof he used 63 small boards of macana. The bumper was made of laminates of guadua.

Asia has pioneered the industrial development of the use of bamboo in laminates (see Chapter 7, "Laminated Elements") and fabrics (*1.2*). Recently in Latin America this process has been initiated in Brazil, Colombia, Costa Rica and Ecuador. Fibres treated with a viscose process are being used in China as are those of wood cellulose, giving a very resistant and smooth fabric.



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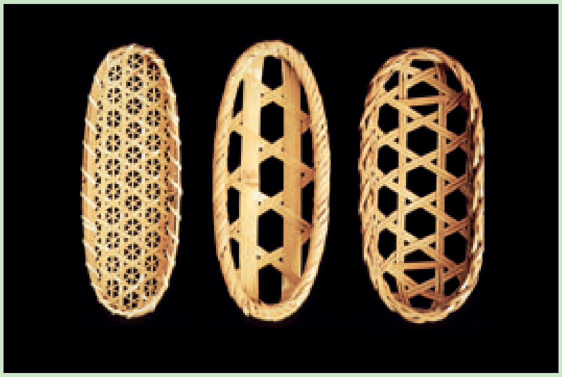

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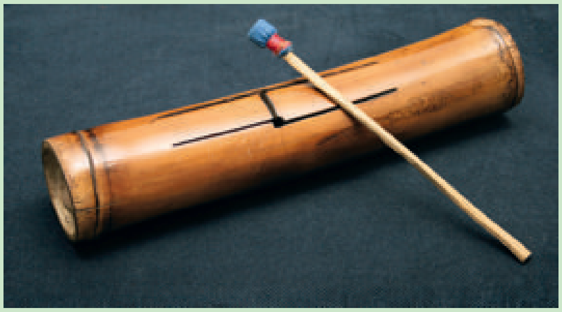

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1.16

1.17

The industrial production of paper using bamboo pulp was developed in India around 1910 (Hidalgo, 2003). One of the oldest and most diversified techniques of uniting bamboo elements are fabrics in a plank style (*1.2* and *1.3*). Because of the friction between their elements they form stable structures. Fine strips braided into large ropes were also used in nautical applications. These have a greater resistance to abrasion than those of hemp (Dunkelberg, 1985).
Thomas Edison tested thousands of vegetable fibres for use as filaments in light bulbs and found that the fibre of a bamboo from Japan was the best. It lasted 2450 hours when lit. After this discovery, the General Electric Company used this type of filament for 14 years.
A scientist from China studied the different applications of bamboo, classifying 1386 different uses (Lübke, 1961).

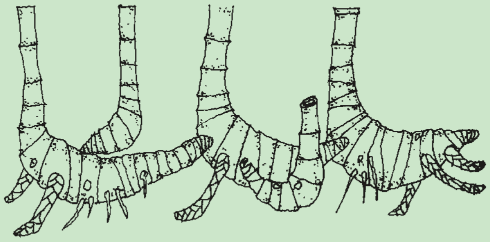
1.18

1.19

2

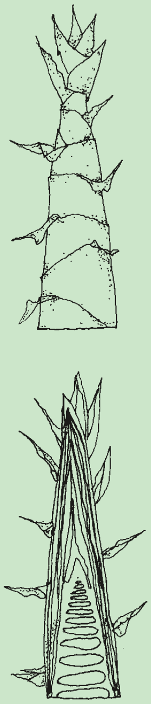
The Plant

The bamboo stalk grows directly from the rhizome (subterranean stalk). The rhizomes of pachymorphic bamboos grow in all directions, forming a three-dimensional network with a height of up to 2 m (*2.1*). The stems grow very close together, forming a bush (*2.9*). Bamboos with leptomorphic rhizomes grow from a horizontally lineal rhizome (*2.2*). There are also combinations of these types.
Bamboo is characterised by having all of the nodes and internodes of the adult culm compressed in the heart (sprout); only the internodes stretch during its growth, beginning with the lower ones (*2.3*). In the same way, the difference in diameter of the nodes is maintained when the cane reaches its definitive height, obtaining its slightly conical form. The mother plants (first generation plants) have a smaller diameter; in the following three generations, they thicken a little each time (Londoño, 2003). The *Guadua angustifolia Kunth* grows up to 21 cm per day and in one month reaches 80% of its maximum height, which it completes in five more months, reaching between 15 m and 30 m (Londoño, 2003). The productivity is between 1,200 and 1,350 canes per hectare per year. The process of lignification (becoming woody) takes between four and six years; after this period its vascular bundles close and dry out, and the stalk can be used for construction.



2.1

2.2



2.3

2.4

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2.6

2.7

2.8

2.9

During the growth state, the humidity content can be up to 80% in the first part of the stalk, and after four to six years, when the stalk is hard, lowers to approximately 20%. Bamboos which grow on inclined land with little water are stronger and, therefore, more appropriate for construction than bamboos that grow in flat humid areas. They are stronger in compression since their tissue is denser and has more fibres.

Bamboos are grass plants that have very long flowering periods, with a cycle between two and 100 years (for large bamboos between 40 and 80). The flowering of a species can be gregarious; that is, it blooms at the same time all over a continent, or the world, generally only once in its lifetime. Afterwards the plant dies (*2.7* and *2.8*). The *Guadua angustifolia* does not die after its yearly flowering period, which is associated with strong summers, be they occasional or continuous (Londoño, 2003). The colour of bamboo canes is generally green; after becoming woody they change colour to between yellow and brown. Black bamboo and *Bambusa vulgaris* (*2.10* and *2.11*) are exceptions.

2.10

2.11

Reproduction can be by:

- Chusquin method (small plants that emerge from the mother rhizome).
- Parts of the stem with node and bud. If a part of the stem with more nodes is used, one must open the internodes so that water can enter.
- Parts of the rhizome.
- Seeds.

3

Cutting, Drying, Treatment and Storage

Bamboo contains a large quantity of starch, which attracts insects, especially when the level of sap is high. Also the presence of humidity can cause the appearance of fungus and lichens. To guarantee durability in bamboo construction elements, it is important to take into account good procedures for cutting, drying and treatment.

Cutting

Cutting bamboo is done with a machete or saw directly above the first or second aboveground node, keeping in mind that the cut should be inclined, to avoid the penetration of rain into the rhizome, thereby rotting it. It is advisable to make the cut during the dry season when the stems have minimum humidity. Field observations have demonstrated that a correlation exists between the humidity content of the canes and the phases of the moon, and that there is also a correlation with the humidity content of day and night. The humidity of the plant interior is lower in the waning phase of the moon and in the early hours of morning, before the sun rises. The optimum age at which to cut *guadua angustifolia* for structural use is between three and five years, when its tissue is hardened.

Drying in the bush

The most common method of curing is to dry in the bush: one places the culm with its branches and leaves from the ground onto a stone, maintaining its vertical position. This is done for a minimum of four weeks so that it dries through evaporation. Afterwards the branches and leaves are cut and the culm is left to dry further in a covered, well-ventilated space.

Air Drying

The simplest method to dry the canes is to arrange them in a form similar to a tripod, exposing them to the sun and wind (*3.1*). The process of drying is optimised in a greenhouse with a plastic enclosure. It is favourable to open it at night so that the less humid air can enter, and close it during the day. Figure *3.2* shows a method practiced by Ecobamboo, Colombia, where hot air is injected into the bamboo by a fan that transfers the heat from a solar collector, pushing it through a sleeve into the canes, which have already been longitudinally perforated.

3.1

3.2

Microwave Drying

One can use high-frequency electromagnetic waves to evaporate the humidity from the canes. This has the characteristic of drying from the inside out, as opposed to the other drying systems that work from the outside in. This method uses large equipments and a lot of energy.

Drying and Curing Using Heat

A primitive method of heat curing is to put the canes horizontally over live coals at a distance sufficient to avoid burning them with the flames. This method is very laborious and there is a great probability that the canes will crack.

Earth Curing

In rural areas of Bangla Desh a simple method is used: the canes are laid in a slurry of clayey earth for some weeks. By this method the starch is extracted from the stalks (Chowdury, 1992).

3.3

3.4

3.5

Smoke Curing

Smoke in an enclosed space is most efficient for curing bamboo. Figure *3.3* shows an oven that was constructed by the author for the project shown in Chapter 12, "Walls Reinforced with Bamboo", where the canes stayed between eight and twelve hours over a low-temperature fire. These ovens produced large amounts of smoke using humid leaves and fresh branches as fuel.

Cleaning the Surface

Steel wool has been widely used to clean lichens from the surface of bamboo. Nevertheless, this method turns out to be costly, slow and dangerous for the respiratory systems of the workers. Furthermore the use of metal sponges and brushes is not recommended as it can weaken the shell. A more effective, inexpensive and healthy option is to use a hydrowash with a stream of high-pressure water (*3.4*). The use of metal sponges and brushes is not recommended as it can weaken the shell.

Lime Protection

A simple solution to protect the bamboo surface against fungus, lichens and insects is to paint it with lime ($Ca(OH)_2$), which due to its low pH level acts as fungicide and insecticide. The lime paint does not last very long because it has low resistance to abrasion and erosion due to its low adhesive capacity. To augment it, one can first paint the cane with an asphaltic emulsion, throw sand over this and wait until the asphalt dries.

Preservation by Flooding the Internodes

A primitive method widely used in rural areas and known as "vertical sap diffusion" consists of putting the canes with branches and leaves in a vertical position in a container, perforating the diaphragms of the upper nodes until the penultimate one and pouring in the immunising agent from above (*3.5*). If there are cracks or holes in the shell, one must first close them with paraffin or wax. Afterwards, one opens the last diaphragm so that the remaining liquid, which can be reused, escapes. The disadvantage of this method is that the poison also goes to the branches and leaves, contaminating the surroundings after their cutting. If the branches are cut before the immunisation process, this pollution is eliminated, but the preservation time takes much longer, as there is no enhancement of penetration through the suction by the evaporation of the leaves.

3.6

3.7

Preservation by Immersion

An effective method to immunise the canes against insects and fungus is immersion in a liquid that functions as both insecticide and fungicide. It is necessary to perforate the wall of the canes in each one of its internodes (but not in a straight line, in order to avoid cracks) or, more intelligently, make a longitudinal perforation pushing an iron rod through all of its nodes; see *3.6*. Figure *3.7* shows the immersion pool where the canes are left submerged for several days. It is important that the canes are not too dry. The immunising salt does not enter into a totally dry skin of the cane, only the water does (the salt stays on the surface). The salt penetrates through osmosis, which only works if there is sufficient humidity.

There are many immunisation products on the market with a base of copper sulphate, sodium dichromate or zinc chloride. Cheaper and less contaminating for its users is "pentaborate", which consists of 5% borax and 5% boric acid in a water solution. According to the experience of Jörg Stamm, it is sufficient in industrial processes to use 2.5% borax and 2.5% boric acid. Another proportion suggested by the National Bamboo and Guadua Investigation Centre, Colombia, is to use 2 kg of boric acid and 1 kg of borax in 100 liters of water.

Preservation by Injection

To use the injection treatment, one perforates all of the internodes to apply between 10 ml and 20 ml of the immunising agent per internode. It is necessary to seal each perforation afterwards. This method requires a lot of care since one must guarantee that the entire cane receives sufficient treatment; for this reason this method is not recommended.

Preservation by Pressure

An effective but more expensive variant is to pass the immunising agent by pressure through the longitudinal tissues of the cane; it is commonly called the "Boucherie method". In the last 20 years this method has been changed and perfected to arrive at a portable plant that permits treatment in the bush immediately after cutting; see *3.8*.

3.8

3.9

Surface Bleaching

One can use the sun to ensure that the surfaces of the canes are lighter and uniform in colour. Figure *3.9* shows a tripod-like structure where the canes are left in the sun and are manually rotated each day.

Surface Protection

In order to avoid deterioration of the exterior surface by ultraviolet rays and by rain, one can use commercially available paints with a base of linseed oil and beeswax, which close the open pores but do not totally block moisture transfer. One can also use commonly available oil-based paints, normally applied to wood.

Fire-Retardant Treatment

For this, one can use the same products that are used to protect wood. One suggestion of the United Nations (1972) is to add the following to 100 liters of water:

– 3 liters of ammonium phosphate
– 3 liters of boric acid
– 1 liter of copper sulphate
– 5 liters of zinc chloride
– 3 liters of sodium dichromate
– a few drops of hydrochloric acid

Storage

Bamboo is a hygroscopic and porous material; it absorbs water in vapour and in liquid form. If the bamboo cane becomes wet, its shell will swell and its mechanical properties will diminish. For this reason the bamboo must be stored in a covered, dry and well-ventilated place.

4

Physical Properties

Introduction


4.1

The physical characteristics of the bamboo stalk depend on:
– climate
– topography
– soil
– altitude above sea level
– cutting and treatment
– age
– the part of the stem
– humidity

Relative Humidity

The relative humidity of a cane is the weight of its water content in relation to the cane's weight in a totally dry state, expressed as a percentile. In a growth state, the humidity content can be more than 70% in the first part of the stem, falling to approximately 20% after four to six years when it hardens. Humidity can be measured with an apparatus calibrated for bamboo, which shows the electricity that is transferred by the shell of the cane between two metallic pins (*4.1*).

Contraction During Drying

Contraction during drying is a product of water loss. According to Liese (1985), the length of the cane from its green state to its woody state (when the water content is approximately 20%) decreases between 4% and 14%; in its diameter the contraction is between 3% and 12%. According to Hidalgo (2003), the length of the *Guadua angustifolia* decreases between 3% and 10%.

Joints

Joints of bamboo canes are considered articulated and will not have moment transmission between the joined elements.
The perforations for the location of a bolt must be well-aligned with respect to its axis and have a diameter 1.5 mm greater than the diameter of the bolt. According to the Colombian regulation on the seismic strengthening of guadua constructions (NSR-10, see p. 28), the spacing between bolts must not be less than 150 mm or over 250 mm in joints submitted to tension, and no less than 100 mm in joints submitted to compression. Internodes through which pass bolts have to be filled with cement mortar, see also Chapter 9. According to the Colombian regulation, any type of joint is permitted, if it has been verified by a scientific study with no less than 20 trials.

Admissible Forces

Admissible forces depend on many factors, amongst others: the type of force, the duration factor of the load, the security factor, the humidity content, the temperature, the average value of the data from laboratory tests, and the number of trials (minimum 20). For more detailed information consult Colombian regulation NSR-10, chapter G12, see p. 28.

Net Area

The net area of the transverse section of a cane is calculated, according to NSR-10, using the following equation:

$$A=\frac{\pi}{4}\left(D_e^2-(D_e-2t)^2\right)$$

A = Net area of the transverse section of the guadua, mm^2
D_1 = Exterior diameter of the guadua, mm
t = Wall thickness of the guadua, mm

Splitting

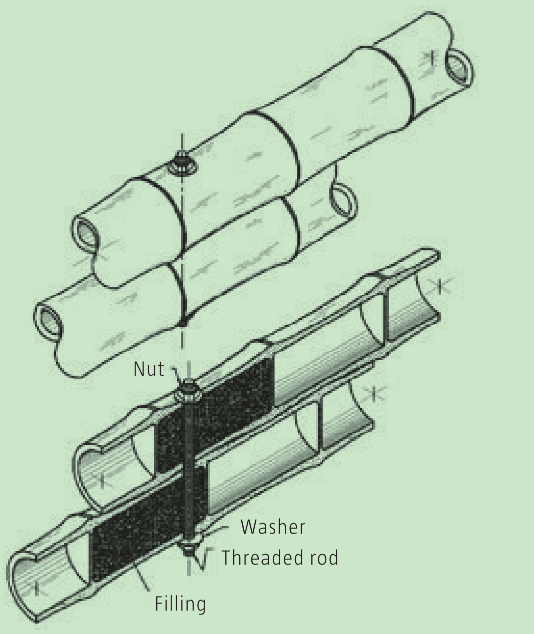
To avoid splitting, all of the internodes that are submitted to compressive forces perpendicular to the fibres must be filled with cement mortar (*4.2*). If the internodes are not filled with cement mortar, the admissible force must be reduced to the fourth part (NSR-10, see p. 28).

Resistance in Compression and Tension

A bamboo cane has a high resistance to tension, especially in its external layer. This layer bears up to 40 kN/cm² (= 400 N/mm² = 400 MPa), reaching the resistance of steel. When referring to the total area of the bamboo section, including all of the layers, the tensile resistance is of course less.
The compressive resistance offered by one culm is dependent on its slenderness. The FMPA materials testing laboratory in Stuttgart, Germany, conducted experiments on stalks of *Guadua angustifolia* used for the design of the ZERI Pavilion at the EXPO 2000 in Hanover (see p. 132f.); the experiments gave the following values:

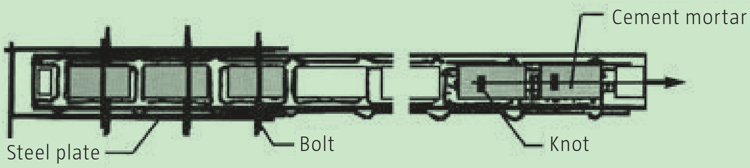
Compressive Resistance
$ß_c$, Lambda = 10 : 5.6 kN/cm²
$ß_c$, Lambda = 56 : 3.9 kN/cm²
$ß_c$, Lambda = 86 : 2.7 kN/cm²
(Lambda = slenderness ratio)

Tensile Resistance
$ß_t$:9.5 kN/cm²



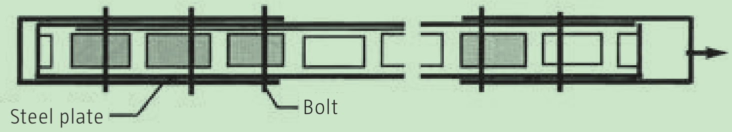
4.2

4.3



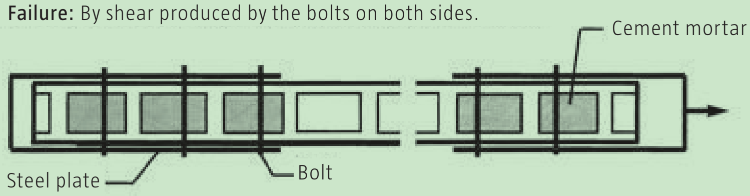
A. Test T.45. A long bolt or bar 3/4" in diameter with nuts and 2 internodes with cement mortar. Number of tests 5.

Failure: The cement mortar cylinders removed the internal nodes. There are cracks along 2 sides of the internodes.



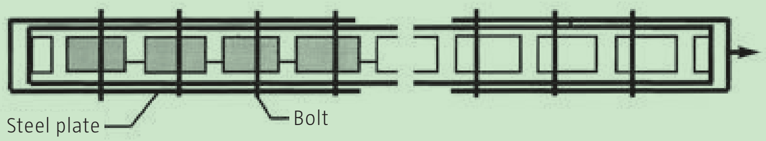
B. Test PP85. 2 internodes without cement mortar and 2 bolts Ø 3/4". Number of tests 3.

Failure: By shear produced by the bolts on both sides.



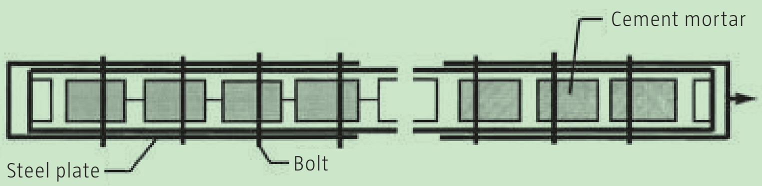
C. Tests PP80. 2 internodes with cement mortar and bolts Ø 1/2". Number of tests 7.

Failure: By shear produced by the bolts on both sides. In some cases the cylinders were cut by the bolts longitudinally in 2 sections.



D. Tests PP95. 3 internodes with bolts Ø 1/2", without mortar. Number of tests 3.

Failure: By shear produced by the bolts on both sides.

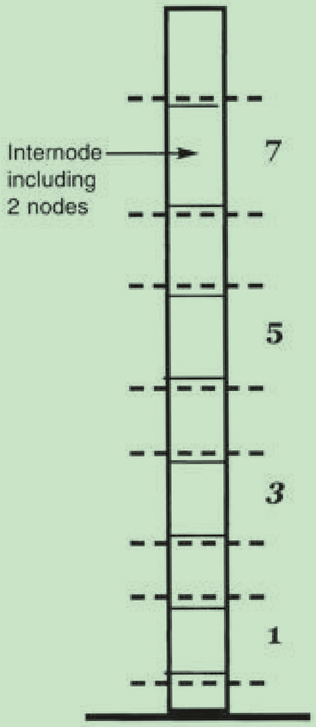


E. Tests PP90. 3 internodes with mortar and bolts Ø 1/2". Number of tests 6.

Failure: Same as C.

Rupture load (Kg)	Length section (m)	Exter. diamet. (cm)	Wall thickn. (cm)	Average Internode (cm)
4000	1.93	11	1.00	25
4200	1.96	11.5	1.75	25
4200	1.88	12.5	1.75	23
4250	1.75	10.5	2.00	20
4800	1.94	11.5	1.75	25
4000	2.03	10	1.00	27
3300	2.80	9.5	0.85	27
3.500	2.50	10	1.00	36
7450	2.48	9.00	1.00	34
5800	2.47	10	1.25	35
6750	2.53	10	1.35	34
7510	2.42	8.5	1.00	39
7500	2.78	12.5	1.5	33
8000	2.00	11	1.5	28.5
10000	1.97	10.5	1.75	26.5
6750		9.5	1.25	26.8
3600		11	1.60	30
3100	3.02	10	1.00	33
	3.06			
	2.99			
13500	2.52	11.5	1.75	29
11530	3.10	10	1.00	26
12800	2.54	12	2.00	28
11900	2.69	10	1.25	27
9800	3.00	11	1.75	26
11730	2.94	10	1.25	28

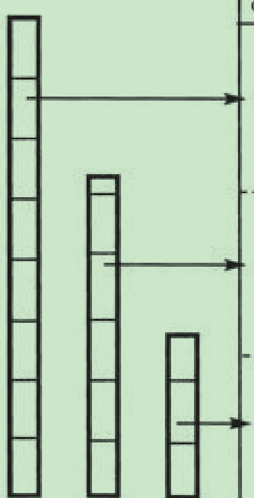
4.4 Tensible resistance in bamboo joints (Garzón 1996, mentioned in Hidalgo 2003)



Species	Internodes of basal part	Modulus of elasticity Kg/cm^2	Modulus of rupture Kg/cm^2	Compres. strength Kg/cm^2	Tensile strength Kg/cm^2
Dendrocalamus giganteous	1	172,097	1828	602	1836
	3	122,463	1758	619	1946
	5	147,912	1827	640	1880
	7	130,352	2880	646	1966
	Average	143,206	1823	627	1907
Dendrocalamus asper	1	122,073	1637	639	2145
	3	149,587	1741	592	2040
	5	129,542	1595	622	2220
	7	123,966	1578	566	2104
	Average	131,292	1638	605	2127
Gigantochloa robusta	1	94,208	1384	533	1970
	3	92,367	1294	510	1767
	5	109,217	1398	511	1854
	7	97,381	1345	530	2066
	Average	98,293	1355	521	1914
Bambusa vulgaris var. striata	1	60,652	1075	484	1392
	3	71,931	1123	443	1196
	5	88,297	1105	475	1352
	7	83,939	1286	417	1346
	Average	76,205	1147	455	1322

Source: after Sjafii (1984) in Widjaja & Risyad (1985)

4.5 Mechanical properties of various internodes of different bamboos (Hidalgo, 2003)



Length of culm sect.	Culm age (years)	Crushing strength Kg/cm^2		Base Diam cm	Wall thick. cm	Number of nodes
3 meters	1 to 3 years	Maximum	4,930	9.08	0.79	8
		Minimum	2,740	9,44	0.97	10
	3 to 5 years	Maximum	8,350	10.76	1.58	13
		Minimum	2,775	9.04	0.96	9
	more than 5 years	Maximum	16,600	13.09	1.92	13
		Minimum	3,200	9.89	0.87	9
2 meters	1 to 3 years	Maximum	10,125	11.33	1.15	7
		Minimum	3,830	7.86	0.71	6
	3 to 5 years	Maximum	12,830	11.73	1.52	7
		Minimum	5,100	9.53	1.26	7
	more than 5 years	Maximum	22,500	14.33	1.62	7
		Minimum	6,600	9.09	0.88	6
1 meter	1 to 3 years	Maximum	14,050	9.27	1.50	5
		Minimum	7,350	8.39	0.73	3
	3 to 5 years	Maximum	19,000	11.57	1.72	4
		Minimum	8,000	8.28	0.98	4
	more than 5 years	Maximum	23,650	13.50	1.55	4
		Minimum	9,910	10.23	1.20	5

Source: Martin, Mateus, Hidalgo (1981) - Total number of tested samples 129

4.6 Compressive resistance of *Guadua angustifolia* in 1m, 2m and 3m long sections

For bamboo canes of the *Guadua angustifolia* type, 10 cm in diameter and 3.50 m long with an internode thickness of 1.5 cm, as used for the Zeri Pavilion, the structural engineer Felix Weber calculated a strength of 70.4 kN (= 7.040 tonnes); the base was the value from the FMPA test in Stuttgart. The tensile resistance of the tested joint gave 140 kN (= 14 tonnes) as a result. The values realised in the majority of tests are superior to these, and change according to the age, growth and humidity of the canes.
Experiments conducted at the University of Valle, Cali, with the Research Centre for Bamboo and Vegetable Fibres (CIBAM) in Palmira, Colombia, using 163 samples with nodes, resulted in a tensile resistance of 12.17 – 20.68 kN/cm². The results of experiments by Garzón and Díaz (1996) testing the resistance of joints in tension are documented in *4.4*. It must be noted that the results can be improved if the iron rods are not installed linearly (some failures were produced by rods that split the canes longitudinally into two parts). Also, the results will be better if the lower part of the stalk is used, where the internodes are shorter and the thickness of the bamboo wall is greater.
Figure *4.5* shows the mechanical properties of various internodes of different bamboos. Results of experiments regarding the compressive resistance of *Guadua angustifolia* in 1 m, 2 m and 3 m long sections are seen in *4.6* (Hidalgo, 2003).
The HTW Technical Institute in Chur, Switzerland, performed tensile experiments with bamboo stalks 3 – 4 cm in diameter, in parallel position, with three different joint options (*4.3*). In the first option, the canes were fastened ten times with only galvanised wire (*4.6*); in the second option, small pieces of rubber (30 × 20 × 5 mm) were also put between the stalks; and in the third option, the canes were also connected with 8 mm diameter wooden pegs. In the first option, a maximum force of 1.30 kN was obtained with an elongation of 12 mm; in the second, a force of 1.9 kN was reached with an elongation of 20 mm; and in the third, 6.5 kN with an elongation of 13 mm. Structural calculation data of *Guadua angustifolia* bamboo stalks and joints can be found in López and Trujillo (2002). Normally the behaviour of a three-dimensional structure cannot be exactly calculated, so the load-test method is used. The load simulates all of the possible forces; see Chapter 6. Figures *4.7* and *4.8* illustrate the simulation of building loads using sandbags.

4.7

4.8

Modulus of Elasticity

The modulus of elasticity, abbreviated as E, is reduced by between 5 – 10 % with increasing tension. At the materials testing laboratory in Stuttgart trials were conducted for the E value of *Guadua angustifolia* bamboo with a 12 cm diameter, and the following results were found (used for the structural calculations for the ZERI Pavilion for the EXPO 2000 in Hanover):

E (compression):	1,840 kN/cm²
E (bending):	1,790 kN/cm²
E (tension):	2,070 kN/cm²

Experiments conducted at the University of Valle, Cali, together with the Research Centre for Bamboo and Vegetable Fibres (CIBAM) in Palmira, both Colombia, with 65 tests of *Guadua angustifolia*, resulted in a compressive E of between 1,350 – 2,770 kN/cm² (average 2,150 kN/ cm²). The E of guadua is almost double that of wood.
In NSR-10, chapter G12 (see p.28), there are specific values of modification coefficients, according to the load duration.

Performance in Fire

Bamboo, as it is hollow, burns rapidly. The bamboo wall has a high concentration of silicic acid. For this reason bamboo canes are designated according to the German regulation DIN 4102 as flammable but flame-resistant.

Earthquake Resistance

Due to its high resistance against forces in relation to its weight, its capacity to absorb energy and its flexibility, bamboo is an ideal material for earthquake-resistant structures. Studies show that in the region of the Andes, buildings with a first storey of solid mud walls (rammed earth) and a second storey of bamboo, resisted high-magnitude earthquakes. It is also common to use bamboo as reinforcement in adobe and mud walls in zones of high seismic risk; see Chapter 12, "Walls Reinforced with Bamboo".
In Quepos, Costa Rica, in November 2004 a surface earthquake of magnitude 6.9 occurred. Located in the zone of the epicentre, the Timarai Beach Hotel and Eco Bamboo Resort, with 2,500 m² built in *Guadua angustifolia*, responded without failures in the structure.
In April 1991, 20 bamboo houses built in Costa Rica under the consultation of Jules Janssen survived an earthquake measuring 7.5 on the Richter scale without structural damage.
For more information about the seismic resistance of adobe houses, see the two manuals of the Colombian Association of Seismic Engineering mentioned in the bibliography.
The architectonic design of seismically resistant bamboo houses complies in general with similar requirements for houses constructed in other materials. These include the following:
– The structure must be well-anchored to the foundation.
– The roof must be well-anchored to the walls.
– The roof must not be too heavy in relation to the rest of the structure.
– Structures of more than one volume must behave independently from one another.
– The floor plan must not be very elongated (the optimum is a circle).
– The parts of the wall between openings must be sufficiently sized.
For more specific information, see Minke (2001).

5

Building with Bamboo in Europe and North America

Introduction

Until the end of the 20th century, bamboo was used in Europe and the USA principally for making furniture or decorative elements. In recent years, through the development of new bonding and laminating techniques, bamboo has become widely available as a flooring material in Europe and America. In both continents, however, there is no tradition of using bamboo for the construction of building structures. The construction of the ZERI pavilion at the World EXPO 2000 in Hanover, designed by Simón Vélez (see p. 130f.), marked a turning point, attracting the attention of European engineers and architects to the excellent construction properties of this "exotic" material. The pavilions built ten years later for the World EXPO 2010 in Shanghai (see p. 136 to p. 141) demonstrate that bamboo is now recognised around the world as a high-performance building material that is simultaneously suitable for sustainable building with a small ecological footprint.

Availability

In Europe and the USA, bamboo plantations that can serve as a source of construction materials are non-existent. At the most, there are tree nurseries in some countries that cultivate and sell bamboo. The best product for building with bamboo in Europe and America is *Guadua angustifolia Kunth*, which grows primarily in Colombia in forest-like "guaduales" along the banks of rivers or other moist areas. The bamboo used for the construction of buildings with thick bamboo members in Germany and Italy originates from Colombia (see p. 128f. and p. 130f.) or from Ecuador (see Chapter 10, "Vaults" and "Domes", in particular figure *10.72*). Other bamboo profiles with a thicker cross-section, such as those of the *Dendrocalamus asper*, are imported primarily from Indonesia, although these have been used until now only for making furniture.

Split bamboo profiles made of thinner bamboo poles, such as can be seen in the washroom building in La Selva, Spain (see p. 114f.), and in the bamboo sculptures and roofs on p. 126f. and on p. 140 to p. 149, originate from Indonesia.

Although the transport of bamboo from Colombia to Europe can be regarded as a cost and energy factor, one should note that unlike wood, the harvesting and processing of bamboo requires very little energy; the material is very lightweight and, when transported by boat, causes comparatively little environmental pollution. The ecological footprint of imported bamboo is therefore generally thought to be lower than that of wooden profiles. According to Waltjen (1999), 588 kWh/m^3 is required to manufacture a cubic meter of wooden profiles, while 1276 kWh/m^3 is required for OSB panels (according to Hegger et al. [2005]).

In the southeast of the USA and in Oregon and Washington, a series of small producers have planted bamboo plantations, although these are typically bamboo species suitable for use as hedges, screening elements or decorations. An exception is the plantation on Avery Island in Louisiana where "Moso" (*Phyllostachys pubescens*), a species originally from China, is cultivated. In the USA it is cheaper to import bamboo from China or Colombia than it is to harvest and process bamboo locally.

1.
- ISO 22157-1: 2004 “Determinación de las propiedades físicas y mecánicas del bambú.”
- NSR-10: “Norma de Sismo Resistencia”, chapter G12: “Estructuras de guadua”, updated 2010.
- NTC 5300 “Cosecha y postcosecha de los culmos de Guadua angustifolia Kunth”.
- NTC 5301 “Secado e inmunizado de los culmos de Guadua angustifolia Kunth”.
- NTC 5405 “Propagación vegetativa de Guadua angustifolia Kunth”.
- NTC 5407 “Uniones para estructuras construidas en Guadua angustifolia Kunth”.
- NTC 5458 “Artesanías y muebles en Guadua angustifolia Kunth”.
- NTC 5727 “Terminología de la guadua”.

Statutory regulations

In Europe there are currently no building regulations for the use of bamboo for building structures. Because bamboo is not a certified building material, special case approval must be sought from the respective building control authorities in each and every case. Regulations from other countries can, however, serve as a basis for obtaining permission. In most cases permission is granted based on prior laboratory tests of individual elements or on the basis of load tests.

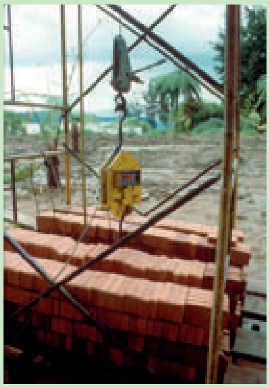
The “AC162 Acceptance Criteria for Structural Bamboo”, issued in March 2000 in California, set out how such tests on bamboo structures and their joints should be undertaken.

These criteria also stipulate a safety factor of 2.25, i.e. that the permissible load may not exceed the tested material strength divided by 2.25. Similarly, the criteria also prescribe that the length of a structural bamboo member may not be larger than 25 times its smallest cross-section.

Aside from this, the International Network on Bamboo and Rattan, INBAR, issued a 20-page set of general regulations in 2002. These detail how parameters such as moisture content, compressive strength, tensile strength and bending strength should be measured. In the “National Building Code of India. Part 6: Structural Design, Section 3: Timber and Bamboo”, chapter “3B – Bamboo” lays down the permissible physical properties such as the strength of bamboo members and their joints for the different kinds of bamboo used in India.

The most detailed regulations for building with bamboo, which cover the use of *Guadua angustifolia Kunth*, the most common kind of bamboo used in Latin America, are available in Colombia. These govern the physical and mechanical properties of bamboo (ISO 22157-1), the seismic strengthening of guadua constructions (NSR-10), the harvesting, drying and preservation of guadua (NTC 5300 and 5301), the vegetative propagation of this kind of bamboo (NTC 5405), structural joints made with guadua (NTC 5407) and the terminology applied to guadua and its processes (NTC 5727).[1]

5.1



5.2

5.3

As part of the planning application submission for the ZERI Pavilion at the EXPO 2000 in Hanover, tests were undertaken at the FMPA materials testing laboratory in Stuttgart to determine the compressive and tensile strength of *Guadua angustifolia*. Tests showed that a 3.5 m long bamboo member with a 10 cm cross-section and 1.5 cm wall thickness can sustain a load of 70.4 kN (7040 kg). The tensile strength of the joint was measured as 140 kN (14 tons). These values were used for the structural calculations and recognised by the building control authorities.

A key contributory factor for obtaining planning permission was the fact that an identical prototype had been constructed in Manizales, Colombia, and subjected to initial load testing (*5.2* and *5.3*). In addition further tests were undertaken on the ZERI Pavilion in Hanover using more precise measuring methods (*5.1*).

For the design of an office in Darmstadt with a structural bamboo construction (see p. 128f.), values obtained in a materials testing laboratory were likewise used as a basis for structural calculations, and were in turn accepted for planning permission.

Fire performance

Because bamboo members are hollow, they represent a high fire risk. Nevertheless, the external layer of the bamboo canes contain a high concentration of silicates and are therefore not highly flammable. Tests conducted in association with the design of a façade of a car park building in Leipzig, Germany (see p. 126f.), established compliance with building material class B2 (moderately flammable) according to the German DIN 4102. In such cases where the façade construction does not serve a structural function, it is not necessary to prove the fire resistance rating (e.g. F30). It is, however, important to prevent the transmission of fire from one storey to another, for example through the provision of a solid concrete upstand.

6

General Aspects of Construction

Advantages and Disadvantages

Advantages

- Bamboo as a construction material is light and forms structures that have a low mass-to-flexibility ratio compared with those of wood. These structures are important for earthquake-resistant solutions.
- The external layer of the shell offers very high resistance to tension, equalling that of steel.
- Bamboo grows extremely rapidly and is usable as a construction material after four to six years. According to the regulations ISO 22156 and ISO 22157-2, 78.3 tonnes per hectare of bamboo are produced each year in the Coffee Triangle of Colombia, as compared with only 17.5 tonnes per hectare of wood. In dry material, 36 tonnes per hectare of bamboo is produced, compared with 10.8 tonnes per hectare of wood. As a result, the yield of bamboo is 3.3 times that of wood.
- Bamboo sequesters CO_2 (see Chapter 1, "Positive Environmental Effects").
- Bamboo has a very low primary energy. This means that the ecological footprint is very low (see Chapter 1).
- Cutting and transportation costs are relatively low.
- Bamboo does not have bark, which, as with trees, must be peeled.
- The branches are easy to remove.
- Laminated bamboo, as used for example for floors, shows an extreme resistance to abrasion.

Disadvantages

- Its structural behaviour can vary greatly, depending on the species, the growing site, its age, the moisture content and the part of the stalk that is used.
- Bamboo is vulnerable to exposure to ultraviolet rays and rain; accordingly it requires protection during the handling, execution and maintenance of the project.
- Bamboo is sensitive to attack from insects and fungus. It must be impregnated or treated against them.
- Its round section and its tendency to crack easily complicates the execution of joints and supports.
- Its conical profile changes the diameter and the thickness of the bamboo stem along its length.
- Rarely does the stem grow totally straight.
- The dulling of work tools is higher than with wood.
- The structural calculations and construction permits are difficult to obtain since official regulations do not exist.

Selection of Bamboo Canes for Construction

The canes that will be used in construction must be selected to be of good quality. The following rules are recommended:

- Use only mature and dry bamboo, normally between four and six years of age.
- Canes with cracks that go from one internode to another must not be used.
- The canes must be straight or smoothly curved, but not with internal curves. If they are used as columns that transfer large forces, the eccentricity of the axial force must not be greater than 0.33% of the element's length (see Colombian regulation NSR-10, p. 28).
- It is not recommendable to use canes that show damage caused by insects or fungus.
- Canes that have fungus and lichens must be cleaned before use.
- For columns, the first third of the stem should be used, where the nodes are closer together and the culm is thicker.
- Bamboos that grow in high altitudes and with drier soil normally have nodes spaced more closely together (shorter internodes), and are therefore stronger.
- Canes must not taper more than 1%.
- Canes used as beams must not have longitudinal fissures along the neutral

axis of the element. If there are fissures, they must be located in the upper or the lower external fibre.

- Canes must not have perforations caused by xylophagous insect attack (NSR-10).
- To avoid fungal attack, the relative moisture content must not be over 20% (NSR-10).

Incorrect and Correct Details

The illustrations in this chapter show incorrect designs, badly built details and parts with insufficient protection.

- It is indispensable to construct sufficiently large eaves and a plinth of 30–50 cm to prevent rain from damaging the bamboo. Figure *6.1* shows insufficient eaves, and in *6.2* there is no plinth.
- Perforations for immunisation or for pins, aligned in the internodes, can produce cracks; see *6.3* and *6.4*. A better solution is shown in *6.5*.
- If bamboo is in contact with earth, the surface in contact decays rapidly; see *6.6*.
- If the base of a column directly touches or penetrates the foundation, and if rain reaches this point, water penetrates through capillary action, causing the end of the cane to rot; see *6.7*. In this case, one must separate the cane from the foundation with an iron rod, cone or tube; see *6.8*.
- Worse is the detail in *6.9*, where water can enter through expansion between the cane and the concrete.
- If there are termites, one can put a barrier of galvanised or aluminium sheeting with an overlap of 30 – 40 mm above the foundation. However, it is known that termites, like other creatures that attack bamboo, only eat the soft interior part of the culm and not the hard exterior part.
- The endpoints and nodes of canes in contact with rain, which are not protected by eaves, must be covered with metal panels or, for example, with a mud stucco stabilised with asphalt emulsion or lime and cement; see *6.10* and *6.11*.


6.1


6.2


6.3


6.4


6.5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6.8


6.9


6.10


6.11


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6.13


6.14


6.15

- Canes with fungus or lichens must be cleaned or not be used. The majority of the fungi that damage the cane require a moisture content higher than the saturation point of the fibres. Therefore one must ensure that the areas exposed to rain are well-ventilated.
- Canes that have splits going from one internode to another should not be used (*6.12*).
- Cane endpoints must not be secured with screws or nails (stitches); see *6.13* and *6.14*.
- Joints designed for contact must be exact. In *6.12* one sees that there is insufficient contact between canes, so forces are transferred only by the screw. If the joint is subjected to high loads, the screw will split the bamboo.
- For finishes, do not use paints that create a vapour barrier. If the moisture inside the cane condenses below the finish, this expands the culm and the finish. In consequence, the shell is affected by rain, solar rays and fungus; see *6.15*.
- A loaded beam must not bend excessively; as a rule no more than 1/150 of its length; see *6.16*.
- Optimally, the endpoint of the cane must have a node; if this is not so, the distance from the cut to the node must be no more than 12 cm (rule of thumb for *Guadua angustifolia*). If there is no node at the

end, it must be reinforced, for example with a wire or a band; see *6.17*.

- Figure *6.18* shows the connection of a bracket with a column that is not structurally optimal. Correct solutions are shown in *6.19* and *6.20*, where the force is transferred through one short piece at the column.
- Figure *6.21* shows a joint in the lower part of a truss that transfers tensile forces. The endpoint of the cane does not have a node. Therefore the pin is opening the cane and the joint is separating, allowing the truss to flex.

6.16

6.17

6.18

6.19

6.20

6.21

7

Basic Construction Elements

Canes, Planks, Strips, Laths and Belts

The **cane** is the bamboo stem without branches, leaves and rhizome (the roots). The lower part, where the difference between the diameter and the height of the internode is smaller, and the stem thickness is greater, is used for columns and posts. The canes are generally also used for beams, trusses and three-dimensional structures. Its multiple applications are shown in the following chapters.
The **plank** is obtained from the intermediate part of the stem (*2.1*), which, when opened, forms a flat surface. This is achieved by making successive longitudinal cuts around the area of its nodes with a hatchet; the stem is then opened and the leftover knots and soft tissue are removed with the help of a spade (*7.1* to *7.3*). Figure *7.4* shows the preferred method of drying and storing the plank. To successfully make a plank, it is necessary to use mature, recently cut bamboo that is sufficiently moist.

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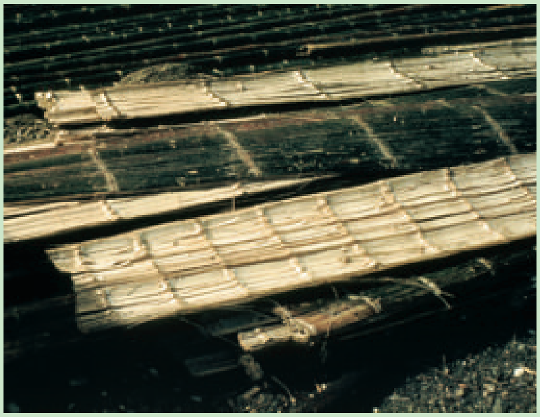

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Planks have been popularly used without plaster (stucco) in rural houses in tropical climates (*7.5*), and also with stucco in urban houses. These days in Latin America, planks are used as economical formwork for concrete structures and as stabilising elements in the construction of bamboo cane walls (see p. 110f.), and also as structural elements between beams or purlins in roofs (*10.37* and *10.38*).

Strips and **laths** are longitudinal segments of the canes; they are obtained by making cuts parallel to the fibres; one simple method of cutting with a special knife is shown in *8.14* and *8.16*. In China, mechanical systems have been developed for the industrial fabrication of strips. A machine adapted for *Guadua angustifolia* that produces strips is shown in *7.6*.

To bend strips, it is preferable to soak them in advance in water for some hours (*7.7*). Figure *7.9* shows a plank made from vertical strips joined with bamboo pins, used for benches and tables. A weave of strips is shown in *7.8*.

For laminated elements, only one part of the strips is used, called a lath or spacer; this has a rectangular section obtained by cutting the exterior shell and the soft interior tissue; see Chapter 7, "Laminated Elements".

Belts are longitudinal segments of the exterior part of the canes, much narrower than laths, normally up to 1 cm wide, and therefore more flexible. Traditionally they have been used to weave baskets and panels. Currently they are used in construction as ties to join many strips in parallel; see p. 86f. and figure *7.10*.

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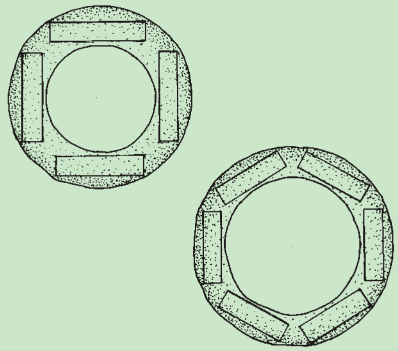
Laminated Elements

Bamboo laminates can be used as an alternative construction material. For laminated elements such as planks, boards, columns, beams and panels, laths joined with glue or wooden bolts are used. To produce laminates, the interior and exterior of the strip must be cut, from which pieces with rectangular sections are obtained (*7.11*) and joined (*7.14*). One can also use planks, closing their cracks (*7.12*).

Panels of laminated bamboo were developed in China in 1982. They consist of three or five lines of strips of 4 mm or 5 mm thickness, glued with phenol formaldehyde or urea formaldehyde, orthogonally in an alternating manner (Hidalgo, 2003). The pieces can also be united with the help of heat and high pressure. In China these laminates are produced on an industrialised scale at a density of up to 1,200 kg/m^3. They are absolutely impermeable and can be used for the restitution of hardwoods from primary forests.

According to López and Correal (2009), the average density of laminated guadua is 715 kg/m^3, with an average moisture content of 12%. The results of their tests were, among others:

- Resistance to compression parallel to the fibre: 48 MPa (N/mm^2)
- Modulus of elasticity to compression parallel to the fibre: 19.137 MPa (N/mm^2)
- Resistance to compression perpendicular to the fibre: 5 MPa (N/mm^2)
- Resistance to tension parallel to the fibre: 132 MPa (N/mm^2)
- Modulus of elasticity to tension parallel to the fibre: 17.468 MPa (N/mm^2)
- Resistance to tension perpendicular to the fibre: 1.1 MPa (N/mm^2)



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The resistance to compressive forces parallel to the fibre is up to ten times greater than the resistance to compressives forces perpendicular to the fibre. Tensile strength parallel to the fibre is up to 120 times greater than in the perpendicular direction.
Figures *7.13* and *7.15* show the use of laminates in furniture and doors. In Terminal T4 of the Madrid-Barrajas Airport, planks of laminated bamboo with a width of 10 cm were used to form an enormous ceiling (*7.16*).
Tests of the potential of laminates as a structural material can be seen in Lee et al. (1998), Nugroho and Ando (2001), Barreto (2003) and López and Correal (2009). Figure *7.17* shows laminated floorboards.

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Tools and Their Uses

Given that the exterior layer of bamboo is very hard, one must cut it using saws meant for cutting metal (*8.1* and *8.2*). Saws for cutting wood quickly become blunt (*8.3*). Also, for the making of holes, one must use a drill (*8.4*) or hole saw. The best bits are those with a centred point (*8.9*). The perforation must be made with high speed and low pressure on the piece, since the edges crack or fray easily. To avoid this, one can burn the shell using a hot iron rod. In order to insert wooden pins, a wooden hammer is used (*8.5*). Large openings are made using a drill with a hole saw (*8.6* to *8.8*).

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Figure *8.9* shows the application of this hole saw to make a "fish mouth", and *8.10* shows a tool where the cut can be perfected or polished with the help of a rotating roller of sandpaper. Figure *8.11* shows the finishing of a surface with a chisel and *8.12* with a mechanical polisher. With the sanding of the surfaces, a fine dust is produced, for which the use of a mask is recommended.

Bamboo canes are easily divided or opened since they only have longitudinal fibres. To divide them, it is sufficient to use knives, machetes or specially designed tools; see *8.14*. The tool is inserted a few centimeters into the cane, and then the cane is knocked vertically against a hard surface (*8.16*).

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If one wishes to bend strips of bamboo, it is recommended to soak them for a time in water so that they become more flexible. Thicker canes can be bent if one uses a young cane between two and three years old, warmed to a temperature of between 120 and 150 degrees centigrade. Figure *8.13* shows a warmed cane that has been bent around a barrel.

Nodes of cut canes are removed with a chisel as seen in *8.15* or with a plane (slicer), made of a metal tube, diagonally cut and sharpened (*8.17*). To produce planks, axes are used to open the canes (*8.18*). To remove the remainder of the nodes, tools such as those seen in *8.19* are used.

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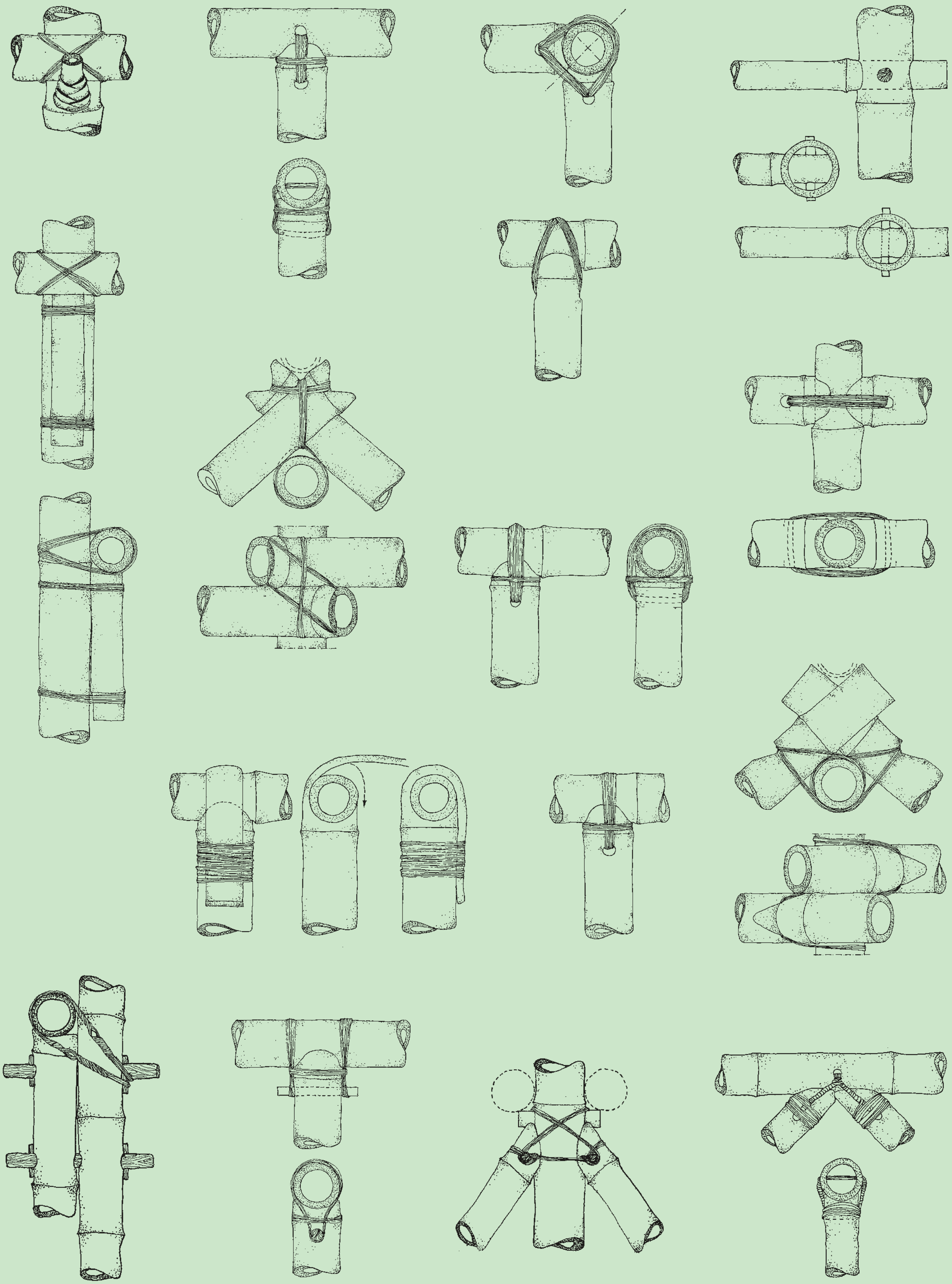

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Joints

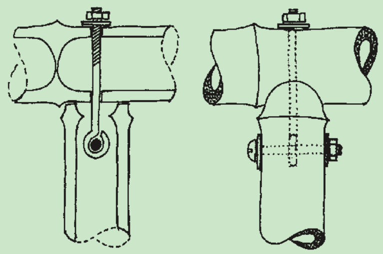
The most important aspect of bamboo construction is the formation of joints that transfer forces from one element to another. Given that canes have a hollow round section, and the parts between their nodes only have longitudinal fibres, canes cannot be joined in the same manner as wooden elements. For example, if nails or screws are put into the internodal parts without first drilling a hole, longitudinal splits occur because there are no circular fibres there. Perforations for positioning a bolt must be well-aligned with respect to their axis and should have a diameter 1.5 mm greater than that of the bolt. Metallic elements used in outdoor joints must be anti-corrosive or must have an anti-corrosive treatment. If the canes are submitted to loads that could produce splitting, it is necessary to fill the internodes adjacent to the joint, and those where bolts pass through, with a mixture of cement mortar, preferably with a plastifying additive that improves the fluidity of the mixture.

Spacing between bolts must not be less than 150 mm or greater than 250 mm in joints submitted to tension and less than 100 mm in joints submitted to compression. Traditionally, to fix the joints one uses "lianas" or bindings of natural fibres or of dampened leather that tighten as they dry (*9.1*). Nowadays bindings of synthetic fibres are used or, more commonly, galvanised wire (*9.16* and *9.17*). Figures *9.5* to *9.7* and *9.9* show solutions by Marcel Kalberer for joints that transfer minor loads; these solutions use commonly available connection elements. In *9.3* and *9.7* we see solutions by the same author for articulated nodes. One can also use wooden elements for the joint (*9.19*).

The transferral of forces from one bamboo element to another is favoured by complete contact. The most common cut for these connections is called a "fish mouth" and is perpendicular (see *9.13* and *9.15*). If the cut is inclined, it is called "flute tip" (see *9.13* and *9.20*). To avoid the flute tip connection, one can use a perpendicular element called "muneco" (doll) in Colombia (*9.21* to *9.25*). A more adequate and sustainable solution is the use of hard wooden or palm pins. Figure *9.23* shows a connection made with a "chonta", a pin made from a very hard palm tree, resistant to termites, the sun's rays, moisture and microorganisms.

Figure *9.24* displays the use of inclined pins as connectors between parallel canes to make a stronger beam. Figure *9.27* shows a solution by Jörg Stamm, built for the end of a double truss. This solution guarantees an optimum transfer of forces through wooden pins. If the forces transferred are great, it is advisable to fill the internodes that receive the forces with a mortar of cement and sand, or epoxy resin and sand. In this case, a hole is opened in the upper part of the internode with a 3.8 cm diameter hole saw; after filling with mortar, the opening is sealed; see *9.26* and *9.28*.

When an internode is filled with concrete mortar, keep in mind that the concrete contracts during curing, leaving a space between the concrete and the cane; for this reason it is not recommended to use a mix of cement and sand in 1:2 proportion, as is mentioned in some literature. The contraction can be reduced using a mixture of 1 part cement for 3 or 4 parts coarse sand and gravel up to 4 mm in diameter. When perforating the cane to conduct this procedure, it is usually better to make a perforation no greater than 2.5 cm in diameter, so as not to weaken the resistance of the cane.



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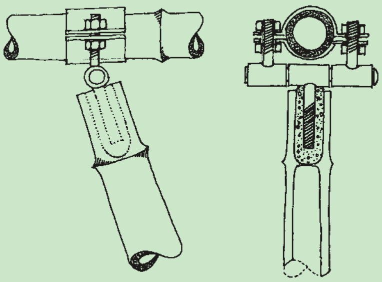

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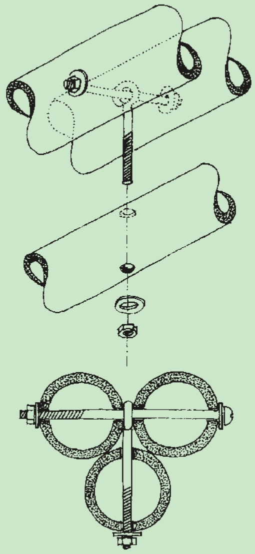

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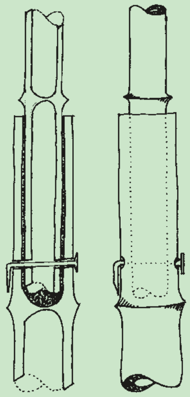

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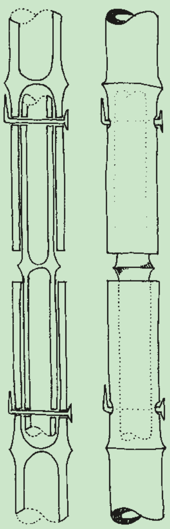

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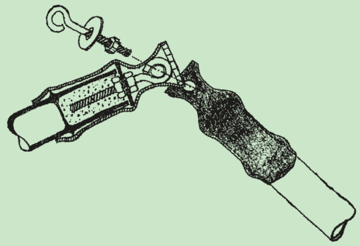

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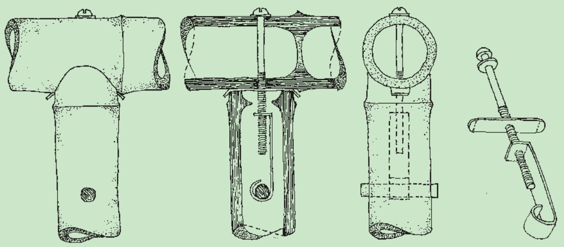

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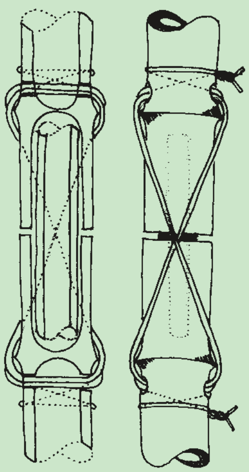

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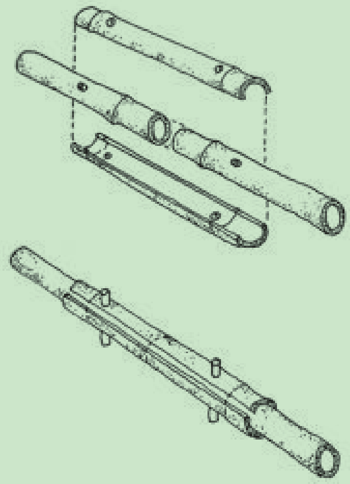

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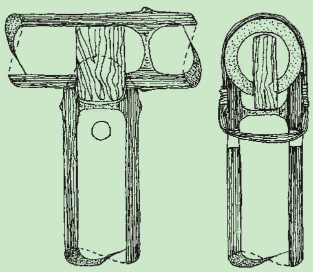

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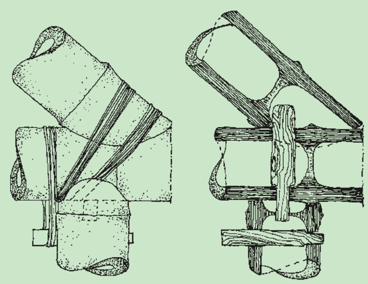

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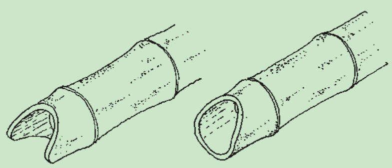

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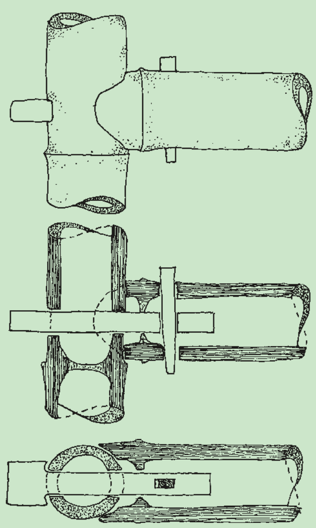

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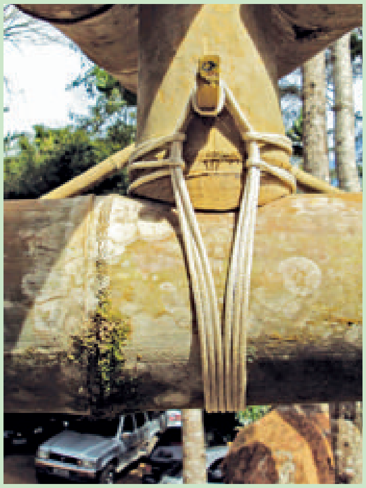
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In order to provide an equal distribution of pressure from screw to cane, Marcelo Villegas has developed different metal connectors (*9.29* and *9.30*). A simpler solution to distribute the pressure to the cane is seen in *9.31*. Instead of using a flute tip end, Marcelo Villegas has developed a specific metal element; see *9.32*. More adequate seems to be the development of connections made of rubber, which facilitate good contact over the whole area, without having to insert "fish mouth" cuts at the ends of the canes (*9.33* and *9.34*); this development is by Adán Piza.

There are many solutions that use elements commonly available in the market. Tim Obermann, for example, used a metallic ball with drilled openings, into which one can screw several metallic conical connectors, each one inserted into the end of a cane; see *9.35* and *9.36*. Jörg Stamm used the MERO node for three-dimensional structures, with conical endings in the canes (*9.37*).

Hamura Shoei Yoh developed a simpler solution in 1989 with metal tubes inside the canes; see *9.38* and Chapter 10, "Domes". A similar solution was used by the author for a column (*9.39*) and by Vitor Marcal for spatial joints (*9.40* and *9.41*). His solutions for joints are not particularly strong but adaptable to different angles, as seen in *9.42* and *9.43*. Markus Heinsdorff developed quite strong joints made of stainless steel that are adaptable to different angles for his German pavilions in China; see *9.44* to *9.47* and p. 134f.


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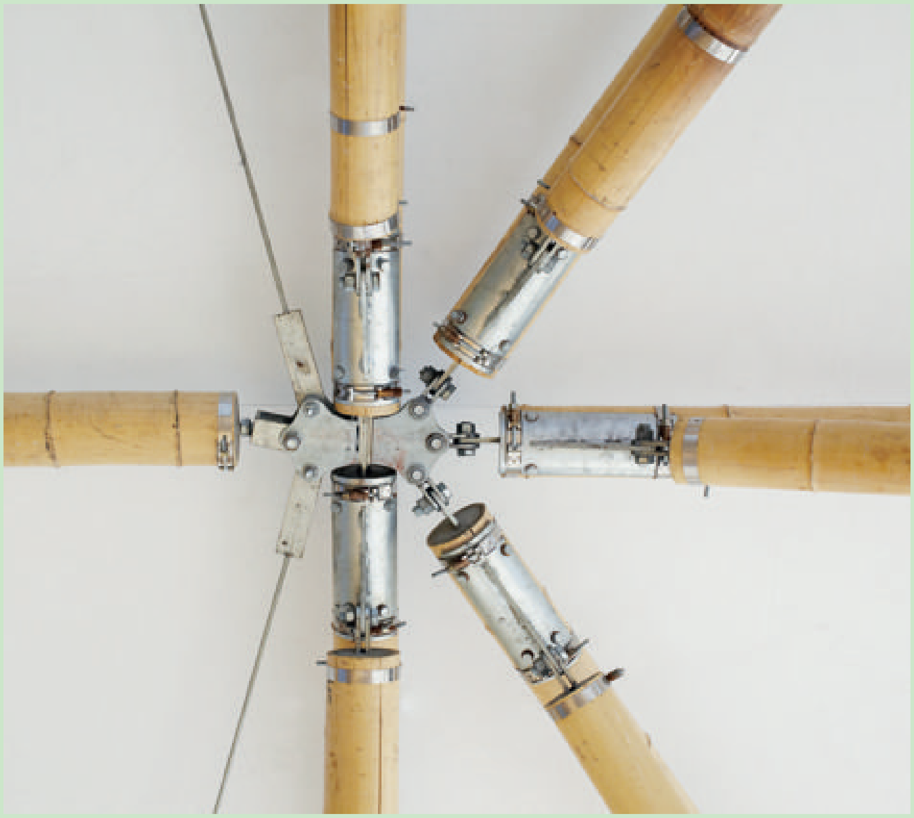
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A very simple but relatively weak solution is seen in *9.48*. A more intelligent construction is the "BAMBOOTIX" system by Waldemar Rothe, which can be installed in a few minutes with common bands that are adjusted perfectly to the circumference of the canes; see *9.49* to *9.52*. A similar detail used in the joining of wooden elements is seen in *9.53*. A commonly used solution is shown in *9.54* and *9.55*, where the fish mouth union is strengthened by means of a spiral rod that at its end hooks onto another perpendicular rod. Instead of bending the rod to make a hook, a washer can be soldered onto its end.
Figure *9.56* shows a three-dimensionally optimised solution designed by Marcelo Villegas, where the tensile elements are iron rods. Figure *9.57* demonstrates that when there is no node at the end of the cane, it must be strengthened with a galvanised wire or a band to prevent the cane from opening. The idea of using conical terminations was developed as long ago as 1941 by C.H. Duff; see *9.60*.
Other people have used conical endpoints with cement or resin filling; these are described in Chapter 10, "Columns". Figure *9.63* shows a sectional view of this endpoint. To connect crossed strips, one can use a galvanised wire, rivet or screw (*9.58* and *9.59*). But if a rivet or screw is used, one must first drill a hole to prevent the strip from splitting.
Figure *9.62* shows a simple welded sheet steel joint developed by Tönges, *9.65* a more elegant variant by the same construction engineer. A similar connection is used by the American company KOOLBamboo (*9.61*). Figure *9.64* shows an articulated joint, also developed by KOOLBamboo.

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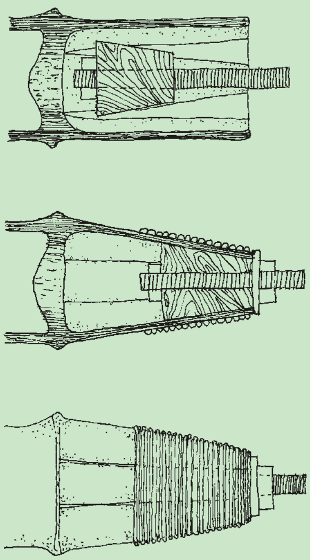

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Constructive Elements and Systems

Columns

Columns are linear, vertically positioned construction elements that transmit compressive forces. It is important to keep in mind that any compressive forces transmitted by the cross-section are the same at both the top and the base of the column.

A frequent solution for the base is to fill the cane with cement mortar up to the first node, to prevent the cane from opening or splitting; for more security, a metal covering can be installed, surrounding the cane; see *10.1*. To protect the foot from moisture, an iron rod is placed and fixed with cement mortar, thereby providing distance between the foundation and the cane. Instead of using cement as a filling, a mixture of epoxy with sand and gravel can be used.

In order to avoid the arduous filling with mortar, and to prevent the expansion or contraction of the cane, a steel tube or roll of hardwood can be inserted. This is connected with wooden pins or screws to the cane (*10.2*). In order to support great compressive loads, a simple solution was developed by Christoph Tönges for a pavilion in Vergiate, near Milan (*10.3*), see also p. 130f. An elegant solution for column bases was realised by Marcelo Villegas, where a cone of steel implanted in mortar was used (*10.5*).

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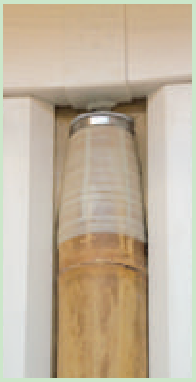
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Figure *10.4* shows a solution by Jörg Stamm, where the end of the cane was moulded into a conical shape and solidified with an epoxy mortar. A similar solution used by Christoph Tönges is seen in *10.6* and *10.7*, where the cone was internally filled with cement or epoxy mortar, and was externally wrapped with a mesh of fibreglass and epoxy resin for greater stability. Tönges wrapped the cone with steel wire (*10.9*).
The simplest solution for an articulated column joint, without using cones or special metallic elements, was realised by the author; see *10.8*. The ends of the canes rest in a recycled bucket filled with sand, which guarantees that if one of the canes transfers more load than another, it will penetrate further into the sand until all transfer the same force. In order to transfer large forces, one can unite various canes in a parallel manner; see *10.10*. More elegant is the solution shown in *10.11*, which is a column in the form of a fish belly, composed of curved and interconnected canes. Figure *10.12* shows the articulated joint developed by KOOLBamboo, USA, already mentioned in Chapter 9. To carry great loads, one can use a group of columns inclined in the manner of a hyperboloid in rotation. This form was used by Marcel Kalberer for his membrane roofs, see p. 68f., and by Jörg Stamm for his jewelry factory building in Indonesia, see p. 124f.


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Beams, Trusses and Porticos

Using a single cane as a beam is normally not adequate, since it is weak in bending, and supports only one line and not an area if there is no special support. For this reason, single canes are used as beams only in short spans or reduced loads. One simple solution to augment bending resistance is to place two or three canes one above another (*10.13*), and to connect them with inwardly inclining wooden pins (*10.14*).

To prevent the cane from opening or breaking, its support must be below a node; or better to fill the extremes of the cane with material that is resistant to compression, such as concrete. Another possibility for transferring forces at cane ends consists of making a conical termination with a threaded rod such as that used by Jörg Stamm for spatial structures (*10.15*).

To augment rigidity against bending, one can pre-tension the beams as seen in *10.16*, where the lower cane acts as a cable in tension. This was used by Andrés Bäppler for the design of a school in Cali, Colombia. Figure *10.17* shows fish belly beams used by Jörg Stamm for various projects.

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For heavy loads it is suitable to use trusses instead of beams as support; see *10.19* and *10.20*. Figure *10.18* shows a very efficient solution for bridges, developed by Jörg Stamm. A variant of a truss made by Francisco Lima can be seen in *10.21*, where the lower central element, which only works in tension, is substituted by a steel rod. The same idea was used for Simón Vélez's Nomadic Museum in Mexico City, shown in *10.23*. In so-called "portico" (frame) structures, where there is a rigid connection between column and beam or truss elements, the joint between them can transmit moment forces. The structure shown in *10.26* was designed by Simón Vélez; that in *10.27* by Markus Heinsdorff (see also p. 134ff.).

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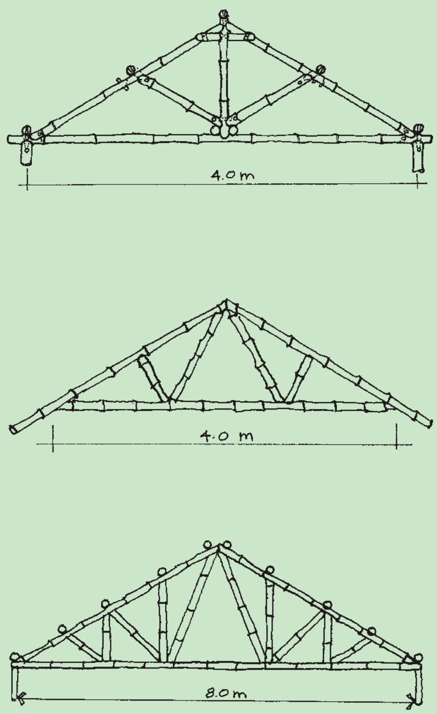

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Arches

It is very difficult to curve bamboo canes into the form of an arch. One simple method consists of using strips of open cane, one above another, joined with bands or pins. A solution by Marcelo Villegas is seen in *10.28* and *10.29*. During a training course directed by Jörg Stamm in India, a stable arch was constructed of six bent bamboo canes of 8 cm diameter of *Gigantochloa atroviolecia*. The arch was fixed only with wooden pins; in this case nuts are not needed, since the pins mutually jam themselves; see *10.31*.

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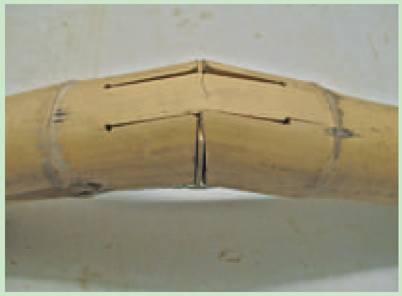

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In a research project directed by the author at the Building Research Laboratory (FEB) at the University of Kassel, Germany, different systems of bamboo arches were tested. One solution was to remove pieces of the lower parts in the form of wedges, at a determined distance, in a manner so that the upper part of the cane remains. Afterwards, the cane is given a polygonal shape, as is seen in *10.30* and *10.35*. Another solution consisted of joining strips of separated bamboo with pieces of canes with nodes, joined with POP rivets at the contact points; see *10.33* and *10.34*. Figure *10.35* shows three tested solutions, where one could verify that the arch with the strips of bamboo, screwed one above another, deformed with a load of 50 kg, while the arch that used the special detail shown in *10.30* supported a load of 500 kg without bending; see *10.32*. Figure *10.36* shows the application of arches using the lower extreme and part of the rhizome of a bamboo cane for a roof, designed by Simón Vélez.

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Floor Slabs and Roofs

A very common solution of using bamboo for the construction of floor slabs or roofs is to cover the openings between purlins or beams with bamboo planks (*10.37*). If the openings are larger, one can place fine bamboo canes (*10.38*) or bamboo strips vertically beside one another. Figure *10.39* shows the use of bamboo canes to support a traditional roof of palm tree leaves, and *10.40* a bamboo construction supporting a conventional tile roof. A solution for a roof that uses split canes is seen in *10.41* and *10.42*. This was used in the construction of a housing prototype built under the author's direction for the German Society for Technical Cooperation (GTZ) in Babahoyo, Ecuador. In *10.43* to *10.46* one sees the prefabrication of the elements: removing the diaphragms of the parted canes with a plane specially developed at the time for this use, submerging them in burnt car oil as a treatment against insects and mould, aligning and fixing them with an iron rod, and installing them in "tongue-and-groove" fashion.


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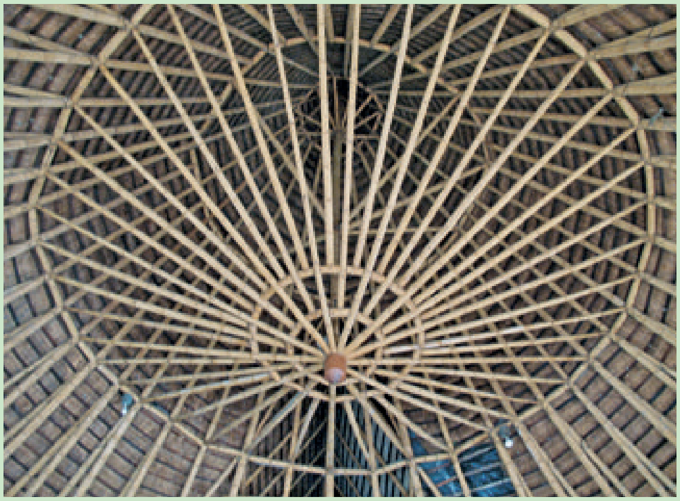
Figure *10.47* shows a pyramidal roof constructed by Marcelo Villegas. The conical spaces between the bamboo canes are filled with ribbed expanded metal and cement mortar. Another system of a pyramidal roof, designed by Clara Ángel, that does not need a central support is seen in *10.48*. Solutions realised by Simón Vélez are seen in *10.49* and *10.50*.

Figure *10.51* shows the roof of the Cañasgordas Club Kiosk in Cali, designed by Carlos Vergara. The centre is supported by a hanging column that receives simultaneous support by three levels of diagonals from all directions.

10.49

10.50



10.51


10.52


10.53


10.54

Walls

Light walls with a cane skeleton can be constructed with a covering of bamboo planks. These are used in warm humid climates, permitting cross-ventilation. Figure *10.52* shows the prefabrication of plank panels, which normally are plastered. Prefabricated woven panels for an interior wall, which cover the plumbing installations, are seen in *10.54*. Another system relying on woven bamboo is seen in *10.53.* Figure *10.55* shows an interior wall with a double curve, designed by Mónica Guerrero, formed by a network of bamboo canes of *Phyllostachys aurea* anchored with pins of guadua. This delimits a space, controlling the vision while allowing air to pass.


10.55

10.56

10.57

A network of bamboo with vertical canes and horizontal strips covered by a thick layer of earth is used in many countries of the world as a wattle-and-daub wall system (called "bareque" in Colombia, "quincha" in Peru and Chile, "bahareque" in Guatemala, and "pão a pique" in Brazil) (*10.56* to *10.60*). This system is normally filled with a mixture of earth, manure and fibres (*10.58*).

To make thick walls, a double layer of vertical canes is placed, covered with strips or planks on both sides (*10.59*). Figure *10.61* shows a solution developed by the author with stacked canes. One third of the section of each cane was cut out to prevent rain from reaching the inside.

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Vaults

10.63

A vault is a structure formed in a single curve (such as the addition of arches), which transfers compressive forces.
At the Building Research Laboratory (FEB) at the University of Kassel two systems of antiseismic vaults were developed between the years 1981 to 1983. The first was constructed with strips of *Guadua angustifolia* placed between two supports in the shape of a catenary. Perpendicular to these were placed guadua canes and on top other strips; the points where the elements crossed and touched each other were fixed with POP rivets (*10.62*). After this, the structure was inverted, forming an optimised structure for vaults without live loads (*10.63*). Afterwards it was stabilised by the ballast of a green roof (*10.64* and *10.65*).

10.64

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The other structure consists of arches of four strips of guadua in the form of a parabola. Above this were placed adobe elements in the form of a "U" fixed with clay mortar (*10.66* to *10.68*). This vault was tightened with an impermeable canvas on both sides, giving antiseismic resistance. The canvas functions as a structural element pre-stressing and stabilising the vault and at the same time as waterproofing for the roof (*10.69*).
The washroom building in La Selva, Spain, designed by Gabriel Barbeta and Esteve Navarrete (see p. 114f.) features a vault formed from a network of bamboo strips that function as formwork for a concrete roof.


10.67


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10.69

Domes

A dome is a structure with double curves in the same direction, which transfers predominantly compressive forces.

A geodesic dome that covers 20 m^2 and weighs 200 kg was constructed at the Building Research Laboratory (FEB). It supports a green roof with a thick layer of earth weighing a total of 12 tonnes, i.e. 60 times more than its own weight (*10.70* and *10.71*). Above the canes there is a semi-transparent membrane of a PVC-covered polyester fabric that functions both as waterproof covering and central skylight. This is pre-tensioned by a hanging column of guadua. The foundation shows an extremely simple solution: the ends of the canes rest in a recycled bucket filled with sand, guaranteeing that if one cane carries more force than another, it will penetrate further into the sand until all canes carry the same force (*10.70*).

In Japan, architect Hamura Shoei Yoh designed two geodesic bamboo domes for the mail office of the Asian Pacific Exposition in Fukuoka (*10.73* to *10.75*).

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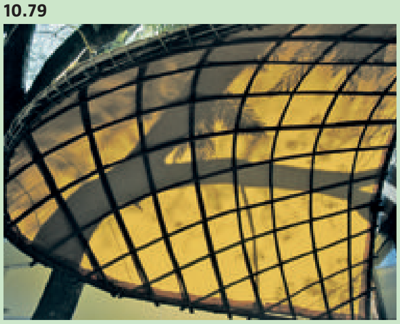
Grid domes constructed from a network of bamboo strips and covered with chickenwire mesh, which functions as formwork for a dome of stabilised clay mortar or concrete, were used in several built examples: a house in Cochahaira Village, Boyacá, Colombia, see p. 88f.; a Kindergarten and Community Centre in Naiju, Japan, see p. 101f.; and a jewelry factory building in Indonesia, see p. 124f.
The two domes of bamboo strips, covered with a membrane, seen in *10.76* to *10.81*, were constructed during a training course at Francisco Marroquín University, Guatemala, directed by the author. Figures *10.82* and *10.83* show a system devised to create domes that are stabilised only by the weight of, and the friction between, the canes. It was constructed by Ricardo de Leyva during a workshop in Candelaria, Colombia. Figure *10.84* shows a dome formed from a weave of bamboo strips. The project is described on p. 70f.

10.78

10.79

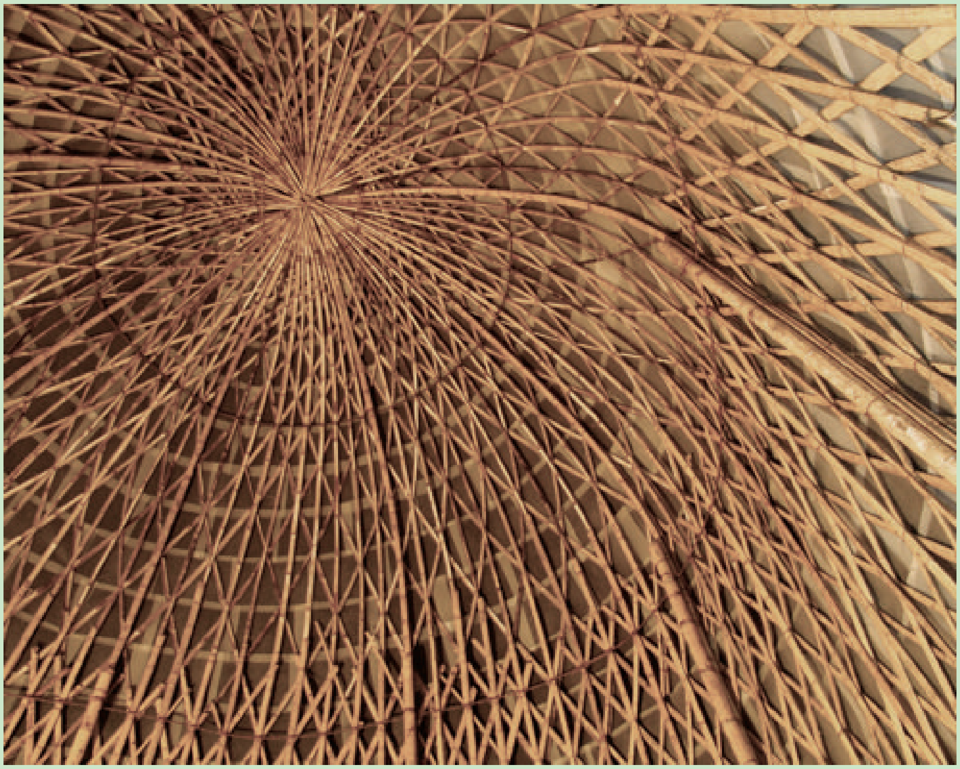


10.80

10.81

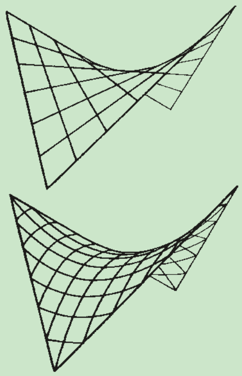
10.82

10.83



10.84

Hyperbolic Paraboloids



10.85

A hyperbolic paraboloid is a form with double curvature in different directions. All of the vertical sections are parabolas and all its horizontal sections are hyperbolas (*10.85*). As this illustration demonstrates, the curved area can be generated either with parabolas or with straight lines. Using straight constructive elements is easier, but structurally it is not ideal since the elements and the edges receive bending forces. It is more structurally effective to use curved elements in the form of parabolas. In this case, the hanging parabolas transfer tensile forces, and the standing parabolas carry compressive forces. The curved elements give an axial component to the straight edge, i.e., there is no bending force at the edge. Because of this, the solution requires much less constructive material than the alternative using straight elements.

Figures *10.86* and *10.87* show the roof of a chapel in San Miguel, Colombia, which was designed by Mónica Guerrero and Daniel Benevides. As the images demonstrate, the structure needs additional supports. Figures *10.88* and *10.89* show a roof that was constructed with students during a training course at Francisco Marroquín University, Guatemala, directed by Gernot Minke. The structure is formed of bamboo strips connected with rivets and fixed with cords to bamboo canes.

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Figures *10.90* to *10.93* show a roof composed of four hyperbolic paraboloids. The roof was designed by the author, and constructed during a training course in Candelaria, Colombia, directed jointly with Jörg Stamm with the help of Xavier Pino. The paraboloids were formed by a mesh of bamboo strips, fixed to each other and at the edges with screws, for which holes were previously drilled. Above this network three roof layers were installed, consisting of an impermeable membrane (a geotextile), 5 – 6 cm of substrate and a layer of local wild vegetation.

10.93

10.94

10.95

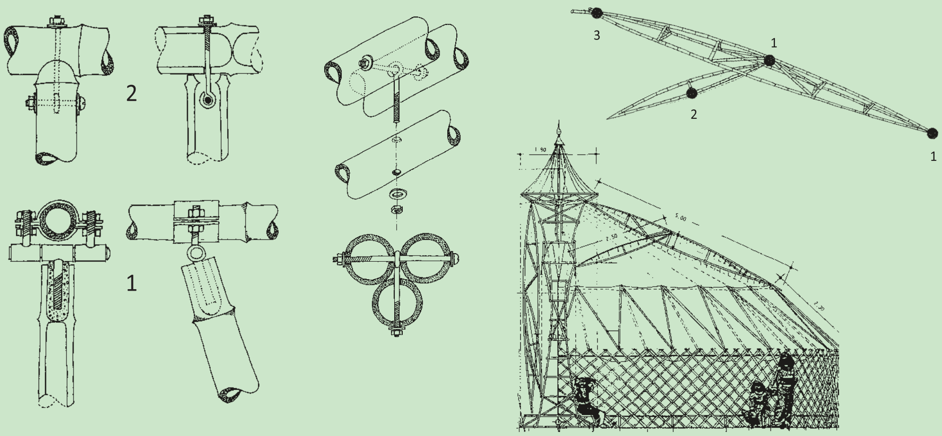
Bamboo-supported Membrane Roofs

The Swiss architect Marcel Kalberer has developed different membrane roofs. One of these is supported by bamboo columns, each one composed of five canes in a fish-belly form around a metal pipe; see *10.94* and *10.95*. Another of his designs is a folding-umbrella structure that covers a surface of 175 m^2; see *10.98* to *10.102*. Figure *10.101* shows the moveable joints. The membrane is tensioned to the floor with fixed cables or large metal keys. The walls were built of a bamboo cane mesh that can be extended or folded.
A similar roof, designed by Jörg Stamm, is seen in *10.96* and *10.97*.

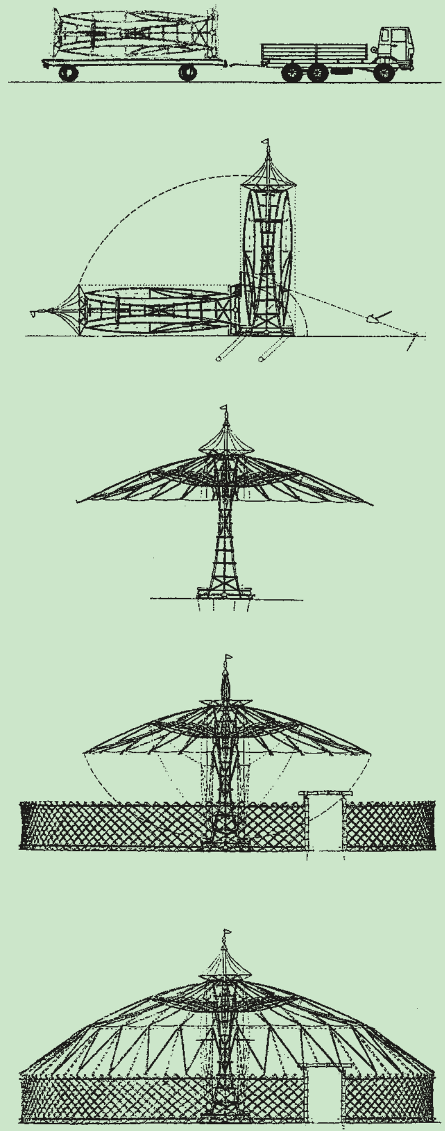
10.96

10.97

10.98



10.99



10.100

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10.103

The structure designed by Elkin Martínez and shown in *10.103* to *10.106* is a basket made with 3 – 8 cm bamboo strips, reinforced with eight guadua rods up to a height corresponding to 60% of the total height, which is 13.5 m. The diameter is 8 m. The basket was covered with a polycarbonate membrane.

10.104

10.105


10.106

11

Complementary Elements

Floors and False Ceilings

A simple and economical solution for floors is to use bamboo planks over bamboo canes (*11.1*); a typical view from below is shown in *11.2*. Figure *11.3* shows a planed surface of planks whose cracks were filled with a mixture of sawdust and synthetic glue with a polyvinyl acetate base (replaceable by linseed oil). After the glue has dried, it is treated with linseed oil and polished wax. The floor shown in *11.4* and *11.5* was designed by Luis Carlos Ríos and constructed of leftover bamboo cuts, with the spacings filled with cement mortar. Figures *11.6* to *11.8* display bamboo ceilings constructed for the Anthroposophical Cultural Centre and Church in Cali, Colombia (see p. 114f.); and *11.9* shows a ceiling from the residential ensemble in Carmen de Apicalá, Tolima, Colombia (see p. 92f.).

In the passenger areas of the new Terminal T4 of the Madrid-Barajas Airport, designed by Richard Rogers, there are thousands of square meters of ceiling made of laminated bamboo planks that have a width of 10 cm with joints of 5 cm that vary with the geometry. The bamboo planks were treated against fire (*11.10*).


11.1


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11.3


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11.10

Handrails, Balconies and Stairs

Images in this chapter show designs of secondary constructive elements. In *11.11*, *Phyllostachys* bamboo is used for balusters, with a special variation in the inclined form of its internodes. Figure *11.17* shows a very simple "Samba" stair. The stairway displayed in *11.18* was built for a kiosk in Colombia, designed by Simón Vélez. Figures *11.19* and *11.20* show the stairway designed for the "stepped house" in El Darién, Valle, Colombia (see p. 82f.).

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Doors and Windows

This chapter presents a variety of solutions for openings. The window and door frames are of bamboo canes, of woven or superimposed strips of bamboo, and of polished bamboo laminates. If the elements are exposed to weather, it is necessary to apply a finish that permits the bamboo to breathe. Figures *11.21*, *11.26* and *11.28* are constructions used for the residential ensemble in Carmen de Apicalá, Tolima, Colombia (see p. 92f.), and *11.23* shows windows with bamboo shades, as designed for the school in Rudrapur, Bangla Desh (see p. 106f.).

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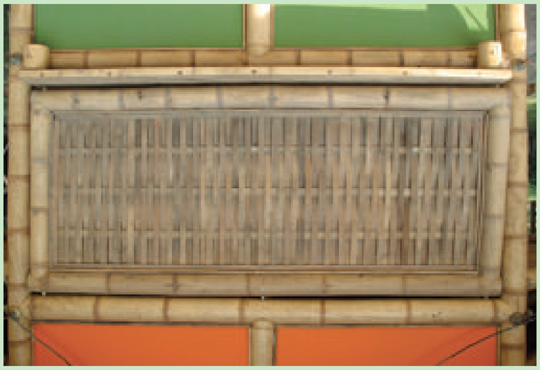
11.23


11.24


11.25

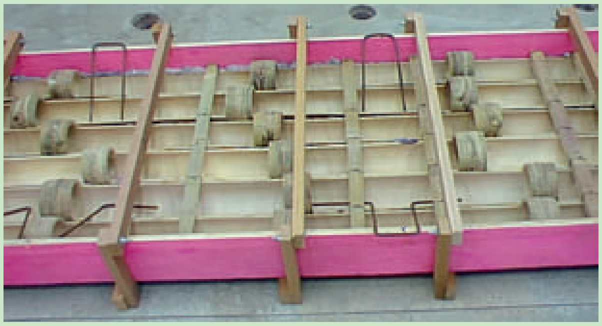

11.26


11.27


11.28

12

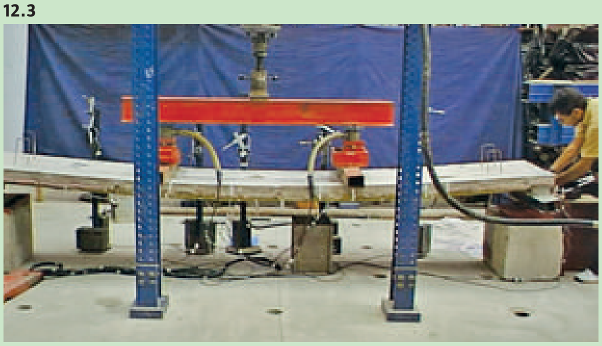
Reinforcing with Bamboo



12.1

12.2

12.3



12.4

Cement Mortar Reinforced with Bamboo Fibres

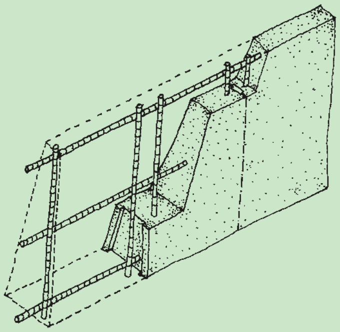
The lifespan of bamboo fibres in cement mortar is extremely limited, due to the fact that the cement's alkalinity destroys the pectin of the cellulose (Gram, 1983). In spite of this, bamboo fibres were successfully used in the fabrication of corrugated fibre cement tiles by the Intermediate Technology Development Group in England in the 1980s. In this case, the fibres only served to reduce both shrinkage and the appearance of cracks during the cement's curing phase. In Korea, bamboo fibres were used instead of asbestos in panels.

Concrete Elements Reinforced with Bamboo Canes

Using bamboo stalks instead of steel reinforcement in concrete is not usually successful. This is because there is not enough friction between the parts, given the bamboo's smooth surface. However, the use of twisted bamboo saplings as reinforcement in concrete has been more successful (Hidalgo, 1986).

At the Cologne University of Applied Sciences, Germany, research was conducted with concrete panels 20 m long and 0.70 m wide, with thicknesses of 8 – 14 cm, reinforced in the tensile zone with bamboo canes. To improve adherence between the concrete and the bamboo, the canes were submerged in a solution of sodium silicate (soluble glass), with a density of 1.15 kg/dm^3, for 15 minutes. The most favourable results were obtained with canes cut in half, offering more friction. Bamboo chips were also used to lighten the concrete. With 90% volume, a density of 0.91 kg/dm^3 and a compressive resistance of 1.7 MPa (N/mm^2) were obtained (Atrops and Härig, 1983).

At the Pontifical Catholic University of Rio de Janeiro, experiments were done by David Guzman under the guidance of Khosrow Ghavami to construct floor panels using bamboo (cut in half) in the tensile zone, and concrete in the compressive zone. Tests showed that if the diaphragms in the bamboo were not removed, resistance in the node improved, due to increased friction between the two elements (*12.1* to *12.4*).



12.5

12.6

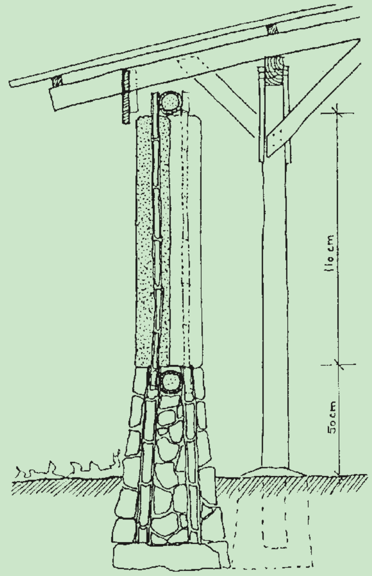
12.7

Walls Reinforced with Bamboo

In Chan Chan, Peru, the largest and most important pre-Colombian city (which had 50,000 inhabitants from 850–1425 A.D.), the royal residence and neighbourhoods were protected by tapered walls of adobe or rammed earth. These walls were 2.50 m wide at the base and 9 m high, reinforced with *Guadua angustifolia bamboo*. The wall elements had vertical expansion joints every 5 m, and were stabilised with bamboo canes, both vertically at the sides, and at three horizontal locations (Hidalgo, 2003); see *12.5*.

At the National Institute of Research and Normalisation of Housing (ININVI), Peru, researchers developed a system of adobe walls stabilised against earthquakes with bamboo canes that are placed vertically in the openings of the adobe blocks (*12.6* and *12.7*). Mortar is filled in around the stalks.

A system of bamboo-reinforced rammed clay was developed in 1978 by the Building Research Laboratory (FEB) at the University of Kassel, Germany, together with the Central American Centre for Studies in Appropriate Technology (CEMAT) in Guatemala. A stone footing is stabilised with a linked ring beam of bamboo, and this, in turn, is stabilised with two inclined bamboo legs. The vertical rammed clay elements are reinforced with four bamboo stalks that penetrate the lower bamboo link, then enter the upper bamboo link, attached with galvanised wire. The stalks were smoked for protection against insects and microorganisms; see *3.3*. The roof was supported on columns separated from the walls, so that they can move independently during earthquakes (*12.8*).



12.8

Another antiseismic house was developed in the same research project. The walls of this house were constructed of cotton sleeves filled with pumice. The cotton was soaked in a lime paste before placement, to deter the effects of microorganism attacks and ultraviolet rays. The bamboo canes, placed on either side of the wall, both stabilise it and give it flexibility for earthquake resistance.

In a prototype for the Landless Workers' Movement (MST), developed by the Building Research Laboratory (FEB) and constructed in São Leopoldo, Rio Grande do Sul, Brazil, bamboo canes were used to stabilise straw bale walls (*12.9* and *12.10*).

The wattle-and-daub system, where vertical bamboo canes and horizontal bamboo strips are covered with an earth paste, is mentioned in Chapter 10, "Walls".

12.9

12.10

II

Built examples

Architects
Opción Timagua
(Mónica Guerrero and Daniel Benavides)
Structural consultant
Luis Carlos Ríos
Completion
2009
Built area
295 m²
Total cost
60,000 USD

Stepped House in El Darién, Valle, Colombia

The five-storey house is located on a lot 12 m wide by 42 m deep, with a slope of 45 degrees. The structure rests on a two-storey base made of concrete and river-stone retaining walls, which bear a three-storey tower structure of *Guadua angustifolia*, in the shape of a pyramidal basket. In the tower, the principal corner columns are formed of three bamboo canes, between which there are secondary columns of one cane every 50 cm. The canes are joined by palm wood pins (*Bactris macana*). The floor slabs are composed of a structure of principal beams of three canes, secondary beams of two canes, and joists of one cane every 40 cm, which are closed off with bamboo planks as a base for a wood floor. The walls are lined on both sides with bamboo planks covered with mud, lime, fibres of fique (sisal fibres) and some cement. The roof of the vaulted tower is stabilised with inclined columns at its perimeter, and is composed of a cane weave and mats, covered by an asphalt membrane and paint.

Architects

Opción Timagua
(Juan Carlos Moreno and Mónica Guerrero, with Luis Carlos Ríos)

Structural calculations

Luis Carlos Ríos

Completion

2009

Covered area

197 m²

Colibrí House, Cali, Colombia

The house is composed of three modules joined with bridges. The first three-storey module contains the kitchen, dining room, main bedroom, living room and den; the second two-storey module three bedrooms and a bathroom; and the third two-storey module bathrooms and a terrace. The bamboo *Guadua angustifolia* is the principal element used in the construction of these modules (structure, walls and roof).

The first and second modules were each built with four porticos of 6 m span, supported on river-stone foundations. Each column is a bundle of 13 canes on the first floor, which converts into 9 canes on the second floor and 4 canes on the third floor. The roof structure is composed of trusses with struts of different height forming the curve of the roof. Above these lie purlins, on which a surface of bamboo planks of *Guadua angustifolia* is fixed, which is the base for a layer of earth stabilised with lime, fibres of fique (sisal fibres) and cement; on top is a coating of asphalt. Later this finish was covered with metallic shingles made from recycled printing plates. The eaves are fixed to the principal structure with diagonal canes.

The bamboo canes are joined with palm-wood pins (*Bactris macana*) and anchors of galvanised wire. The walls are of guadua planks fastened to a structure of secondary columns that occur approximately every 50 cm. The structural joints, most of the weather-exposed canes, and the walls were all covered with a mixture of earth stabilised with lime, fibres of fique (sisal fibres) and cement. The third module is stable due to its oval form constructed like a wattle-and-daub basket.

The floor of the open living room floor is formed with sections of canes left over from construction.

Architect
Jörg Stamm
Completion
2004
Covered area
approximately 120 m²

Guesthouse in Ubud, Bali, Indonesia

The building serves as a guesthouse. In the centre there is an oval of tamped earth that provides shelter for sleeping. The roof structure is that of a leaf, defined by a ridge and beams, all curved. These have a 12 cm diameter and are composed of approximately 100 parallel laths of 1 × 1 cm, wrapped with leather. The rafters are of a slim 6 cm diameter bamboo (*Gigantochloa apus*). The roof is of the "Alang Alang" type (typical straw roof in Indonesia).

Architect
Clara Ángel Ospina
Structural consultants
Claudia Villate, Gustavo Garzón, Julio Salamanca
Completion
2006
Useable area
150 m²
Total cost
45,000 USD

House in Cochahaira Village, Boyacá, Colombia

The house belongs to the facilities of an agro-ecological production and community development project sited on a 23,000 m^2 plot. Alternative technologies are applied: an artificial wetland for treatment of residual waters, garbage recycling, and solar energy for heating houses and hot water. Local materials were used for construction: clayey earth, sand, local woods, *iche* (wild grass), *arundo* (local bamboo) and stone.

The house has an ammonite form, with clay walls over a bamboo structure; the centre is covered with a dome, around which envelopes a vaulted structure of *Guadua angustifolia Kunth*.

The dome was constructed of a mesh of bamboo strips, and acts as a grid shell (see Chapter 10, "Domes"), and as lost formwork. It is covered with sisal fabric, plastic, chicken wire, stabilised earth and a bituminons roof paper. The vault was built with guadua arches, confined with *arundo*, and in the same way as the dome.

Architect
Pradeep Sachdeva
Structural calculations
Arvind Gupta
Completion
2009
Built area
approximately 120 m²

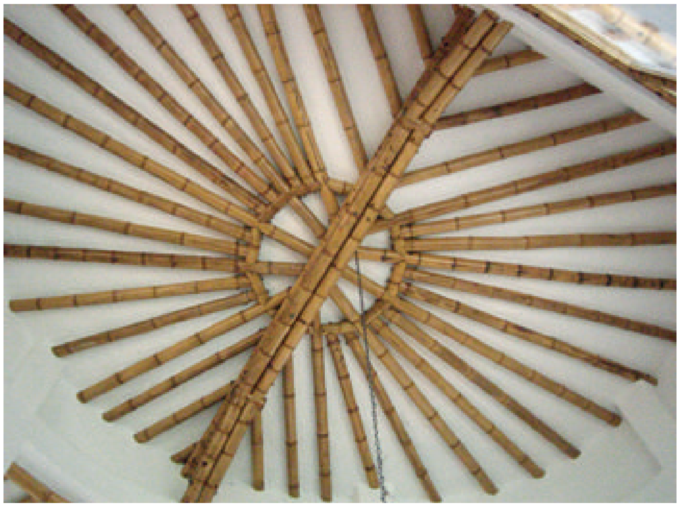
House in Sadhrana, Haryana, India

The house has a bamboo roof of *Bambusa balcoa* covered by a 30–35 mm layer of ferro-cement. For thermal insulation, the roof is covered with 30 cm of thatched straw. The walls are made of adobes (sun-dried brick).

Architect
Carolina Zuluaga
Structural calculations
Andrés Zuleta
Completion
2004
Developed area
14.6 ha
Built area of the houses
between 160 m^2 and 280 m^2

Residential Ensemble in Carmen de Apicalá, Tolima, Colombia

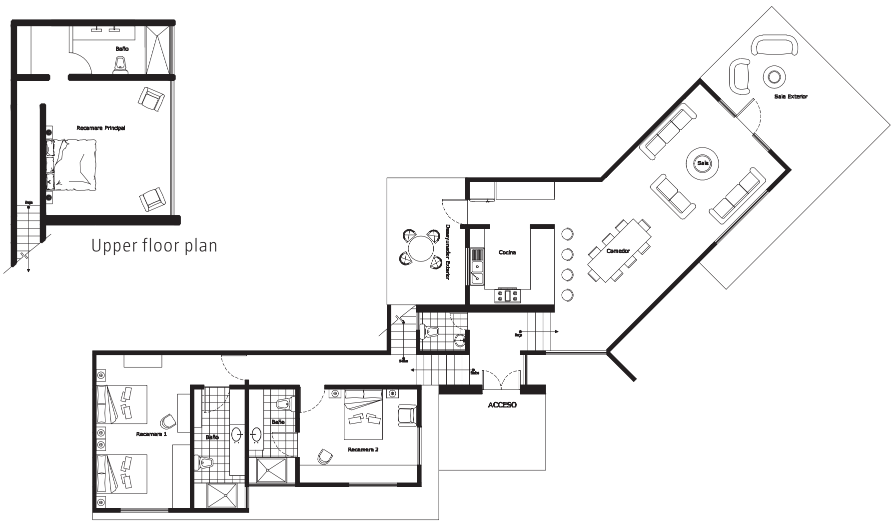
The residential development is located in a rural area 125 km from the city of Bogotá, with an average temperature of 32 degrees Celsius. The average 1,000 m² lots are for 96 individual houses of up to three storeys. *Guadua angustifolia* bamboo is used in the structure of the houses, and forms the walls, floor slabs and roofs, as well as their balconies, windows and doors.



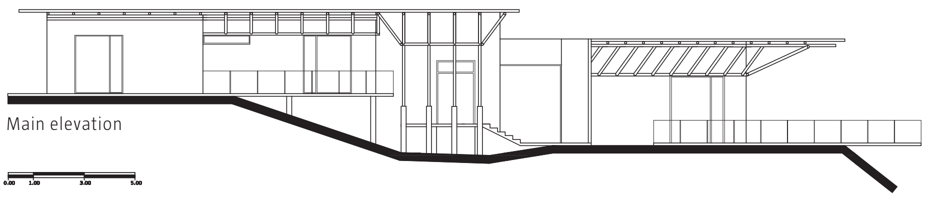
Architect
Ricardo Leyva Cervantes
Assistants
Mariana Lozano Pérez, Oscar Gonzáles
Completion
2008
Gross area
320 m²

Casa Cohuatichan, Cuetzalan, Mexico

This residence lies in a rural area at the edge of a tropical jungle in the Mexican state of Puebla. Its appearance is determined by the way in which it is inserted into the topographic situation. Three large terraces offer an expansive view over the unspoiled landscape. Through the use of natural stone walls, for the most part left exposed, plant-covered roofs and a bamboo roof construction, visible from both inside and outside, the building harmonises with its surroundings. The aesthetically interesting and intelligent structural construction of the roof made it possible to bridge relatively wide spans with only 10 cm thick bamboo profiles (*Guadua aculeata*). Rainwater collected via the roof and terraces is filtered and utilised as domestic process water.



Upper floor plan
Ground floor plan


Main elevation

Architect
David Sands
Floor area
varies

Prefabricated Bamboo Houses in Hawaii

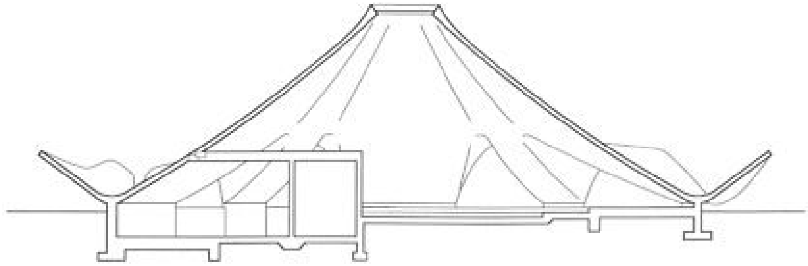
Since 1995, Bamboo Living, a Maui-based company has developed several house types that can be erected out of prefabricated bamboo elements in one to five days. Its co-founder and chief architect is David Sands.
The ZEN house type has a spacious open floor plan that can be individually subdivided with interior walls or extended with additional porches or extensions. The two-storey Bali House shown here has a floor area of 92 m² and additional porches.
The company also develops custom-designed solutions. The modular, prefabricated elements are normally delivered and erected by local contractors.

Architects
Carolina Quijano García and Diomar García Aldana
Structural calculation and consulting
Luis Carlos Ríos
Site supervision
Jörg Stamm
Completion
2001
Built area
approximately 1,000 m²

German School Child Day Care Centre, Cali, Colombia

The day care centre is built for four groups of children from two to five years of age. It is composed of various spaces with different functions: reception, games, resting, eating, bathing and administration. The structure is a skeleton of canes and planks of *Guadua angustifolia*, covered with a mixture of earth, lime, sisal fibres and some cement. Noteworthy is that all parts of the bamboo structure that are exposed to rain and UV light are covered by this kind of plaster.

Architect
Hamura Shoei Yoh
Structural calculations
Motosige Kusaba; Gengo Matsui
Completion
1995
Built area
233 m²



Kindergarten and Community Centre, Naiju, Japan

A network of *Phyllostachis bambusoides* bamboo strips arranged orthogonally was lifted at the centre by means of a temporary column, with the extremes fixed onto a curved foundation. This tensile network functioned as formwork for a reinforced concrete shell structure. Between the bamboo network and the concrete a 3 cm layer of polyurethane was placed as thermal insulation. After three weeks, the column was removed and the structure was converted into a shell, receiving forces of compression and bending. This was covered with a weatherproofing membrane.

Architect
Simón Hosie
Structural consultant
Herbert Ramírez
Completion
2002
Built area
350 m²
Total cost
175,000 USD

"La Casa del pueblo" Library in Inzá, Cauca, Colombia

The library has a bamboo structure of *Guadua angustifolia*, built of porticos with diagonals anchored by 12.5 mm metal rods, and concrete-filled internodes. The structure is covered with lightweight concrete and a straw roof (see Chapter 10, "Beams, Trusses and Porticos"). The porticos also support the mezzanine. The walls are of bamboo structure, filled with ribbed expanded metal and concrete mortar. The project won the Fernando Martínez Sanabria National Architectural Prize.

Architects

Anna Heringer, Eike Roswag

Structural consultant and calculations

Christoph Ziegert

Completion

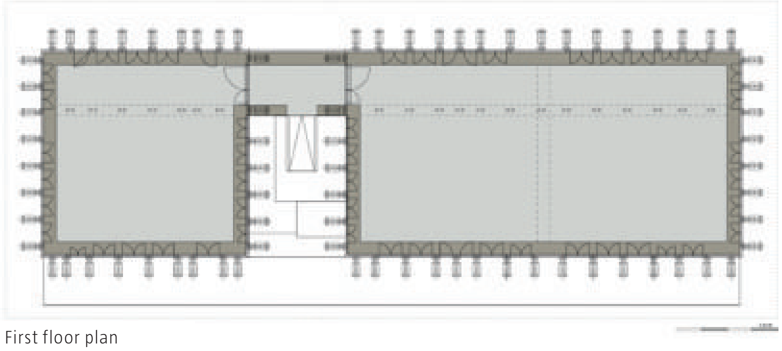
2006

Built area

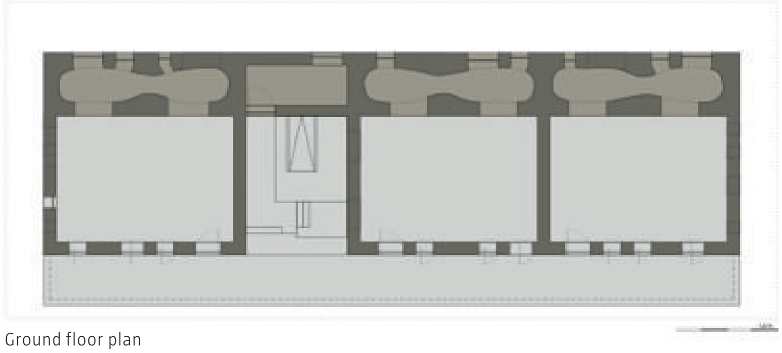
325 m²

School in Rudrapur, Bangla Desh

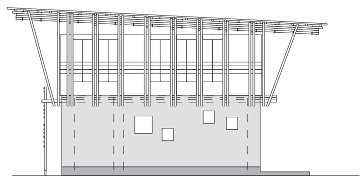
This is a self-build project using the local materials of mud and bamboo. On the first floor there are three classrooms connected by circular openings. The walls are of cob-style earth construction. The second floor is built of bamboo porticos, prefabricated on site. These porticos rest on the ends of the floor beams, which overhang the ring of the walls. The façade of the second floor is composed of windows with wooden frames lined with bamboo shutters. The building won the Aga-Khan Architectural Prize in 2004.



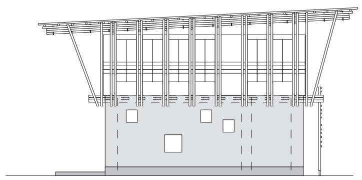
First floor plan



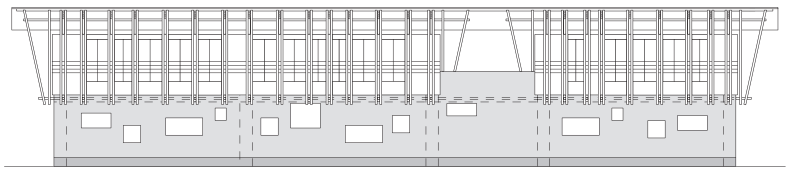
Ground floor plan



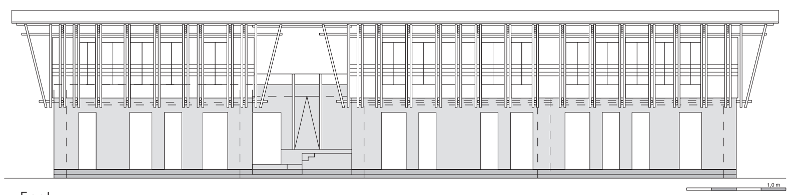
South



North



West



East






Architect
Fernando Orozco
Consultant
Luis Carlos Ríos
Structural calculations
Luis Carlos Ríos
Completion
2003
Built area
approximately 2,500 m²

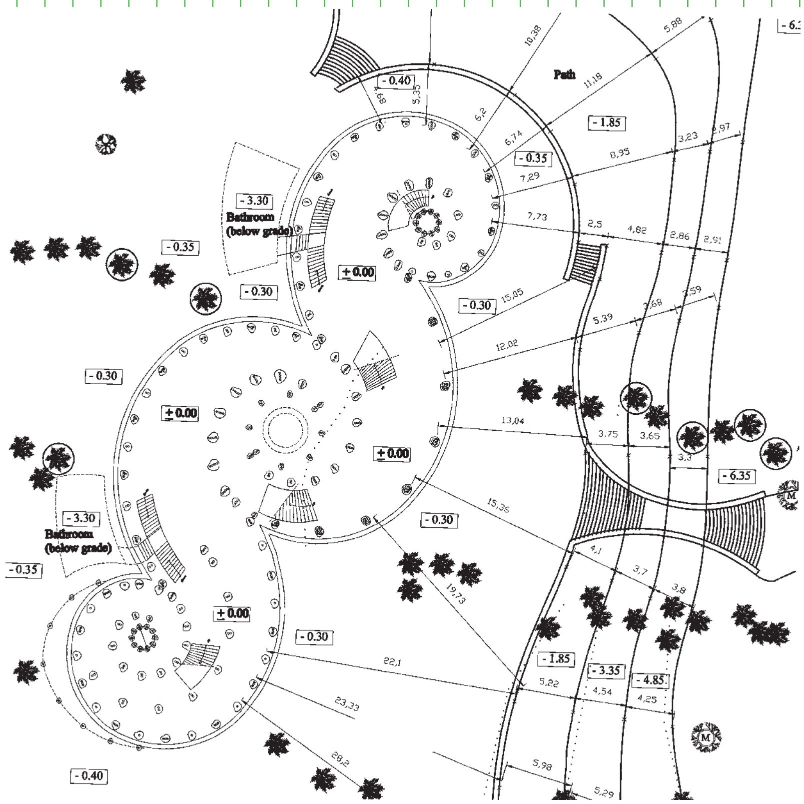
School in Popayán, Cauca, Colombia

The project is a rustic school for children with Down´s syndrome. The structure is a skeleton of rods with *Guadua angustifolia* bamboo mats that form a basket-weave, covered with a mix of earth, lime, sisal fibres and some cement or pozzolanic ash. The roof was built using the same material, adding a layer of earth, lime and acrylic paint.

Concept
John Hardy
Architects
Aldo Landwehr, PT Bambú
Bridge design
Jörg Stamm
Construction
PT Bambú
Completion
2008
Site area / Built area
4.55 ha / 4,350 m²

Green School in Sibajang Kaja Badung, Bali, Indonesia

The school ensemble is composed of different modules: access bridge, four classrooms, gymnasium, kitchen, kindergarten and principal building. The bridge has a span of 22 m and was designed by Jörg Stamm. All of the buildings are built with bamboo and have a straw roof adapted from the roofs of local traditional houses. The buildings do not have walls; they are open in order to allow cross-ventilation. The principal building has three storeys: the lower level is open; above, there are rooms for administration and teachers, a computer room and a children's art gallery. The structures were built with *Dendrocalamus asper* bamboo. The structure, floor slabs, floor surfaces, stairs, handrails and furniture were also built using bamboo. The large canes are *Dendrocalamus asper* with a diameter of up to 20 cm; the smaller are *Phyllostachys aurea* with a diameter of 2 cm.



Architects
Gabriel Barbeta, Esteve Navarrete
Completion
2008
Useable area
41 m²

Washrooms, La Selva, Spain

The half-buried vaulted building serves as bathrooms and showers for a camping area in Catalonia. A vault, acting as a grid shell, of 2 cm diameter bamboo canes was built as lost formwork, forming a 15 cm thick rhomboid mesh. Horizontal canes forming triangular meshes are fixed to stabilise this network. The connections were held in place with plastic wire. Two interlacing chicken wire meshes were anchored below the bamboo structure; these meshes were sprayed on both sides with a mixture of earth with sisal and coconut fibres, cut straw, sawdust and cement. A membrane of EPDM rubber was installed as weatherproofing. The structure is covered with a green roof.

Architect

Enrique José Castro

Structural calculations

Luis Carlos Ríos

Completion

2009

Built area

2,140 m²

Total cost

450 USD/m²

Anthroposophical Cultural Centre and Church, Cali, Colombia

The architectural ensemble is located in the urban zone of Cali. It is composed of two independent buildings: a church and a cultural centre of civil character. The cultural centre has rooms of different sizes, a kitchen and a library. The church has its vestry, a main room and a small meeting room. In both constructions *Guadua angustifolia* was used as a structural element as well as in the ceilings and railings. The basements of both buildings are used for parking.

The structure of the cultural centre consists of a concrete skeleton meeting the regulations of earthquake resistance, complemented with iron beams, joists of *Guadua angustifolia* on which were placed guadua planks, steel mesh and cement mortar. With this structurally mixed system, it was possible to reduce the weight of the floor slab, which represented a 30% saving in construction in comparison to a conventional system. The walls were constructed with a framework of vertical guadua canes, horizontally lined on both sides with bamboo planks and a plaster of earth with lime, sisal fibres and 10 – 15% cement. Some of the guadua posts were left visible, giving a spatial effect to the interior. Noteworthy is the design of the ceilings, vaulted with different bamboo frameworks, and the walls, with the sensitive use of pastel colours characteristic of the anthroposophical philosophy.

The church was constructed like a basket, completely of guadua, where 2,200 canes of 7 m were used with a framework of principal columns formed by bundels of four canes, and secondary columns every 50 cm that were covered with bamboo planks and the same plaster as used in the cultural centre. For safety, and to create a solid base, the lower 3 m were filled in with concrete. The roof was constructed over guadua trusses covered by bamboo planks, which in turn were covered with a layer of earth, lime, sisal fibres and some cement. The final cover is a bituminous roof paper with water-repellent paint. In the interior there is a false ceiling of bamboo for acoustic and aesthetic purposes. The space has a height of 13.50 m.

Architect
Simón Vélez
Completion
2002
Built area
700 m²

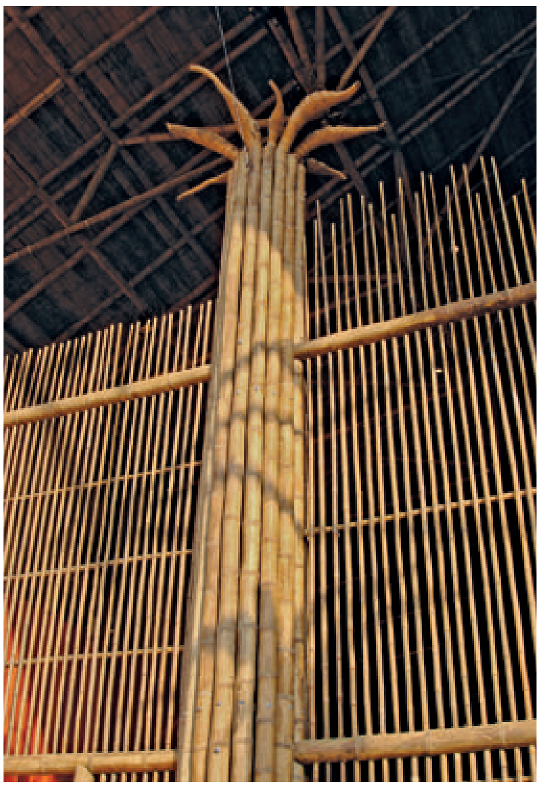
Temporary Church in Pereira, Risaralda, Colombia

After the earthquake in December 1999 in the city of Pereira, a temporary structure was constructed on the site of the collapsed church. It was made of curved canes of *Guadua angustifolia* bamboo. The façade was formed of a smaller-diameter bamboo weave. The walls and roof were made of a guadua structure with a covering of stretched metallic mesh and cement mortar. The church was 16 m wide and 35 m deep, and consisted of three naves; the central space had an 8 m span and was 11 m high. It took five weeks to build this structure.

Architect
Simón Vélez
Completion
2008
Floor area
5,130 m²

Nomadic Museum, Mexico City, Mexico

The museum, designed by Simón Vélez, was installed in the main square (the Zócalo) of the city, to house a photography exhibition. It was a temporary structure formed of waving walls and a roof of bamboo trusses (see Chapter 10, "Beams, Trusses and Porticos"). The wall canes rest on a serpentine metal pipe, which acts as a foundation and rests on top of a layer of sandbags.



Architect

Simón Hosie

Owner and executor

Odinsa Group

Structural engineering

Herbert Ramírez

Completion

2006

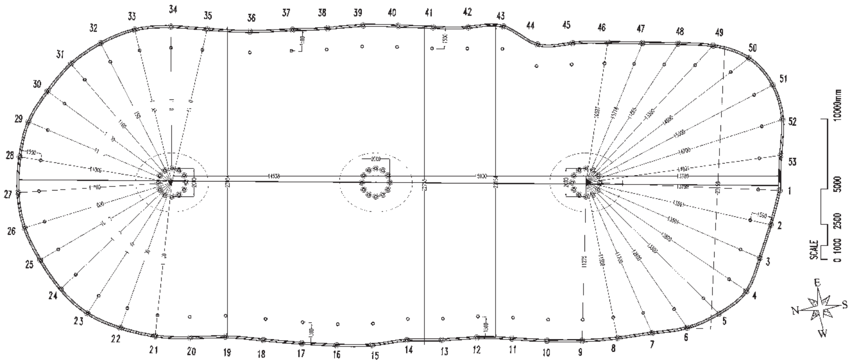
Built area

600 m²

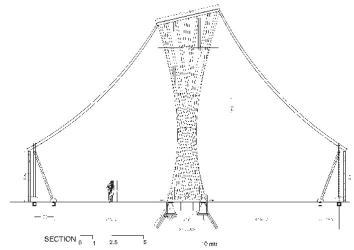
Tollgate, Pereira, Colombia

The tollgate has a bamboo roof of *Guadua angustifolia*, 26 m long with four support points. Each point divides the span into two sections: the outer span is 8 m and the main inner span is 18 m, below which the services and functional elements of the tollgate are housed. The anchorages are of steel, the internodes of guadua are not filled with concrete. The bamboo rods are protected with an impregnation against weather.

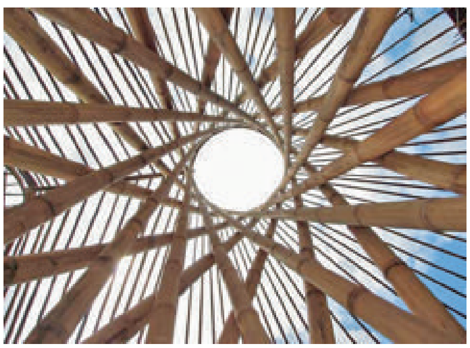
Architect and supervisor
Jörg Stamm
Structural calculations
F. T. Althoff
Completion
2007
Built area
approx. 1,700 m^2
Total cost
50,000 USD



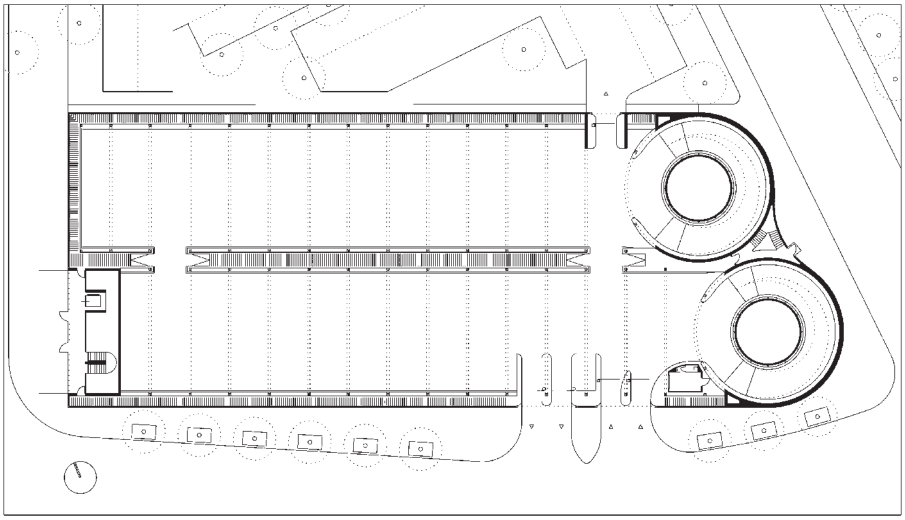
Jewellery Factory in Ubud, Bali, Indonesia



The 30 × 60 m roof was built to provide an ample and dignified workplace for 300 workers. The structure is supported by three 16 m high columns in the form of hyperbolic cylinders, with inclined-hoop ends. These were built of laminated bamboo strips, with a section of 15 × 15 cm, joined with epoxy resin and bamboo nails. The hoops are covered with glass, providing light and a space for natural ventilation. Between the three hoops there are two 10 m yokes. Below, there is a curved wall-plate, whose height varies between 4 m and 6 m and which is supported by columns in the form of a "V" that stabilise the exterior structural ring against horizontal forces from winds or earthquakes. The roof consists of 400 canes in tension, between 15 m and 20 m long, of *Dendrocalamus asper* bamboo, which are placed between the yokes and the wall-plate as crossed scissors, and are covered with "Alang Alang" straw, typical for straw roofs in Indonesia. The bamboo was immunised for three hours, in boiling water with 5% borax. The structure was built in four months.



Architect
Hentrich Petschnigg & Partner
(Gerd Heise)
Completion
2004



Multi-storey car park façade, Leipzig, Germany

The 4,000 m^2 façade of the three-storey parking structure is clad with 7,700 *Guadua angustifolia* bamboo canes, each 2.60 m long and imported from Colombia. It is an attractive façade whose vertical canes produce a visual barrier from the outside and furthermore guarantee sufficient light and air for the interior.

Architects

Susanne Körner, Tilman Schäberle

Completion

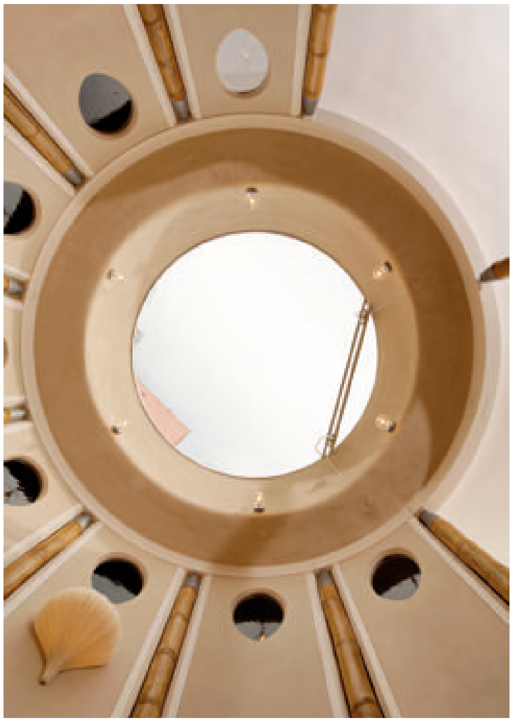
2005

Floor area

85 m²

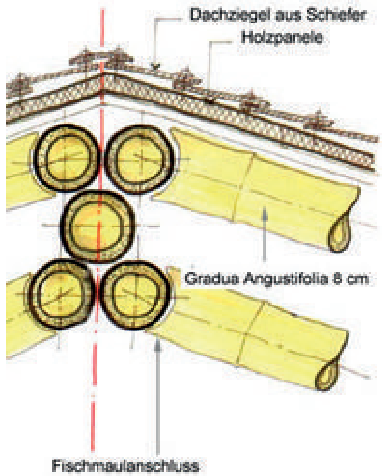
Office building, Darmstadt, Germany

The building, with its undulating perimeter walls, serves as an office for a car repair centre. The timber roof construction rests on 33 internally arranged bamboo columns (*Guadua angustifolia Kunth*). It is the first permanent building in Germany with a load-bearing bamboo construction, which is also part of the building's overall ecological concept. The walls are made of a timber skeleton framework filled with 36 cm thick, upright straw bales. The walls are rendered on the outside and plastered on the inside with a three-coat clay plaster, with an additional coat of mineral paint on the outside to protect it against rain and moisture.



Architects
"emissioni zero" under the direction of Valeria Chioretto and Neri Baulin
Completion
2003
Covered area
512 m²

Pavilion, Vergiate, Italy



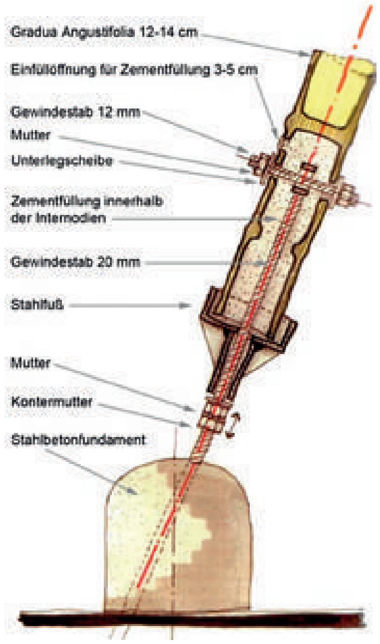
The pavilion stands in Ticino Park in the town of Vergiate, north of Milan, and is used for cultural events and workshops. The building was constructed under the direction of Valeria Chioretto and Neri Baulin from the organisation "emissioni zero" as part of a series of workshops. The pavilion consists of three sections: a central section that is 7 m high and two 1 m lower sections on either side. The roof covers a total area of 32 × 16 m.

The roof construction rests on splayed tripartite columns and consists of inclined twin-section trusses that are pin-joined at the ridge and cantilever at the eaves.

The trusses are connected at their bearing points by steel cables that sustain horizontal forces so that a structural truss frame construction results.

The V-shaped structure of the columns provides sufficient resistance to wind loads.

The 400 bamboo poles (*Guadua angustifolia*) required for the construction were imported from Colombia where they were pre-treated with a smoke-impregnation technique.






Architect

Simón Vélez, Marcelo Villegas

Structural consultant and calculations

Aicher, Lindermann, Steffens

Completion

2000

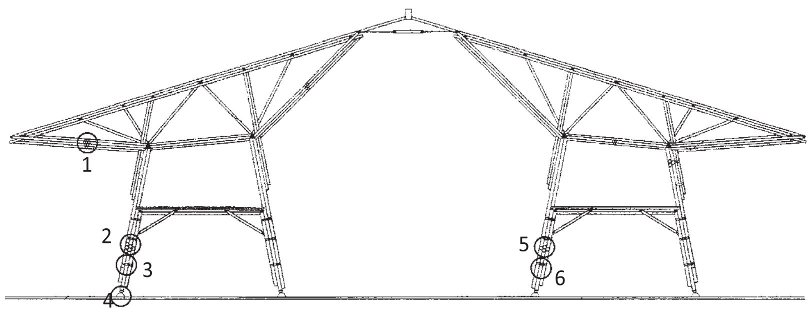
Built area

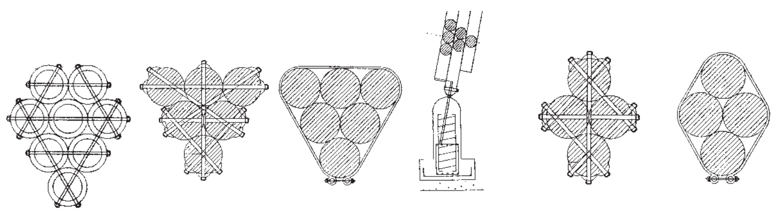
1,650 m², plus gallery of 500 m²

Zeri Pavilion, EXPO 2000, Hanover, Germany

In order to obtain the building permit for this pavilion, a 1:1 scale model was constructed in Manizales, Colombia, see p. 28. After conducting load tests in Manizales, and tests of rods and connections in the FMPA materials testing laboratory in Stuttgart, Germany, the license was approved.

The floor plan has 10 corners, a diameter of 40 m and eaves of 7 m. The columns have a height between 8 m and 14 m. On the second floor there is a 500 m² gallery. For this structure, 3,500 rods of *Guadua angustifolia* bamboo from Colombia were used, installed by 40 specialised workers from Colombia. The structure was assembled without cranes. The roof is covered with a metallic mesh of plaster, covered with 3 cm of cement mortar and cement tiles reinforced with bamboo fibres.





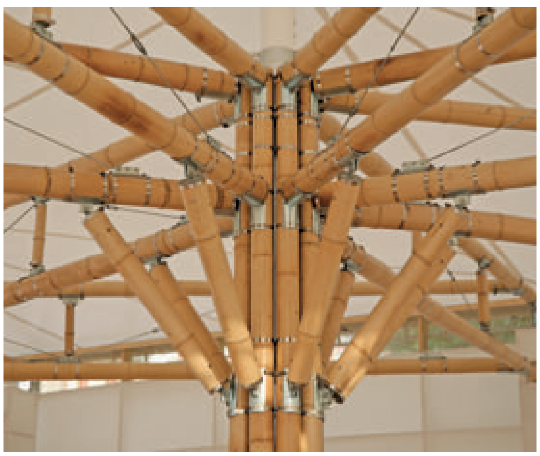
Architect
Markus Heinsdorff
Organisation and realisation
MUDI Architects, Shanghai
Completion
2007

Pavilions for the "German Esplanade", Chongquing, Guangzhou, Shenyang and Wuhan, China

The pavilions were developed by Markus Heinsdorff for the "German Esplanade", a three-year government-sponsored cultural initiative during which Germany presented itself as a modern, creative and future-oriented country in selected large cities in China under the overall theme "Cities in Motion". In 2008 and 2009 Heinsdorff presented an arrangement of different pavilions on city squares in Chongquing, Guangzhou, Shenjang and Wuhan. Each pavilion was composed of different elements that could be combined for different forms and spaces. They are dismountable after their use. The bamboo used is *Phyllostachys pubescens*, called "Mao bamboos" or "moso" in China. Most of the façades are transparent; others have double walls with an intermediate room where air circulation naturally occurs. The roofs are of white and semi-translucent membranes, fixed to steel rings.

The Navette and Lotus types of pavilion have stairways of two bamboo canes, 35 cm apart, diagonally tensed by steel cords. The same elements serve as trusses to support the roof. The membranes of the pavilion roofs are tightened by the centre column, which is composed of bamboo canes. This column can be raised to tension the membrane.
The façades have beams of laminated bamboo, horizontally curved where the gold- or silver-coloured metal weaves are fixed. Behind these are plastic, coloured or translucent membranes to enclose the pavilion space.
The central pavilion has columns in the form of a "V" in the wall, and beams in the form of a "V" in the roof, which are interconnected with a type of portico (see Chapter 10, "Beams, Trusses and Porticos"). More connections can be seen in Chapter 9, "Joints".


中国平安



Concept

Sanjay Prakash & Ass., Pradeep Sachdeva, Ass., Environmental Design Solutions, New Delhi; Integrated Design, Bangalore

Dome design

Pradeep Sachdeva, Simón Vélez

Structural design

Prem Krishna

Completion

2010

Built area

980 m²

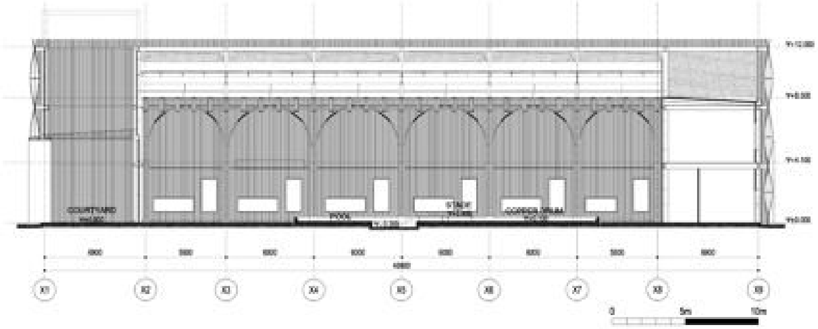
Indian Pavilion, EXPO 2010, Shanghai, China

The pavilion has a domed form, 35 m in diameter and 17 m high. The structure consists of 36 arches, each one formed with a triangular section of six bamboo canes, with secondary horizontal and vertical elements. This dome supports a micro-concrete shell; a membrane functions as moisture barrier. The dome is covered with earth containers with

different plants, forming an ornamental design with integrated copper plates, inspired by the "Tree of Life" jali. In the south there are also some photovoltaic cells. The plants are watered with grey water from the bathrooms.

The bamboo used is *Phyllostachys heterocyda pubescens* or *Phyllostachys edulis*, locally called "Moso" or "Mao Zhu". The canes were treated in a warm solution of boric acid and bleach and were bent while warm. The joints were fixed with metallic pins; the punctured internodes were filled with concrete.

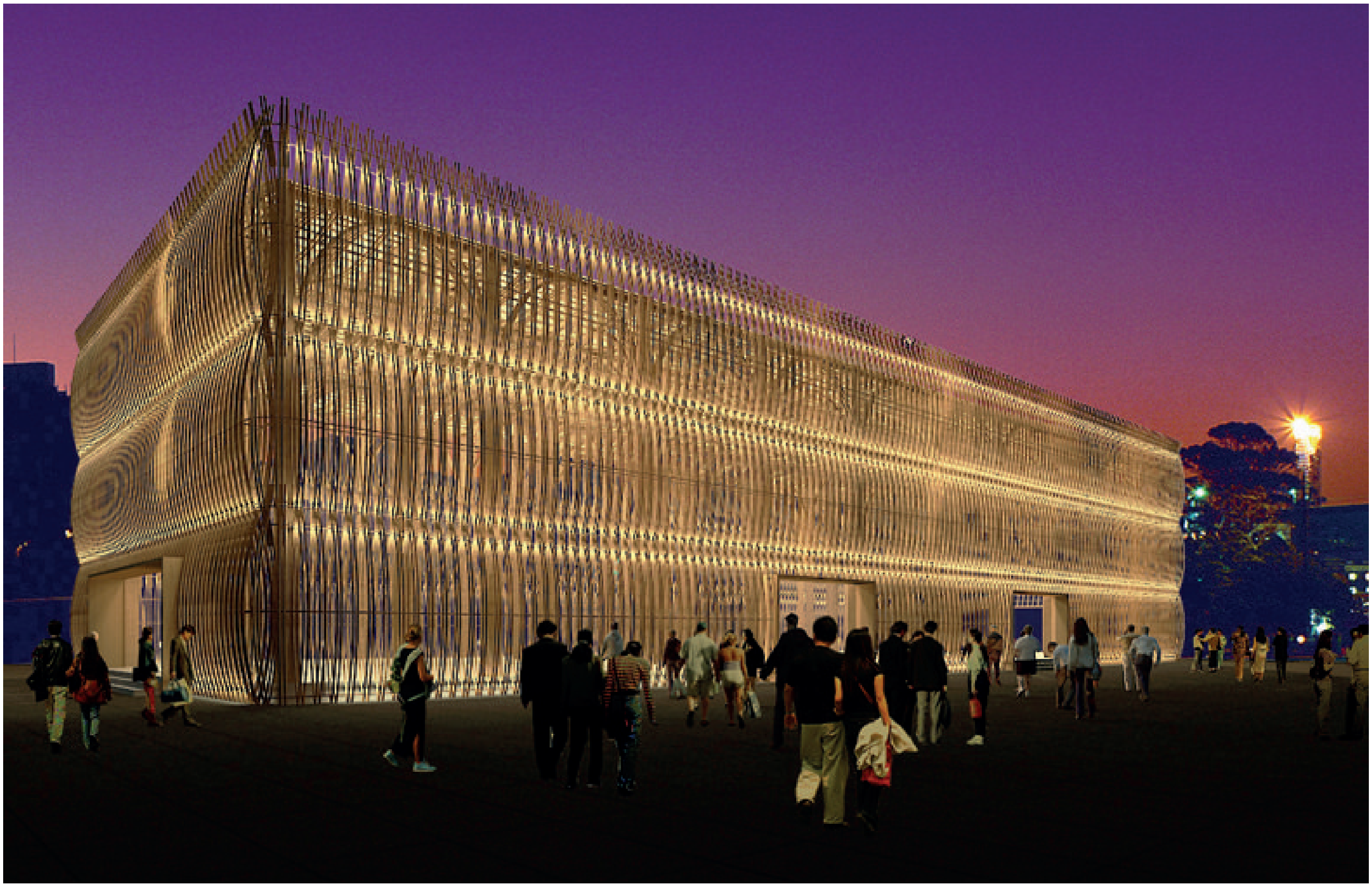


Architect
Vo Trong Nghia
Completion
2010
Floor area
1,000 m²

Vietnamese Pavilion, EXPO 2010, Shanghai, China

Bamboo was chosen as the building material for the pavilion for cost reasons and re-usability. For the external façade and the cladding of the interior courtyard, a total of 80,000 bamboo canes were used, each 12 m long. The canes are bent and bound together with rope.
In the interior the suspended ceilings and cladding of the columns are likewise made of bamboo. The decorative arched elements are formed out of individually bent bamboo poles that are bound together. The bamboo species *Bambusa Oldhamii* was sourced from Anji County in Zhejiang Province, a region of China that is famous for its bamboo plantations. Qualified workmen for manufacturing and erecting the building could not, however, be found in China, and the building was therefore constructed by specialists from Vietnam.



Architect

Markus Heinsdorff

Organisation and realisation

MUDI Architects, Shanghai

Structural planning

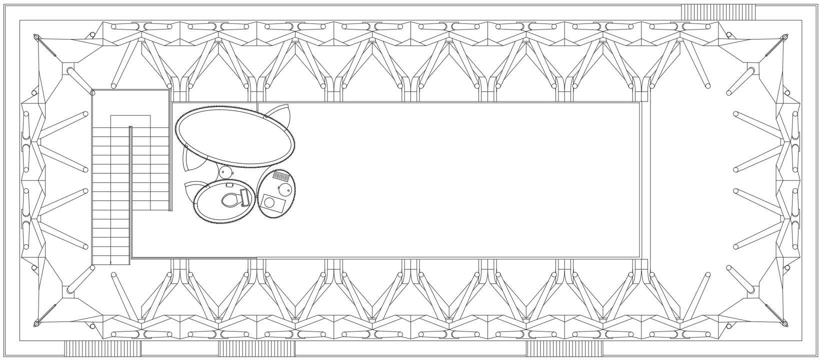
Chair for Timber Engineering and Wood Technology, TU Munich; Institute of Solid Construction and Institute of Materials and Mechanics in Civil Engineering, TU Darmstadt; Tongji University, Shanghai

Completion

2010

Floor area

330 m²



German-Chinese House, EXPO 2010, Shanghai, China

The two-storey, 8 m high building with a footprint measuring 25 × 10 m, contains an exhibition space and game and conference areas.

The roof construction is made of 8 m long poles of *Julong* bamboo from South China with a cross-section of up to 23 cm. Laminated bamboo frames support the floor of the upper storey. All structural bamboo elements have been treated with a fire prevention agent.

The stainless steel connecting pieces were developed especially for this pavilion and are designed so that the building can be easily disassembled after use. Threaded elements at the foot of the columns make it possible to accommodate tolerances.

The ends of the bamboo canes were first soaked with polyurethane resin and a further layer of polyurethane-resin-soaked grit to provide a good mechanical key. The ends were then filled with a concrete mixture made with a high proportion of fly ash, which ensures that the concrete adheres firmly and without pores or cavities to the inner surface of the hollow bamboo section. Steel connecting pieces set into the concrete allow the bamboo sections to be connected to one another.

The façade of the pavilion is covered with a light-permeable ETFE membrane covering, the roof with a PVC membrane. The furniture, also designed by Markus Heinsdorff especially for the pavilion, is made of laminated bamboo profiles.


德中同行之家

Architect
Werner Schmidt
Realisation
Students of Chur University of Applied Sciences
Completion
2004

Sculptures for MERAN FLORA 2004, Meran, Italy

For the MERAN FLORA 2004 exhibition, the Swiss architect Werner Schmidt designed three bamboo sculptures, built with students from the Chur University of Applied Sciences, in two training courses. The entrance structure has a height of 13.50 m and a maximum diameter of 8.50 m, and was made as a basket with bamboo of 2–4 cm diameter and 4.5 m long.
The bamboo canes of the "tensegrity" structure are between 8 cm and 12 cm diameter and 5 m long. They form a system of discontinuous compressive forces, stabilised by a continuous tensile system formed of iron cables. Both structures were prefabricated and transported by means of a helicopter. The third sculpture moves like a waterwheel.

Architect

Auwi Stübbe

Realisation

Students of Coburg University of Applied Sciences

Completion

2006

Covered area

300 m²

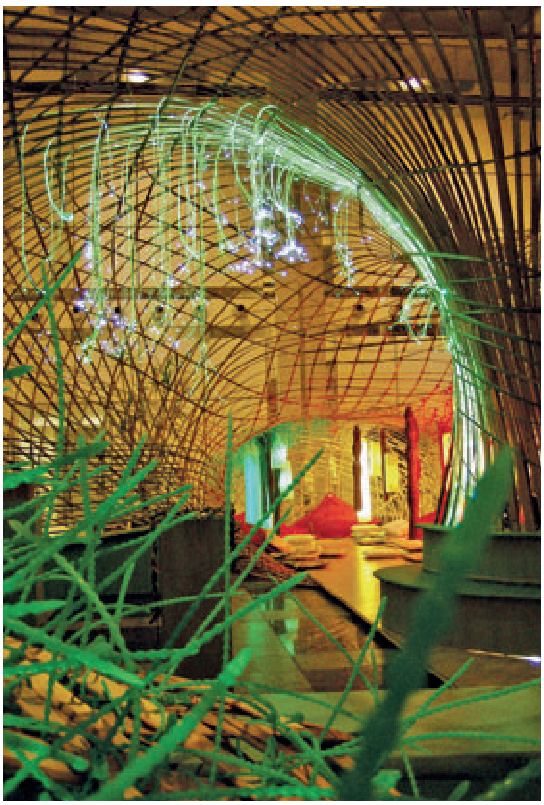
Restaurant roof, Coburg, Germany

Auwi Stübbe and his students at the Coburg University of Applied Sciences, Germany, built a roof with a network of bamboo laths for a "Design Fair" held by their university. Slats made of split bamboo with a length of 6 m form a triangular mesh structure. Where they meet at their ends, the slats overlap and are bound with wire, as are the intersections where the slats cross. The structure covers 300 m^2, has 13 km of laths and approximately 13,000 intersections.

Architect
Auwi Stübbe
Realisation
Students of Coburg University of Applied Sciences
Completion
2006
Covered area
140 m²

Exposition roof, Cologne, Germany

A roof over a rest space, consisting of the same construction as an earlier realised restaurant roof (see p. 146f.), was built by Auwi Stübbe and his students for the furniture exhibition "IMM Cologne 2006". The area has different braided furniture and illumination objects.



Completion
1989

Footbridge, Bietigheim-Bissingen, Germany

In China there is a long tradition of building bamboo bridges. For the 1989 state horticultural show of Baden-Württemberg in Germany, specialised workmen from China constructed a footbridge. The arches are of bamboo canes that vary in section according to the forces. Hanging from these is the floor of canes covered with bamboo planks.

Architects
Jörg Stamm, Juan Carlos Sanz
Structural calculations
Hermann Lehmann
Completion
2005
Total cost
40,000 USD

Footbridge, Santa Fe de Antioquia, Colombia

The bridge has a 30 m span and a free width of 3 m. It was built with 600 canes of *Guadua angustifolia* bamboo, with a section of 10 – 14 cm. This was calculated for a load of 500 kg/m^2, a wind force of 15 tonnes and a life span of 30 years.
Canes with natural curvature were selected for the arches. The compressive forces were transferred to a massive concrete foundation. The floor of the bridge is concrete; the roof has a covering of terracotta tiles. Assembly took three weeks.
The arched elements consist of five bent bamboo canes that are held together in a permanent curve with timber nails. A boiled linseed oil-based varnish mixed with a UV-blocker was used to protect the structure against the weather.

Architects
Jörg Stamm, Xavier Pino
Structural consultant
Gerardo Castro
Completion
2008
Built area
400 m²
Total cost
150,000 USD

Bridge in Cúcuta, Norte de Santander, Colombia

The construction is essentially the same as the one used for the bridge in Santa Fe de Antioquia. Both bridges have the same span and are built from *Guadua angustifolia* bamboo. In Cúcuta, a membrane roof was installed as protection against the weather. The bridge was calculated for a load of 500 kg/m² and a 30-year life span.

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About the Author

Gernot Minke has been lecturing for more than thirty-five years at the University of Kassel, Germany, where in 1974 he founded the Research Laboratory for Experimental Building (FEB – Forschungslabor für Experimentelles Bauen). Apart from bamboo constructions his expertise in the area of sustainable building techniques extends to building with earth, strawbales, low-energy and passive house constructions, and green roofs. He is also an independent architect and advisor for building ecology, and has been invited to more than 50 international conferences. Gernot Minke is the author of numerous books and has published more than 300 articles in journals and professional magazines. His previous volumes *Building with Straw* and *Building with Earth* were published by Birkhäuser as well.

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