Building with Bamboo

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BUILDING WITH BAMBOO

Design and Technology of a Sustainable Architecture

Third and revised edition

Birkhäuser
Basel

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II Built Examples

I

The Technology of Bamboo Building

1 The Material

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 4000 m above sea level. In China and Japan there are also species that can survive temperatures below zero degrees. Approximately 1200 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 Farrelly (1984), 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.
- *Bambusa 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: Philippines.

Guadua

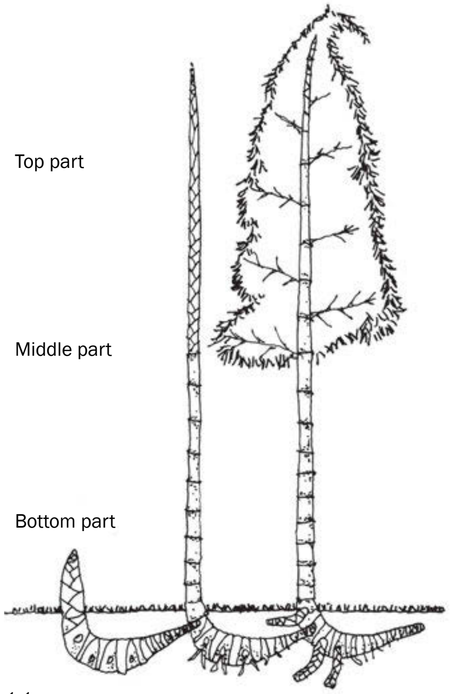
The guadua is a type endemic to South America. Its name was given by Karl Sigismund Kunth in 1822, who took it from the term "guadua" used by the indigenous peoples of Colombia and Ecuador. The forests of guadua are called "guaduales" (*2.4*).

- *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 bicolour 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.
  Origin: China, introduced into Japan and the United States.
- *Phyllostachys vivax*
  Height: 21 m. Diameter: 12 cm.
  Origin: China.



1.1

	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	Because of its diameter, it is the most marketable part of the upper stalk	15 m	4 m
	Elaboration of planks, slender columns and beams	Part of the stalk most used, for its diameter	11 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**	

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

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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 Bangladesh 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 thermal mass.

The ideal use of large bamboos like *Guadua angustifolia* depends on their age. In their first days, bamboo hearts are used as food; between six and 12 months, strips extracted from the external zone of the cane are ideal for making fabrics that can act as board-like components (*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). At the age of two years the canes can be used 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.

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 *(1.6* and *1.7)*. Bamboo strips of 1 × 1 cm arranged in parallel can be used as a structural beam. The example on pp. 78–79, Ubud Guesthouse, has beams of 12 cm in diameter, composed of approximately 100 laths secured with leather.

Another common use in regions where bamboo grows is for crafts and everyday objects *(1.8* to *1.11)*, musical instruments *(1.12* to *1.14* and *1.20)* and furniture *(1.15* to *1.17)*. New is the experimental use in vehicles like bicycles, cars and buses: figure *1.18* shows the design of a bamboo buggy by

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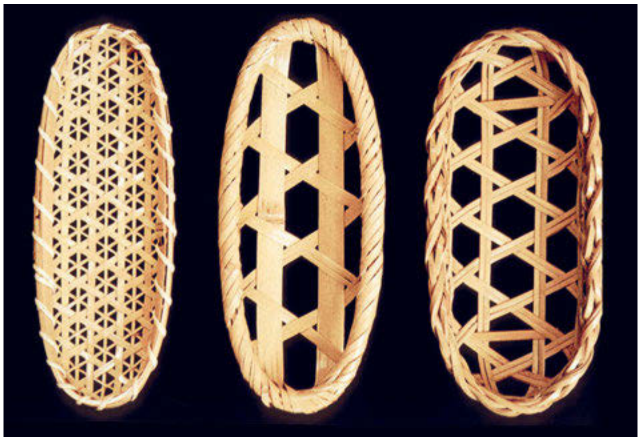

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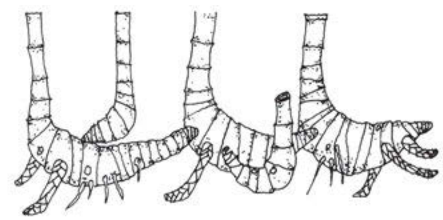
Jörg Stamm; Julio César Toro has designed and built a rural bus for 20 people *(1.19)*. To make the body, the floor and the railings, he used 40 linear metres of guadua and for the roof he used 63 small boards of macana. The bumper was made of laminates of guadua.

In the 1980s, China pioneered the industrial development of the use of bamboo in laminates (see Chapter 7, “Laminated Elements”). Fibres treated with a viscose process are being used in China similar to those of wood cellulose, resulting in a very resistant and smooth fabric.

The industrial production of paper using bamboo pulp was developed in India around 1910 (Hidalgo, 2003). 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). In a similar way, a thorough investigation into the various uses of bamboo was published by the Swiss Hans Spörry. During his travels in Japan between 1890 and 1896, Spörry collected bamboo items and catalogued them, thus gathering a collection of about 1500 bamboo objects. His 1903 book publication *Die Verwendung des Bambus in Japan* (The Use of Bamboo in Japan) lists 1048 uses of bamboo for Japan alone (Hebel, Heisel, 2017).

2 The Plant



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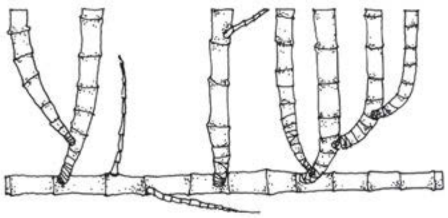

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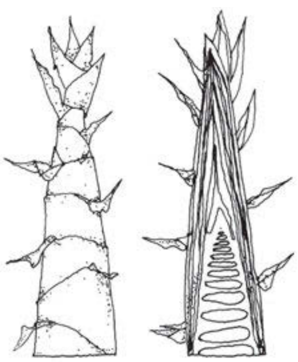

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The bamboo stalk grows directly from the rhizome (subterranean stalk). The rhizomes of pachymorphic bamboos grow in all directions, forming a three-dimensional network with a height of up to 2 m *(2.1).* The stems grow very close together, forming 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 1200 and 1350 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.

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 appropri-

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ate 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.

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

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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

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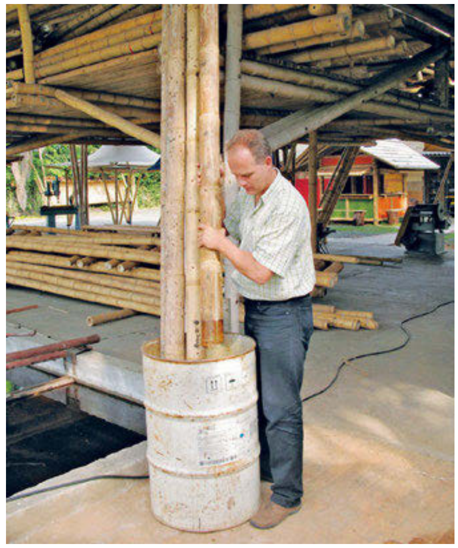

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left to dry further in a covered, well-ventilated space.

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.

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 Bangladesh 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).

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, “Earth 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 rec-

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ommended 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

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. Cheap-

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er 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 litres 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*.

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 litres of water:

- 3 litres of ammonium phosphate
- 3 litres of boric acid
- 1 litre of copper sulphate
- 5 litres of zinc chloride
- 3 litres 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

4.1

Introduction

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.

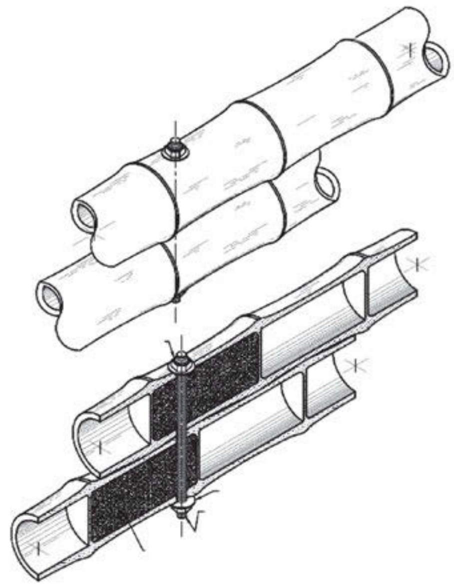
The perforations for the location of a bolt must be well-aligned with respect to its axis and have a diameter 1.5 mm greater than the diameter of the bolt. According to the Colombian regulation on the seismic strengthening of guadua constructions (NSR-10, see p. 28), the spacing between bolts must not 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:



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

A = Net area of the transverse section of the guadua in mm^2
D1 = Exterior diameter of the guadua in mm
t = Wall thickness of the guadua in 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).

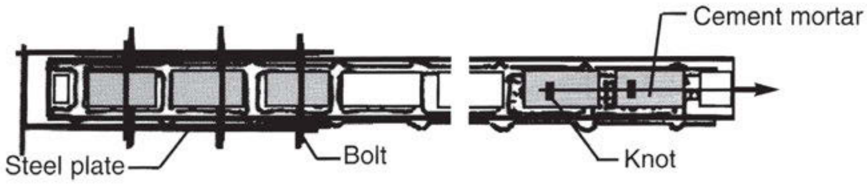
Resistance in Compression and Tension

A bamboo cane has a high resistance to tension, especially in its external layer. This layer bears up to 40 kN/cm^2 (= 400 N/mm^2 = 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 pp. 140–141); the experiments resulted in the following values:

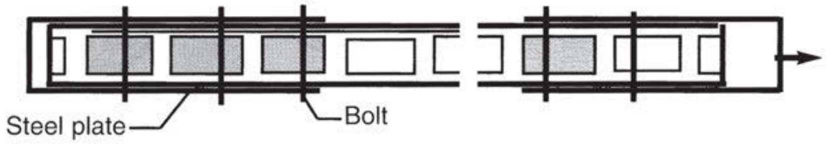
Compressive Resistance
ß_c, Lambda = 10 : 5.6 kN/cm^2
ß_c, Lambda = 56 : 3.9 kN/cm^2
ß_c, Lambda = 86 : 2.7 kN/cm^2
(Lambda = slenderness ratio)

Tensile Resistance
ß_t: 9.5 kN/cm^2

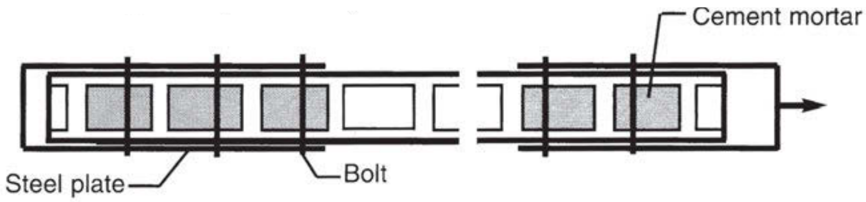
For bamboo canes of the *Guadua angustifolia* type, 10 cm in diameter and 3.50 m long with an internode thickness of 1.5 cm, as used for the ZERI Pavilion, the structural engineer Felix Weber calculated a strength of 70.4 kN (= 7040 tonnes); the base was the value from the FMPA test in Stuttgart. The 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/cm^2. The results of experiments by Garzón and Díaz (1996) testing the resistance of bamboo 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; 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



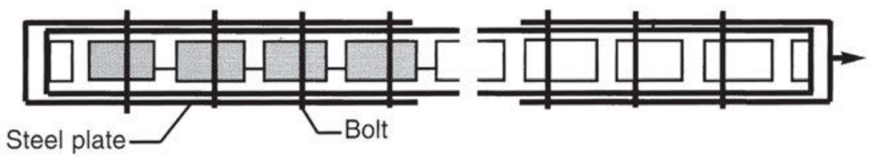
A. Test T.45 – A long bolt or bar of 19 mm diameter with nuts and two internodes with cement mortar.
Number of tests: 5
Failure: The cement mortar cylinders removed the internal nodes. There are cracks along two sides of the internodes.



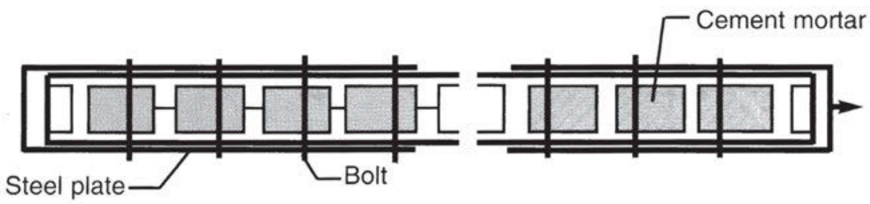
B. Test PP85 – Two internodes without cement mortar and two bolts of 19 mm diameter.
Number of tests: 3
Failure: By shear produced by the bolts on both sides.



C. Test PP80 – Two internodes with cement mortar and bolts of 12.7 mm diameter.
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 two sections.



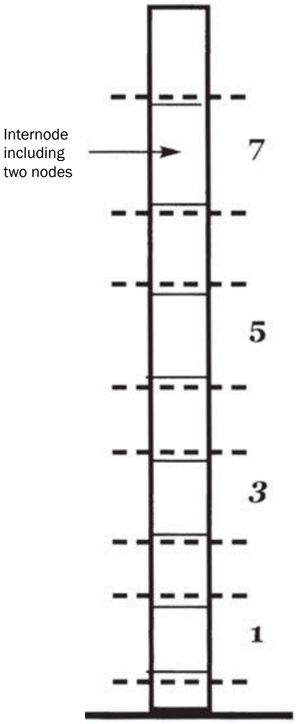
D. Test PP95 – Three internodes with bolts of 12.7 mm diameter, without mortar.
Number of tests: 3
Failure: By shear produced by the bolts on both sides.



E. Test PP90 – Three internodes with mortar and bolts of 12.7 mm diameter.
Number of tests: 6
Failure: By shear produced by the bolts on both sides. In some cases the cylinders were cut by the bolts longitudinally in two sections.

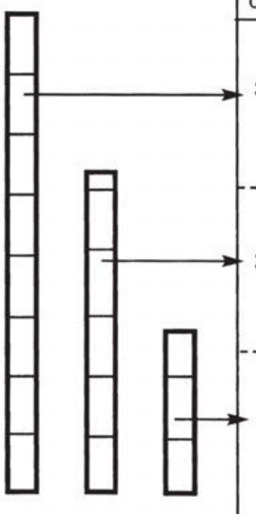
Rupture load (Kg)	Length section (m)	Exter. diamet. (cm)	Wall thickn. (cm)	Average Internode (cm)
4000	1.93	11	1.00	25
4200	1.96	11.5	1.75	25
4200	1.88	12.5	1.75	23
4250	1.75	10.5	2.00	20
4800	1.94	11.5	1.75	25
4000	2.03	10	1.00	27
3300	2.80	9.5	0.85	27
3500	2.50	10	1.00	36
7450	2.48	9.00	1.00	34
5800	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	3.02	9.5	1.25	26.8
3600	3.06	11	1.60	30
3100	2.99	10	1.00	33
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 Tensile resistance in bamboo joints



Species	Internodes of basal part	Modulus of elasticity Kg/cm2	Modulus of rupture Kg/cm2	Compres. strength Kg/cm2	Tensile strength Kg/cm2
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

4.5 Mechanical properties of various internodes of different bamboos



Length of culm sect.	Culm age (years)	Crushing strength Kg/cm2		Base Diam cm	Wall thick. cm	Number of nodes
3 metres	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 metres	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 metres	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

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

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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. Figures *4.7* and *4.8* illustrate the simulation of building loads using sandbags, here for a building by Simón Vélez.

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): 1840 kN/cm^2
E (bending): 1790 kN/cm^2
E (tension): 2070 kN/cm^2

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 1350–2770 kN/cm^2 (average 2150 kN/cm^2). 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, “Earth 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 2500 m^2 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 pp. 140–141), 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 pp. 150–155) 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 Multi-Storey Car Park Façade (pp. 130–131) and Office Building Darmstadt (pp. 132–133), or from Ecuador (see Chapter 10, "Vaults" and "Domes", in particular figure *10.70*). 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 can be seen in the Washroom Building in La Selva, Spain (*10.63*), in the Ubud Guesthouse (pp. 78–79), the Vietnamese Pavilion (pp. 152–153) and the Restaurant Roof Coburg (pp. 144–145).

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/m³ is required to manufacture a cubic metre of wooden profiles, while 1276 kWh/m³ is required for OSB panels (according to Hegger et al., 2006).

In the southeast of the USA and in Oregon and Washington, a series of small producers have planted bamboo plantations, although

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- 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".

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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.

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 parametres 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]

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 pp. 132–133), 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 pp. 130–131), 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

6.1

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.
- Cutting and transportation costs are relatively low.

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- 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

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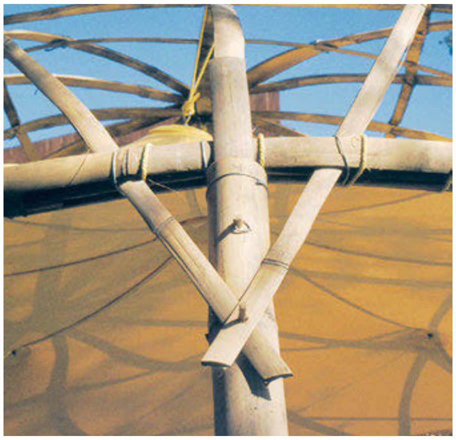
must be located in the upper or the lower external fibre.

- 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.*
- 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 *(6.11).*
- Cane endpoints must not be secured with screws or nails (stitches); see *6.12* and *6.13.*



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- Joints designed for contact must be exact. In *6.11* 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 *6.14.*
- A loaded beam must not bend excess ively; as a rule no more than 1/150 of its length; see *6.15.*
- 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 *6.16.*
- Figure *6.17* shows the connection of a bracket with a column that is not structurally optimal. Correct solutions are shown in *9.21* and *6.18,* where the force is transferred through one short piece at the column.
- Figure *6.19* 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.

7 Basic Construction Elements

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7.2

7.3

7.4

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.

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, and also as structural elements between beams or purlins in roofs *(*see *10.35* and *10.36).*

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 the Colibri House in Cali, see pp. 84–85. and figure *7.10.*

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 rectan-


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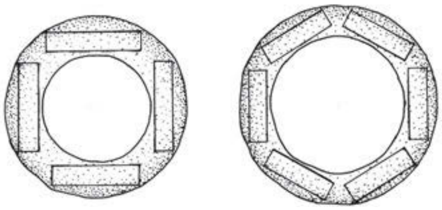
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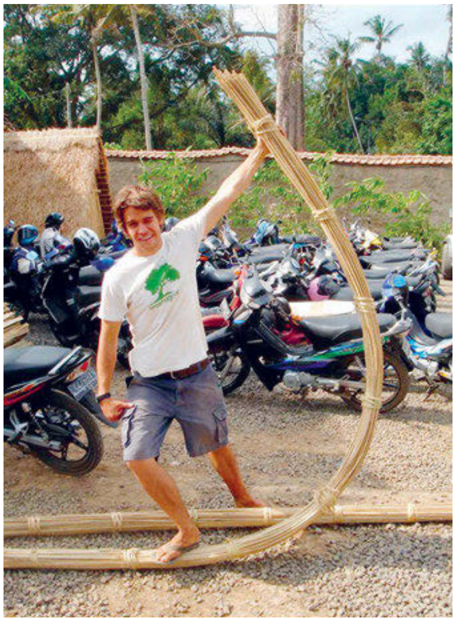
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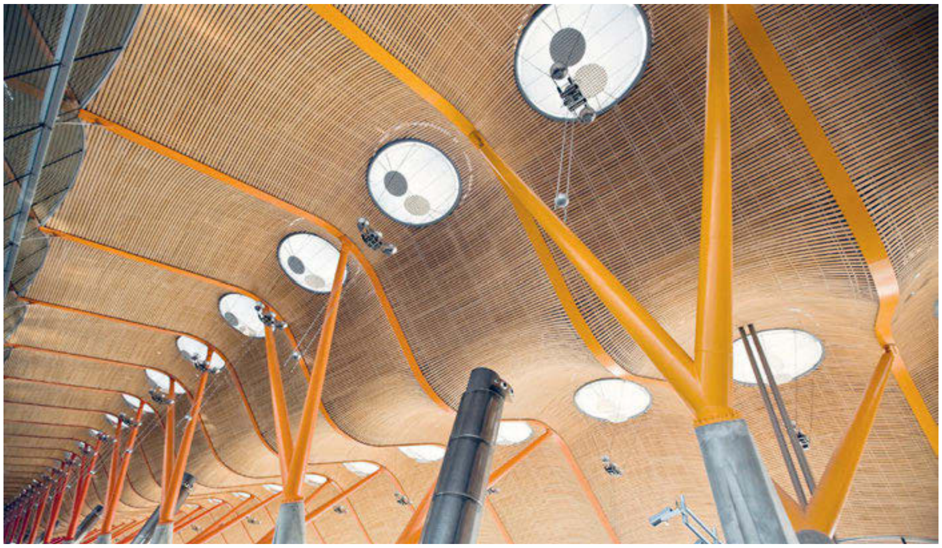

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gular sections are obtained *(7.11)* and joined *(7.14)*. One can also use planks, closing their cracks *(7.12)*.

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 1200 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)

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 (Rogers Stirk Harbour + Partners, 2005), 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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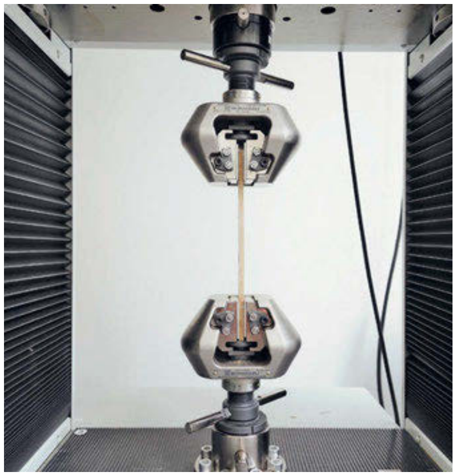

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Engineering Bamboo

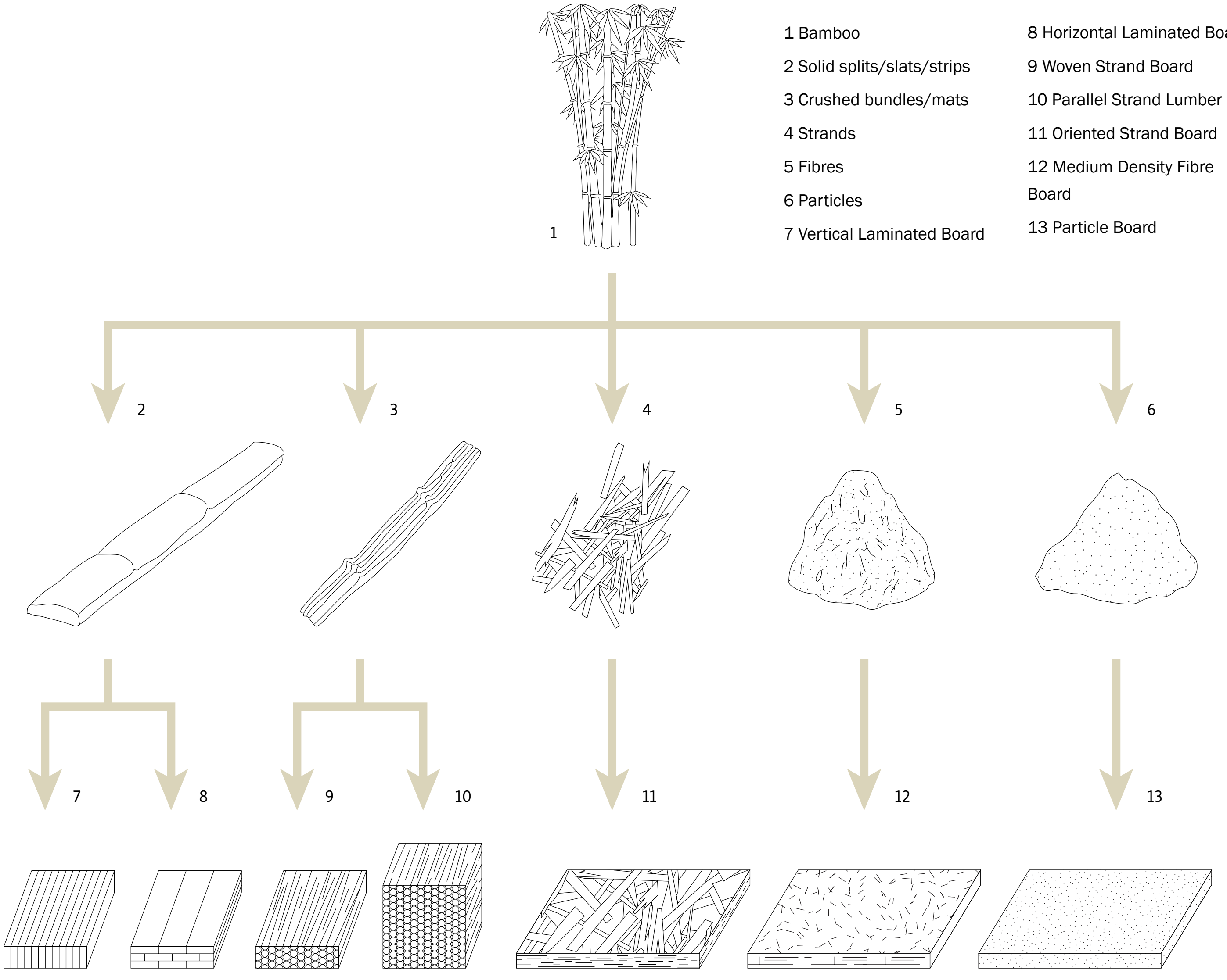
In recent years, several universities have heavily invested in research on the plant's potential, including ETH Zürich in Switzerland and its Future Cities Laboratory in Singapore (2012), the University of Cambridge in England, MIT, University of British Columbia and Karlsruhe Institute of Technology (KIT). As part of the research at the Future Cities Laboratory in Singapore and ETH Zürich, the development of a novel engineered bamboo material was explored. The aim was to produce a high-strength, formable, water-resistant, non-swelling, non-corrosive and durable biologically based composite material that benefits from bamboo's superior physical properties while mitigating its undesirable qualities. Fibre bundles are extracted from the natural bamboo culm and treated to achieve the desired properties before binding them back together. The characteristics and the form of the resulting composite can be manipulated. Figure *7.18* shows the bamboo composite material developed by the Advanced Fibre Composite Laboratory at the Future Cities Laboratory in Singapore. In *7.19* the composite material is subjected to a tension test.

Through such engineering, the biological bamboo material is being made suitable for an industrial production process. To this end, three aspects were investigated: treatment of the fibre, appropriate adhesives and a standardised production process. The treatment of the fibre (Hebel, Javadian, Heisel et al., 2014) is crucial to the success of the project. Only if the capacity of the fibre stays intact during extraction and composition, the naturally existing properties will be maintained. This is the most important difference from existing products in the market, which usually lose the inherent strength of the natural material as it is exposed to harmful treatment procedures. Tests on floorboards or kitchen tops of such kind, for example, show a dramatic decline of strength compared to the untreated bamboo material.

The second focus, the development of effective adhesives, investigates the behaviour of and interplay between organic and inorganic materials. The adhesive matrix controls factors such as water resistance, thermal expansion and refractability. The third aspect, the standardisation of the production process, is crucial also for production in developing countries in order to guarantee safety factors and certify the product as a building material (Hebel, Heisel, 2017).

Structural Bamboo Products

A way forwards might be engineered bamboo products. There has been an increasing interest in the development of bamboo-based industrially manufactured goods, known as Structural Bamboo Products (SBP). The technology from engineered wood products has been adapted to provide a range of bamboo materials. Most of these bamboo products originate from Asia and are known as Strand



1 Bamboo
2 Solid splits/slats/strips
3 Crushed bundles/mats
4 Strands
5 Fibres
6 Particles
7 Vertical Laminated Board
8 Horizontal Laminated Board
9 Woven Strand Board
10 Parallel Strand Lumber
11 Oriented Strand Board
12 Medium Density Fibre Board
13 Particle Board

7.24

Woven Bamboo (SWB), featuring densities over 1 kg/cm³. Figure *7.23* shows a Strand Woven Bamboo (SWB) product in section.
SWB is produced by compressing bamboo fibres under extreme heat and pressure, resulting in great strength and durability. After the bamboo has been harvested, it is cut, stripped down and shredded into bamboo fibre strands, before being woven together. Figures *7.20* to *7.22* show the production of Strand Woven Bamboo (SWB) in a small-scale facility in Southeast Asia. In *7.21*, the bamboo splits are dipped into an adhesive bath and in *7.22*, the bamboo bundle is subjected to high pressure in a large-scale press. This product is used in applications where otherwise plywood, Oriented Strand Board (OSB), Oriented Strand Lumber (OSL), and other glue-laminated composite wood products are employed, such as for interior flooring, wall cladding and roofing systems. Figure *7.24* shows the various extracted raw materials used for industrial bamboo products, ranging from strips to fibres to particles. All engineered bamboo products currently available on the market are produced in mostly labour-intensive, manual or half-automated processes. Driven mostly by outdated equipment that has been incrementally adjusted over time in order to react to developments in material processing, glue or press technology, the global bamboo industry today is facing its technical limits. A study undertaken by the laminated bamboo flooring and strand woven sector has shown that the majority of engineered bamboo manufacturers are using cold-press or discontinuous hot-press technologies with rather low production volumes, averaging 8000 m³ per year. New production technologies and optimised management of the material supply is needed for upscaling the bamboo industry to higher volumes and more industrialised processes. Compared to production volumes in the wood industry, a more widespread use of SBP is currently limited by a lack of efficient manufacturing yet an increase in production volume seems feasible (Böck, 2017).

8 Tools and Their Uses

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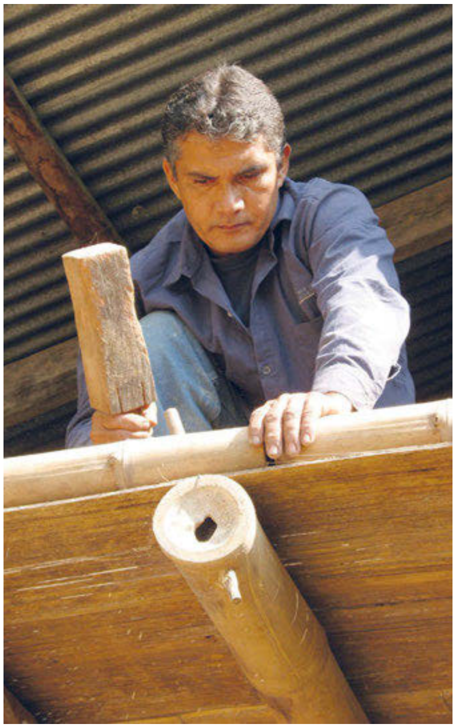
Given that the exterior layer of bamboo is very hard, one must cut it using saws meant for cutting metal *(8.1* and *8.2).* Saws for cutting wood quickly become blunt *(8.3).* Also, for the making of holes, one must use a drill *(8.4)* or hole saw. The best bits are those with a centred point *(8.9).* 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).*

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 centimetres into the cane, and then the cane is knocked vertically against a hard surface *(8.16).*

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 *(10.41).* To produce planks, axes are used to open the canes *(8.17).* To remove the remainder of the nodes, tools such as those seen in *8.18* are used.



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9 Joints

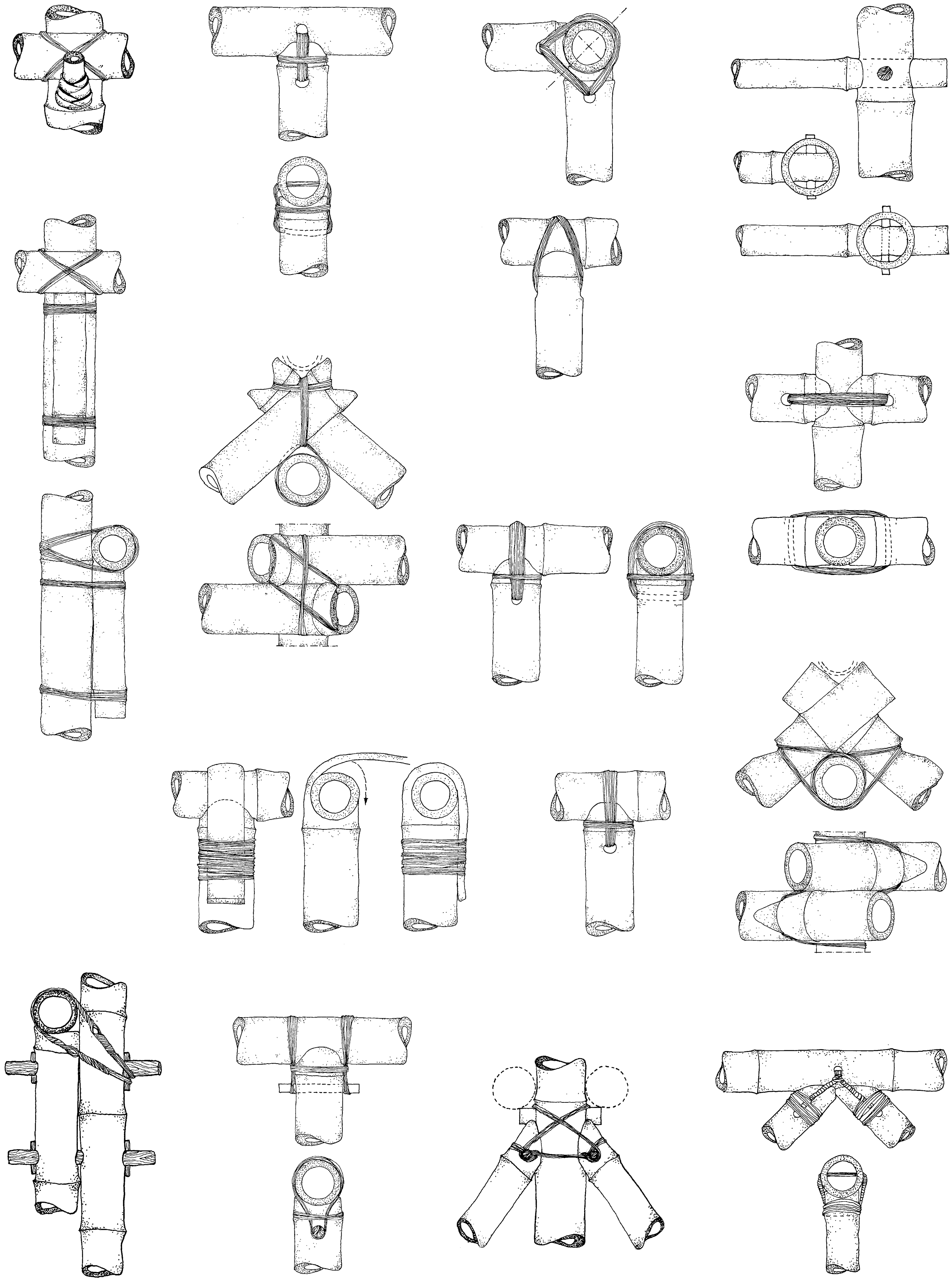
The most important aspect of bamboo construction is the formation of joints that transfer forces from one element to another. Given that canes have a hollow round section, and the parts between their nodes only have longitudinal fibres, canes cannot be joined in the same manner as wooden elements. For 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 designer 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 "muñeco" (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 *8.8.*

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



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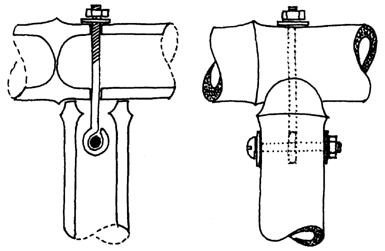

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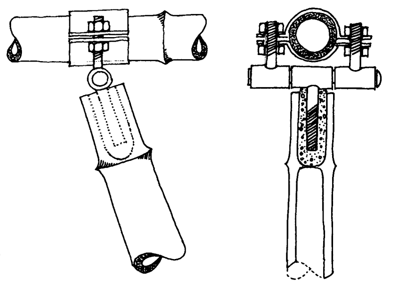

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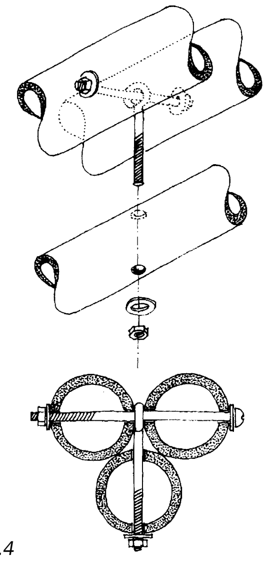

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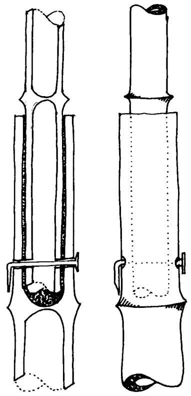

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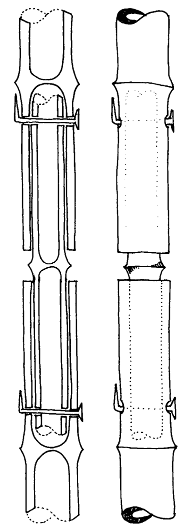

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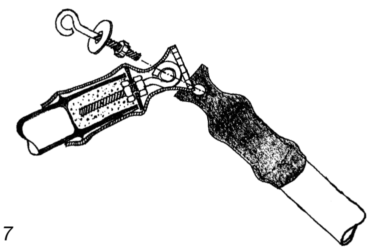

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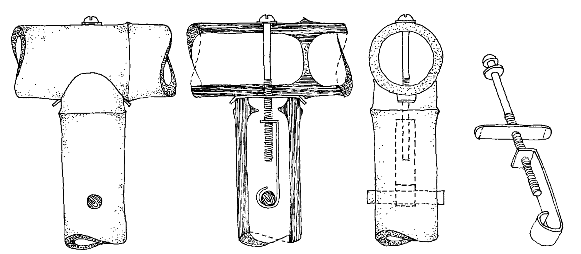

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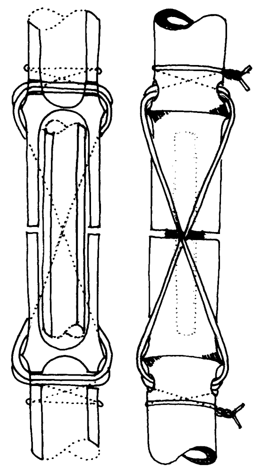

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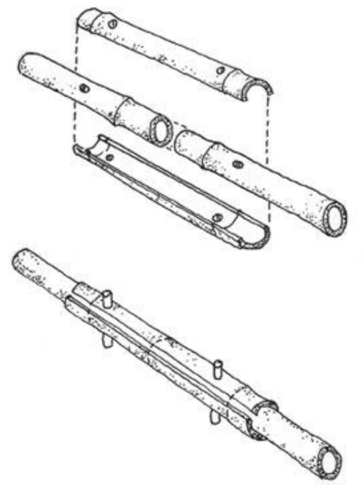

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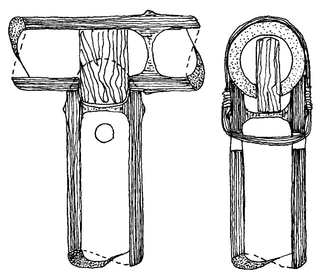

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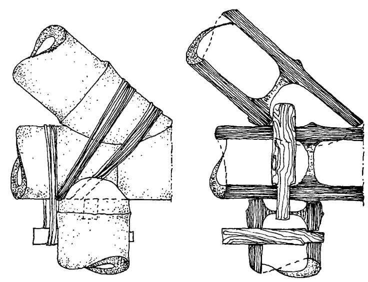

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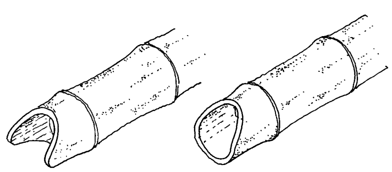

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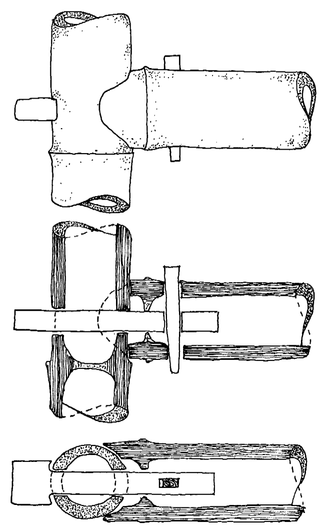

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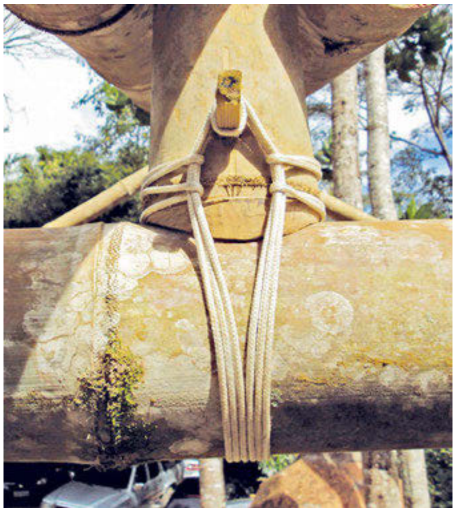

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is not recommended to use a mix of cement and sand in 1:2 proportion, as is mentioned in some literature. The contraction can be reduced using a mixture of 1 part cement for 3 or 4 parts coarse sand and gravel up to 4 mm in diameter. When perforating 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.

In order to provide an equal distribution of pressure from screw to cane, Marcelo Villegas has developed different metal connectors *(9.28* and *9.29).* A simpler solution to distribute the pressure to the cane is seen in *9.30*. Instead of using a flute tip end, Marcelo Villegas has developed a specific metal element; see *9.31.* More adequate seems to be the development of connections made of rubber, which facilitate good contact over th whole area, without having to insert “fish mouth” cuts at the ends of the canes *(9.32* and *9.33);* this design 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 *9.34* and *9.35.* Jörg Stamm used the MERO node for three-dimensional structures, with conical endings in the canes *(9.36).*

For the mail office at the Asian Pacific Exposition in Fukuoka in 1989, Hamura Shoei Yoh developed a simpler solution with metal tubes inside the canes; see *9.37, 10.74* and *10.75*. A similar solution was used by the author for a column *(9.38)* and by Vitor Marçal from Brazil (projetobambu) for spatial joints *(9.39* and *9.40).* His solutions for joints are


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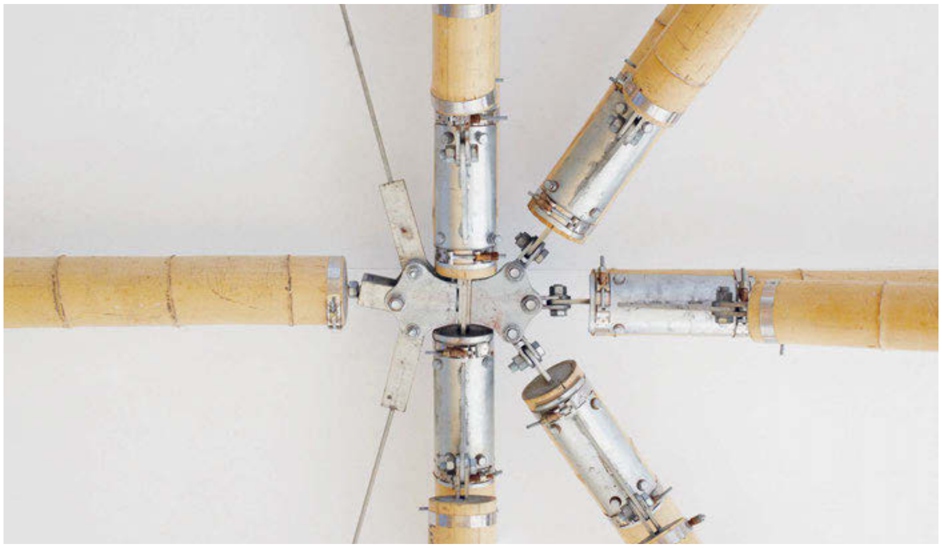
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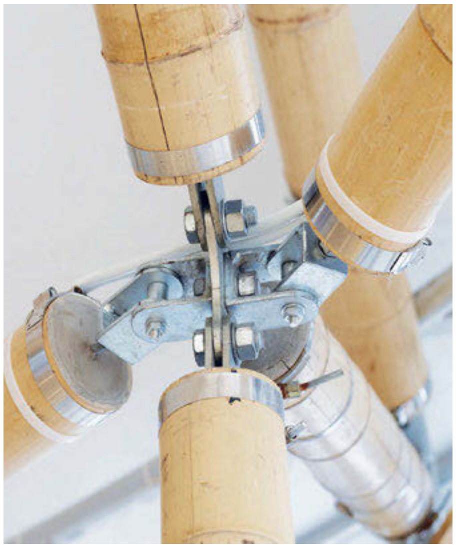
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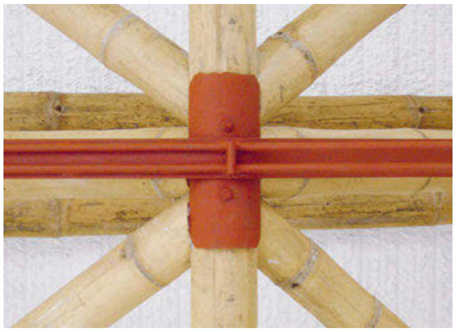
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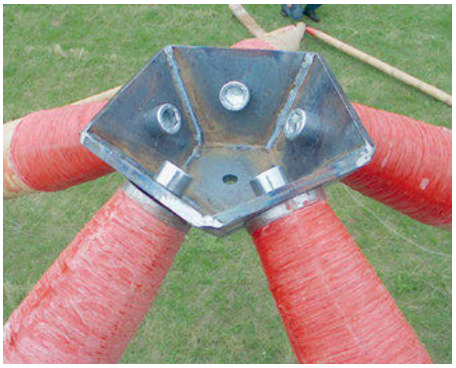

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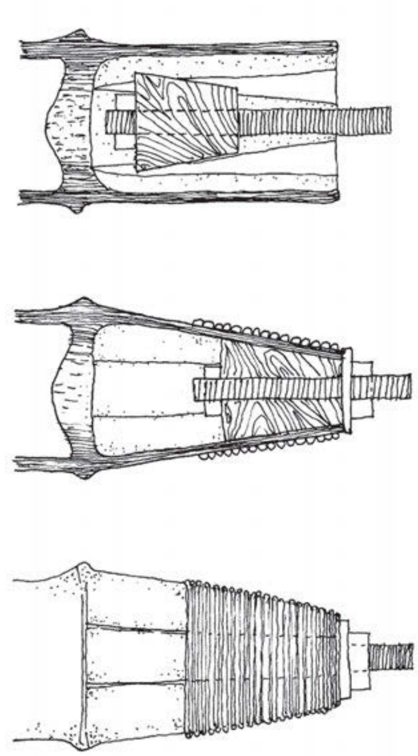

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not particularly strong but adaptable to different angles, as seen in *9.41* and *9.42*.

Markus Heinsdorff developed quite sturdy joints made of stainless steel that are adaptable to different angles for his German pavilions in China; see *9.43* to *9.46* and pp. 154–155.

A very simple solution for light loads is seen in *9.47*. A smart option 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 *9.48* to *9.51*.

A similar detail used in the joining of wooden elements is seen in *9.52*. A commonly used solution is shown in *9.53* and *9.54*, where the fish mouth connection 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 *9.55* shows a three-dimensionally optimised solution designed by Marcelo Villegas, where the tensile elements are iron rods. Figure *9.56* 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 *9.59*.

Other designers have used conical endpoints with cement or resin filling; these are shown for instance in *10.3* and *10.4*. To connect crossed strips, one can use a galvanised wire, rivet or screw *(9.57* and *9.58)*. But if a rivet or screw is used, one must first drill a hole to prevent the strip from splitting.

Figure *9.60* shows a simple welded sheet steel joint developed by Christoph Tönges (see also *10.70*), *9.61* a more elegant variant by the same construction engineer. A similar connection is used by the American company KOOLBamboo *(9.62)*. Figure *9.63* shows an articulated joint, also developed by KOOLBamboo.

10 Constructive Elements and Systems

10.1

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 pp. 142–143. An elegant design for column bases was realised by Marcelo Villegas, where a cone of steel implanted in mortar was used *(10.4).*
Figure *9.33* shows a solution by Jörg Stamm, where the end of the cane was moulded into a conical shape and solidified with an epoxy

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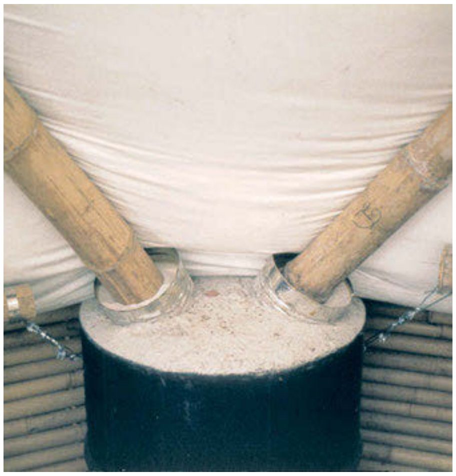

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mortar. A similar solution used by Christoph Tönges is seen in *10.5* and *10.6,* where the cone was internally filled with cement or epoxy mortar, and was externally wrapped with a mesh of fibreglass and epoxy resin for greater stability. Tönges wrapped the cone with steel wire *(10.8).*

The simplest solution for an articulated column joint, without using cones or special metallic elements, was realised by the author; see *10.7.* 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 *10.9* (Restaurant in Holambra, Brazil, Francisco Lima, 2008). Quite elegant is the solution shown in *10.10,* which is a column in the form of a fish belly, composed of curved and interconnected canes. 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 pp. 63–64, and by Jörg Stamm for his Jewellery Factory in Indonesia, see pp. 136–137.

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 *(10.11),* and to connect them with inwardly inclining wooden pins *(10.12).*

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 connection with a threaded rod such as that used

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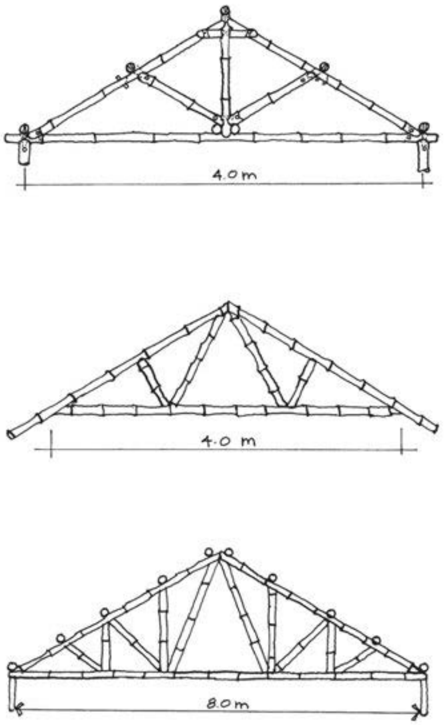

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by Jörg Stamm for spatial structures *(10.13)*. To augment rigidity against bending, one can pre-tension the beams as seen in *10.14,* where the lower cane acts as a cable in tension. This was used by Andrés Bäppler for the design of a school in Cali, Colombia. Figure *10.15* shows fish belly beams used by Jörg Stamm for various projects.

For heavy loads it is suitable to use trusses instead of beams as support; see *10.17* and *10.18*. Figure *10.16* shows a very efficient solution for bridges, developed by Jörg Stamm. A variant of a truss made by Francisco Lima can be seen in *10.19,* 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 (2008), shown in *10.20.* Figure *10.21* also shows a truss in another project by Vélez; *10.22* is a beam structure. *10.23* is the warehouse of a coffee farm in Albertina, Fazenda das Flores, Minas Gerais, Brazil (design: Edoardo Aranha, Francisco Lima, Katia Huertas, 2007). Its roof was built with four porticoes connected with a truss. 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 *10.25* was designed by Simón Vélez; that in *10.24* by Markus Heinsdorff (see also pp. 148–149).

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 *10.26* and *10.27.* 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 *10.29.*

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 *10.28* and *10.33.* Another solution consisted of joining strips of separated bamboo with pieces of canes with nodes, joined with POP rivets at the contact points; see *10.31* and *10.32.* Figure *10.33* 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


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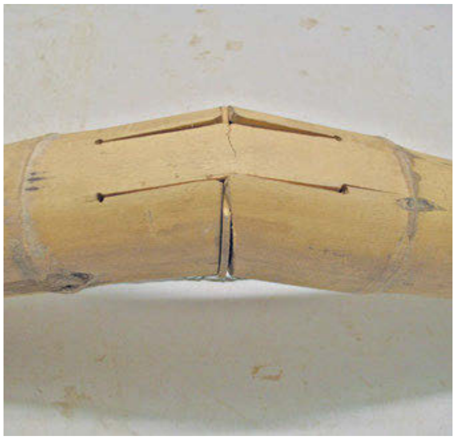
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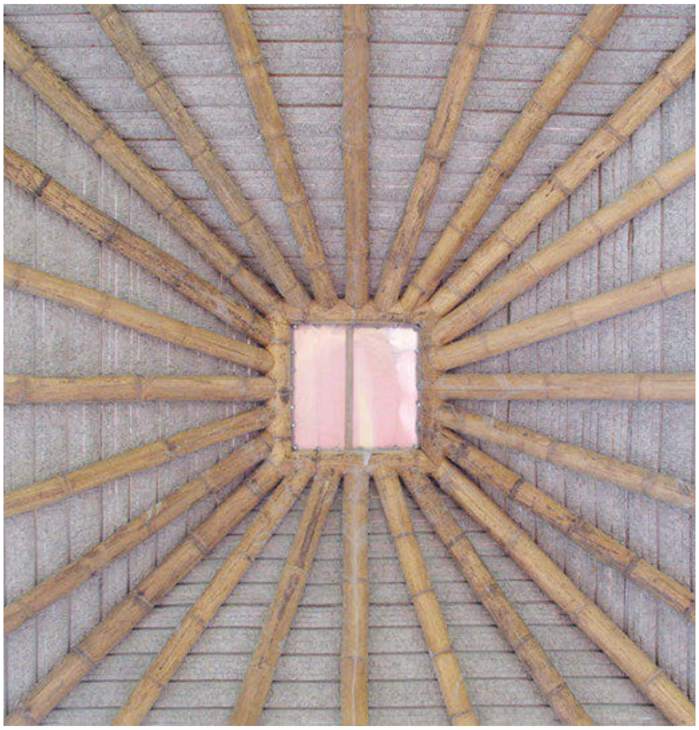

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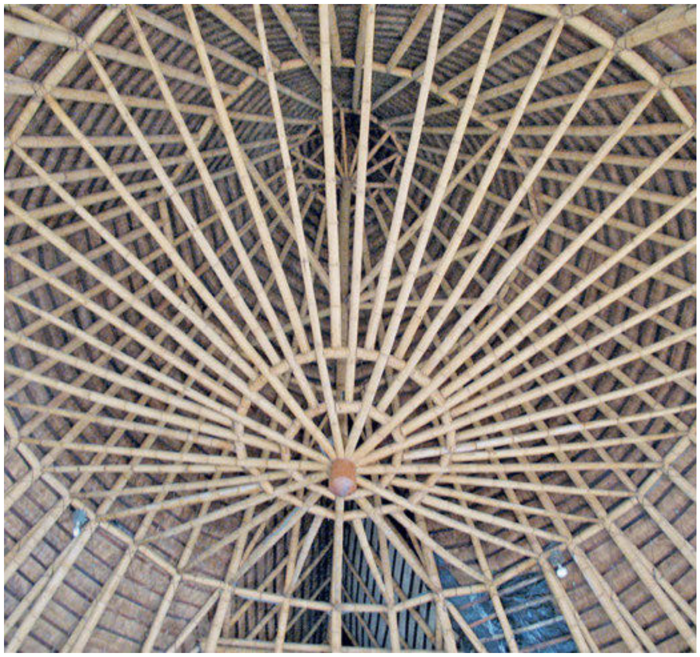

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detail shown in *10.28* supported a load of 500 kg without bending; see *10.30.* Figure *10.34* shows the application of arches using the lower extreme and part of the rhizome of a bamboo cane for a roof, designed by Simón Vélez.

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 *(10.35).* If the openings are larger, one can place fine bamboo canes *(10.36)* or bamboo strips vertically beside one another. Figure *10.37* shows the use of bamboo canes to support a traditional roof of palm tree leaves, and *10.38* a bamboo construction supporting a conventional tile roof. A solution for a roof that uses split canes is seen in *10.39* and *10.40.* 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 *10.41* to *10.44* 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.

Figure *10.46* 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 *10.45.* Solutions realised by Simón Vélez are seen in *10.47* and *10.48.*

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Figure *10.49* shows the roof of the Cañasgordas Club 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 (see also *11.18*).

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 *10.50* 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 *10.52.* Another system relying on woven bamboo is seen in *10.51*. Figure *10.53* 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.

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) *(10.55* to *10.58).* This system is normally filled with a mixture of earth, manure and fibres *(10.56).*

To make thick walls, a double layer of vertical canes is placed, covered with strips or planks on both sides *(10.57).* Figure *10.59* 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.

Vaults

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 *(10.60).* After this, the structure was inverted, forming an optimised structure for vaults without live loads *(10.61).* Afterwards, it was stabilised by the load of a green roof *(10.62).*

The other structure consists of arches of four strips of guadua in the form of a parabola. Above this were placed adobe elements

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in the form of a “U” fixed with clay mortar *(10.64* to *10.66).* 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 *(10.67).*

A Washroom Building at a camping site in La Selva, Spain, designed by Gabriel Barbeta and Esteve Navarrete in 2008, features a vault formed from a network of bamboo strips that function as formwork for a concrete roof (*10.63*).

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 *(10.68* and *10.69).* 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 *(10.68).* Figure *10.70* shows a geodesic dome (icosahedron) made of bamboo built by Christoph Tönges with the help of a group of boy scouts in Luxembourg. The top node of the structure is shown in *9.60*.

In Japan, architect Hamura Shoei Yoh designed two geodesic bamboo domes for the mail office of the Asian Pacific Exposition in Fukuoka *in 1989 (10.71* to *10.72).* 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 such as a Kindergarten and Community Centre in Naiju, Japan, see pp. 96–97, and a Jewellery Factory in Indonesia, see pp. 136–137.

The two domes of bamboo strips, covered with a membrane, seen in *10.73* to *10.78,* were constructed during a training course at Francisco Marroquín University, Guate-


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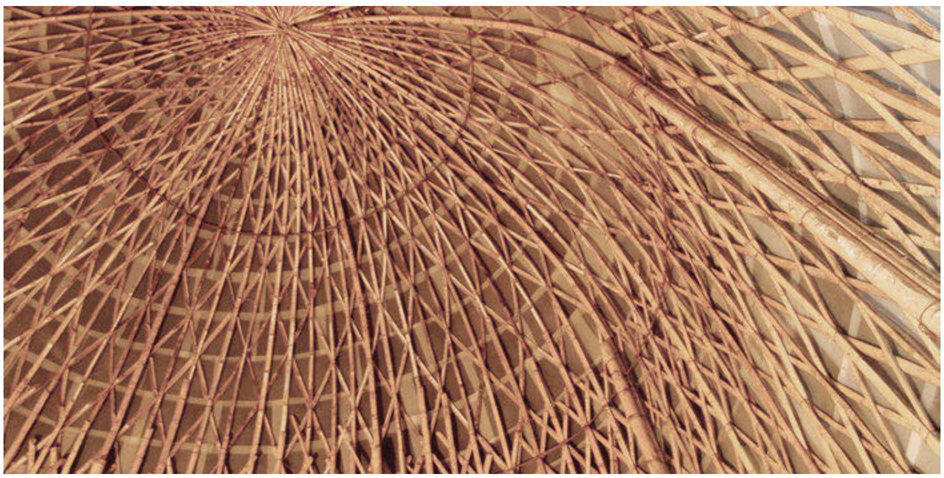

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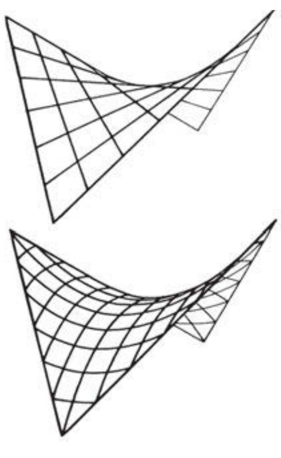

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mala, directed by the author. Figures *10.79* and *10.80* show a system devised to create domes that are stabilised only by the weight of, and the friction between, the canes. It was constructed by Ricardo de Leyva during a workshop in Candelaria, Colombia. Figure *10.81* shows a dome formed from a weave of bamboo strips. The project, a meditation hall in Granada, Cundinamarca, Colombia, by Elkin Martínez (2007), is described on p. 65.

Hyperbolic Paraboloids

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 *(10.84)*. 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 *10.82* and *10.83* 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 *10.85* and *10.86* 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.

Figures *10.87* to *10.90* show a roof composed of four hyperbolic paraboloids. The roof was designed by the author, and con-

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structed 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.

Bamboo-Supported Membrane Roofs

The Swiss architect Marcel Kalberer has developed various 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 *10.91* and *10.92*. Another of his designs is a folding-umbrella structure that covers a surface of 175 m^2; see *10.95* to *10.99.* Figure *10.98* 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 *10.93* and *10.94.*

The meditation hall in Colombia designed by Elkin Martínez and shown in *10.81* and *10.100* to *10.102* 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.

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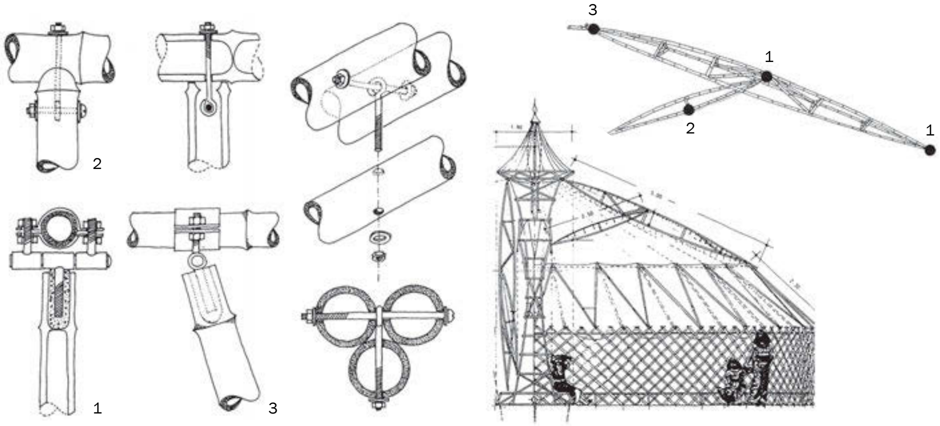

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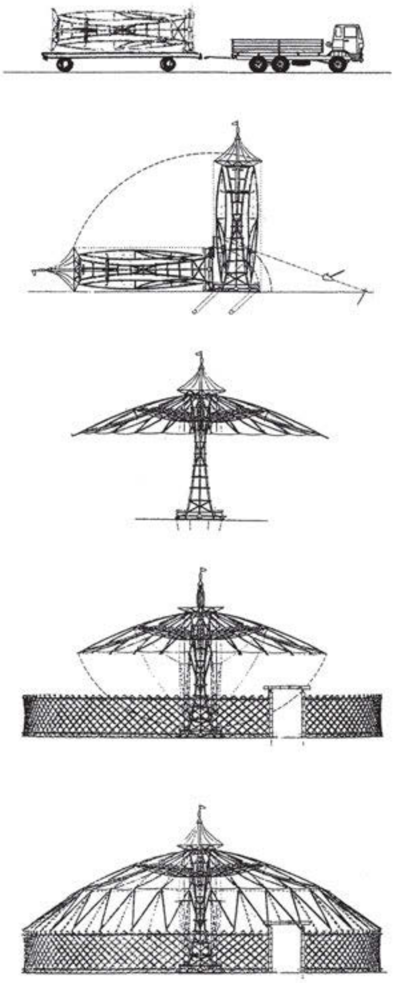

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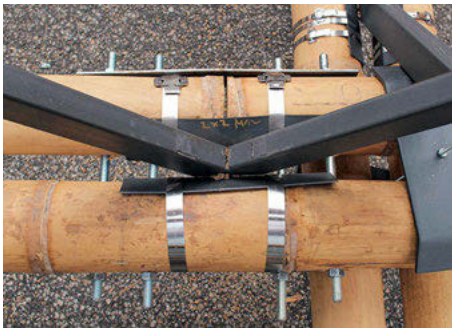

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Space Frames

At Art Basel 2015 in Switzerland artist Rirkrit Tiravanija, chef Annto Melasniemi and architects Nikolaus Hirsch and Michel Müller presented the art installation "Do We Dream Under the Same Sky", staged on Messeplatz. This public space in front of the halls gives visitors the chance to see artworks without purchasing tickets to the show. Consisting of an herb garden, a kitchen and a communal dining and lounge area, the installation provided a sustainable model for future creative life and work in community.

The area was covered by a horizontal space frame roof of 25 × 25 m (*10.106* to *10.109*). All of its horizontal elements were made of bamboo, all vertical and diagonal components were steel. The connections of the bamboo layers and the metal diagonals consisted of folded plates and worm screw clamps (*10.103* to *10.105*). The structure used 400 guadua bamboo poles of 6 m length each, with a diameter of 100–140 mm. The roof was designed by the architects Nikolaus Hirsch and Michel Müller in collaboration with engineers Bollinger + Grohmann, and consulting by Christoph Tönges of CONBAM. Other versions of the structure were realised at the Garden Triennale in Aarhus (3 June–30 July 2017) and LUMA in Arles (14 May–23 September 2018).

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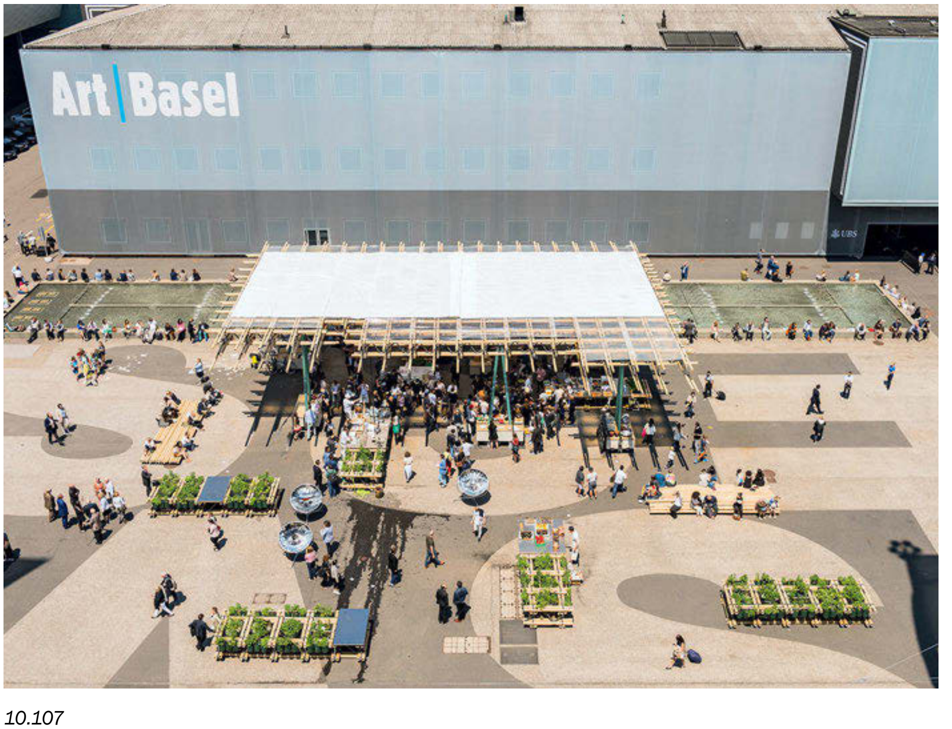

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11 Complementary Elements

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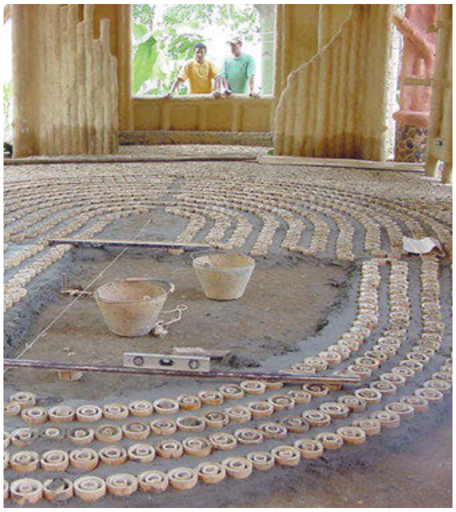

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Floors and False Ceilings

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 of the Casa Colibrí in Cali (2009, see pp. 84–85), 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; and *11.9* shows a ceiling from a residential complex in Carmen de Apicalá, Tolima, Colombia (design: Carolina Zuluaga, 2004).

In the passenger areas of Terminal T4 of the Madrid-Barrajas Airport, designed by Rogers Stirk Harbour + Partners in 2005, there are thousands of square metres 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).*

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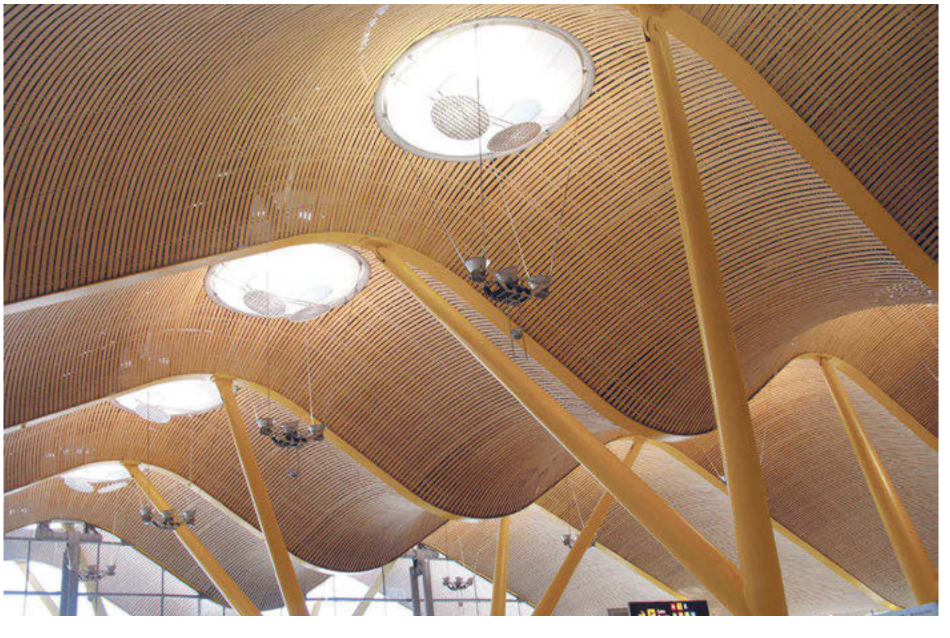

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Handrails, Balconies and Stairs

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 the Cañasgordas Club in Cali, designed by Carlos Vergara (see also *10.49*). Figures *11.19* and *11.20* show the stairway designed for the Stepped House in El Darién, Valle, Colombia (see pp. 82–83).

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 residences in Carmen de Apicalá, Tolima, Colombia (design: Carolina Zuluaga, 2004), and *11.23* shows windows with bamboo shades, as designed for the school in Rudrapur, Bangladesh (see pp. 100–103).

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12 Reinforcing with Bamboo

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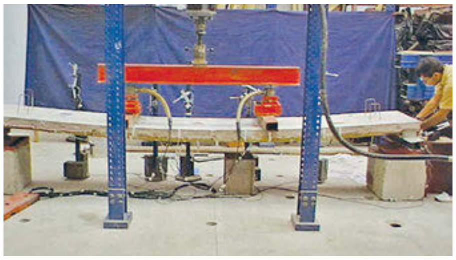

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Cement Mortar Reinforced with Bamboo Fibres

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

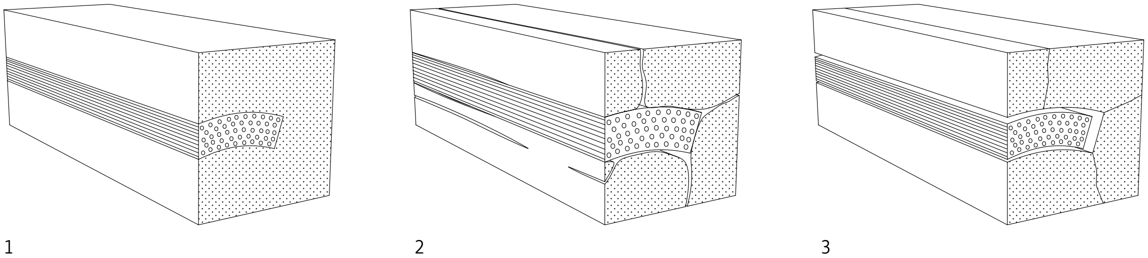
Using bamboo stalks instead of steel reinforcement in concrete is not usually successful. This is because there is not enough friction between the parts, given the bamboo's smooth surface. However, the use of twisted bamboo saplings as reinforcement in concrete has been more successful (Hidalgo, 1986).

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, Härig, 1983).

Further Experiments with Bamboo-Reinforced Concrete

In 1995, 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 (Ghavami, 1995). 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*). The bond behaviour of bamboo reinforcement to the concrete matrix was studied in this investigation through a series of pull-out tests. Treated with an epoxy-resin bonding agent, the bamboo reinforcement showed an increased bonding strength that was 5.29 times higher than untreated bamboo reinforcement. In 2005, Ghavami published a detailed study of bamboo reinforcement in concrete slabs, columns and beams (Ghavami, 2005).

Since then, other studies have confirmed that natural bamboo could potentially replace steel in concrete applications, even



1 Natural bamboo placed in fresh concrete

2 Cracks caused by swelling of bamboo

3 Deponding due to bamboo shrinkage

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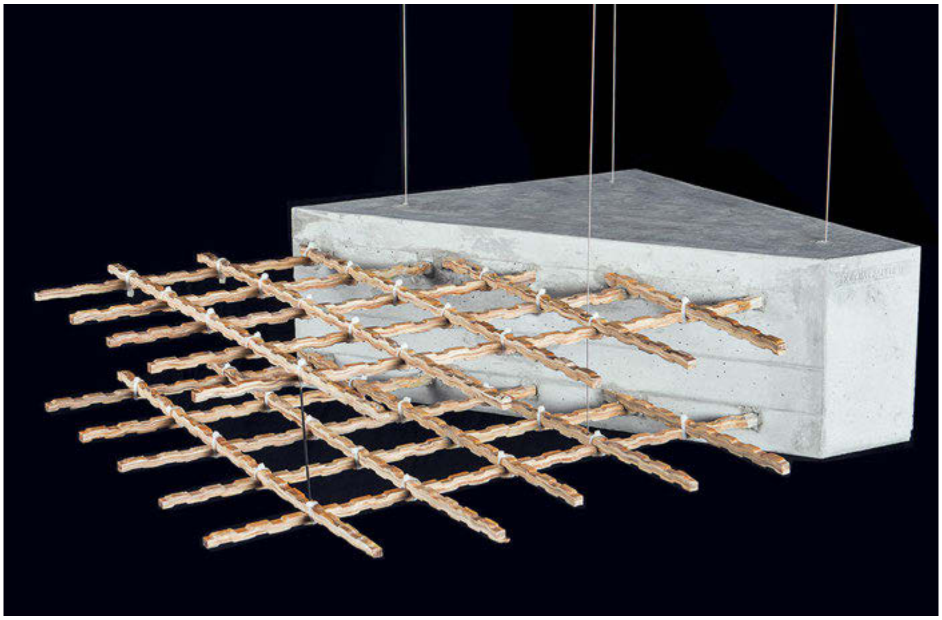

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though the ultimate load-bearing capacity of the concrete elements reinforced with natural bamboo was less than 50% of steel-reinforced concrete. However, the main problem of using natural bamboo in concrete, namely (de)bonding, remained unresolved. Figure *12.5* shows the effects of swelling and shrinking and the resulting de-bonding of untreated bamboo when used as reinforcement in concrete.

In 2011, Masakazu Terai and Koichi Minami of Kindai University in Japan carried out series of pull-out tests as well as tests on bamboo-reinforced concrete elements. A synthetic resin coating was applied on the surface of the reinforcements, which proved to enhance their bond strength. The reinforced concrete slabs displayed signs of bond failure during the bending test, but the concrete beams and columns showed superior performance compared to non-reinforced members. But again, the results also indicated that the bonding strength between bamboo reinforcement and concrete matrix was only half of that of deformed steel reinforcement and concrete (Terai, Minami, 2011).

Makoto Yamaguchi, Kiyoshi Murakami and Koji Takeda of Kumamoto University in Japan carried out a series of four-point bending tests of reinforced concrete beams with Moso bamboo reinforcement and stirrups (Yamaguchi, Murakami, Takeda, 2013), They showed that the load-bearing capacity of the bamboo-reinforced concrete beams could be predicted by section analysis based on the Bernoulli-Euler beam theory. However, this research did not investigate the effect of bamboo stirrups on shear failure and shear resistance capacity. Several further universities in Nigeria and India conducted

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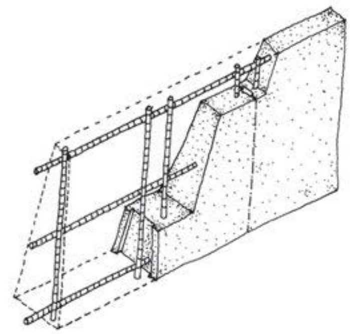

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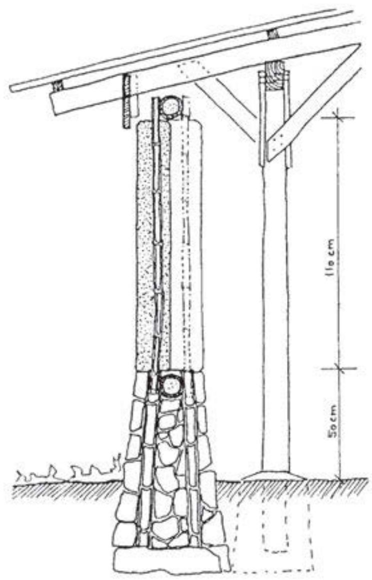

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similar research in recent years to evaluate the suitability of natural bamboo as a replacement for steel in concrete applications (Adewuyi, Otukoya, Olaniyi, Olafusi, 2015). In all these investigations, bamboo proved to be a suitable replacement for steel reinforcement as far as its high tensile and flexural strength is concerned – yet did not measure up to steel in terms of bonding and durability. Figures *12.6* and *12.7* demonstrate the application of the newly developed bamboo composite material introduced in Chapter 7, p. 34, figure *7.18* (Advanced Fibre Composite Laboratory, Singapore) as a reinforcement system in concrete. The bonding between the bamboo material and the concrete mix was investigated in pull-out tests (*12.8*). As a conclusion, the research conducted so far on bamboo-reinforced structural concrete applications had two major findings. Firstly, replacing steel with bamboo for reinforcement is feasible. Secondly, so far, no solution is available to improve durability and control the swelling, shrinking and thermal expansion of the material.

Earth 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,

12.13

12.14

both vertically at the sides, and at three horizontal locations (Hidalgo, 2003); see *12.9.*

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 *(12.10* and *12.11).* Mortar is filled in around the stalks.

A system of bamboo-reinforced rammed earth 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 earth 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 *(12.12).*

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 *(12.13* and *12.14).*

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", p. 57.

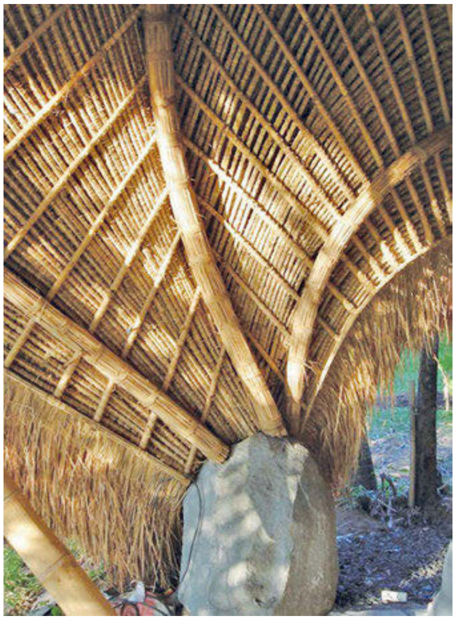
II

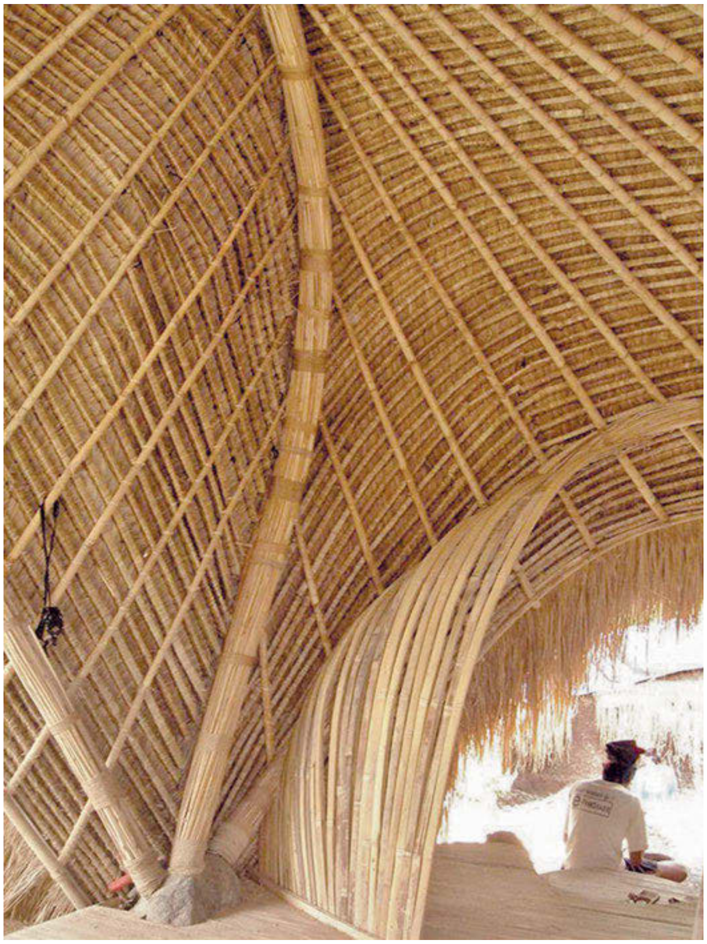
Built Examples

Guesthouse
Ubud, Bali, Indonesia

Architect: Jörg Stamm
Completion: 2004
Covered area: approx. 120 m^2

The building serves as a guesthouse. In the centre there is an oval of rammed 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)*. Split bamboo canes are combined in a bundle and form structural arches. The roof is of the “Alang Alang” type (typical straw roof in Indonesia).

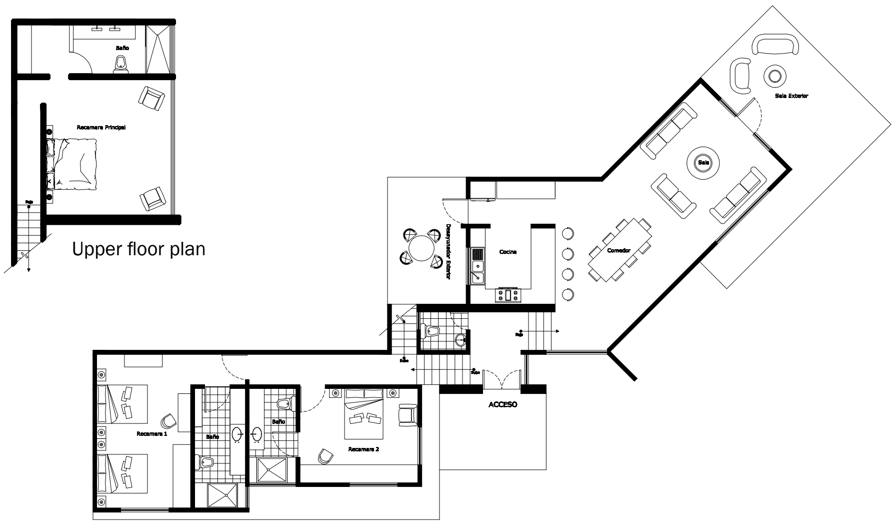




Casa Cohuatichan
Cuetzalan, Mexico

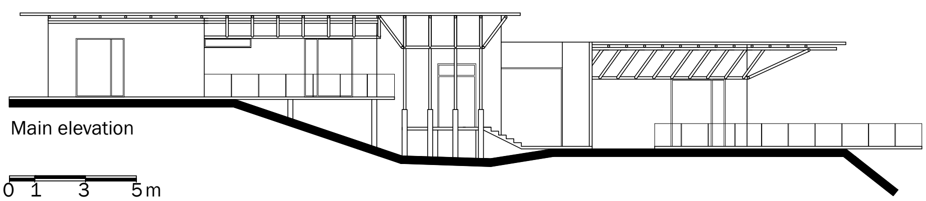
Architect: Ricardo Leyva Cervantes
Assistants: Mariana Lozano Pérez, Oscar Gonzáles
Completion: 2008
Built area: 320 m^2

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

Stepped House
El Darién, Valle, Colombia

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

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 perimetre, and is composed of a cane weave and mats, covered by an asphalt membrane and paint.

Colibrí House
Cali, Colombia

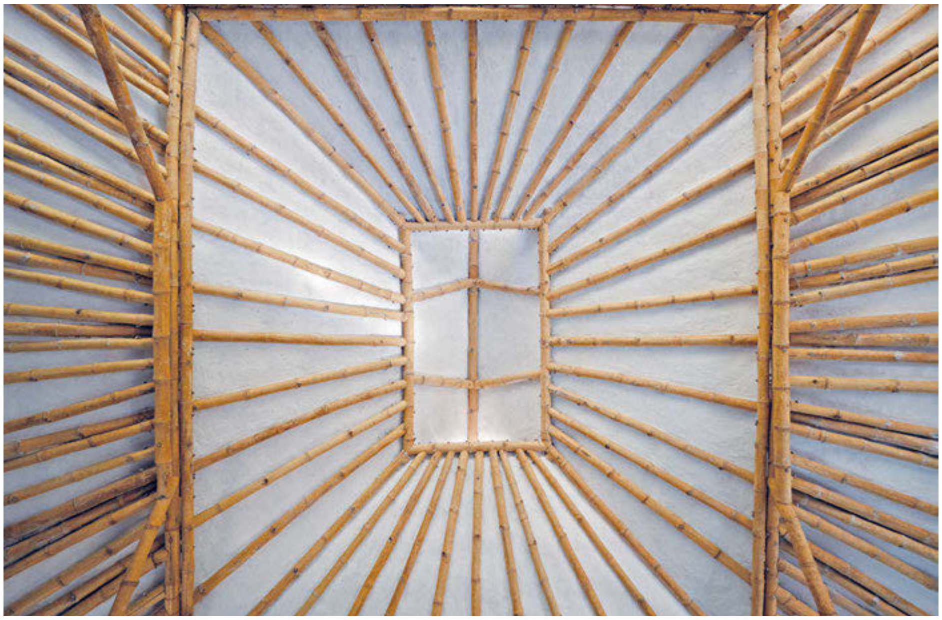
Architects: Opción Timagua (Juan Carlos Moreno and Mónica Guerrero, with Luis Carlos Ríos)
Structural calculations: Luis Carlos Ríos
Completion: 2009
Built area: 197 m^2

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 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 every 50 cm. The structural joints, the weather-exposed canes, and the walls were covered with 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 living room is formed with cane sections left over from construction (see *11.4* and *11.5*).

House in Sadhrana
Haryana, India

Architect: Pradeep Sachdeva
Structural calculations: Arvind Gupta
Completion: 2009
Built area: approx. 120 m^2

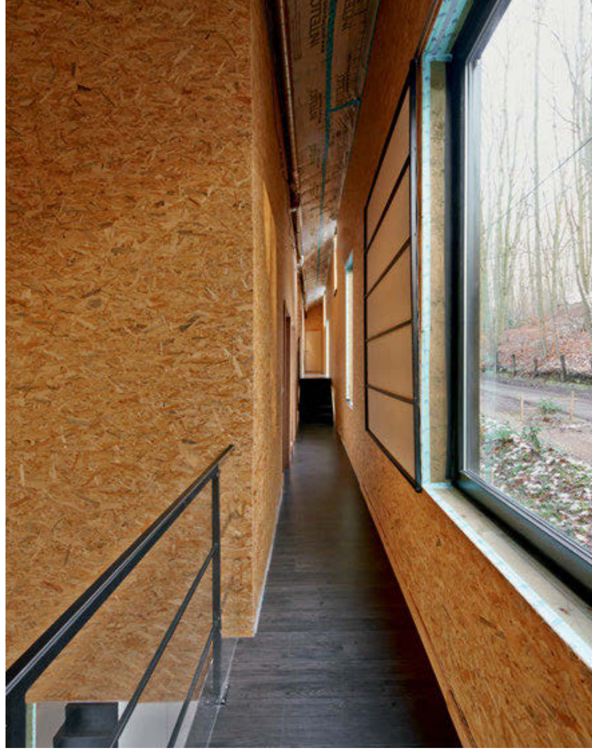
The house, the architect's own weekend home, has a bamboo roof of *Bambusa balcoa* covered by a 30–35 mm layer of ferro-cement. For thermal insulation, the sloping roof is covered with 30 cm of thatched straw. It was designed with the advice of Sachdeva's friend Simon Vélez who was visiting India at the time. The walls are made of adobes (sun-dried brick). A covered walkway connects the smaller kitchen building to the house. The verandah has a coloured tile floor and provides a view of the garden.

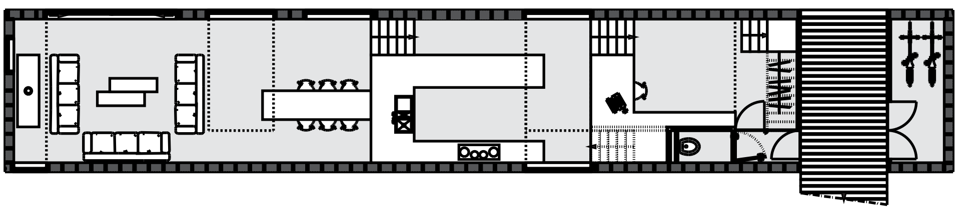


Low-Energy Bamboo House
Rotselaar, Belgium

Architects: AST 77 Architecten (Peter Van Impe)
Completion: 2010
Built area: 118 m²

Built on a narrow sloping and afforested site, the dwelling is 26.3 m long and only 4.5 m wide with its ground floor partially dug into the slope. The façades are clad in bamboo rods, placed vertically in black steel frames.
The entrance is situated in a passage that runs through the building, offering a view towards the garden and forest. Being inside, the house reveals an entirely open space. From the reception hall one can walk down to the kitchen and further down to the living area at garden level. Four bedrooms and a bathroom are situated on the first floor.
During winter, sunlight is able to provide solar heat gain through the windows, while in summer surrounding trees provide a natural sunscreen. The cellar houses installations for water cleansing and recuperation of rain and offers access to the garden. A heat pump, floor heating, extensive insulation, a ventilation system and its favourable orientation make this house an effective low-energy house.





Prefabricated Bamboo Houses
Hawaii, USA

Architect: David Sands
Built area: varies

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 m^2 and additional porches.

The company also develops custom-designed solutions. The modular, prefabricated elements are normally delivered and erected by local contractors.

Sharma Springs Residence
Sibang Gede, Bali, Indonesia

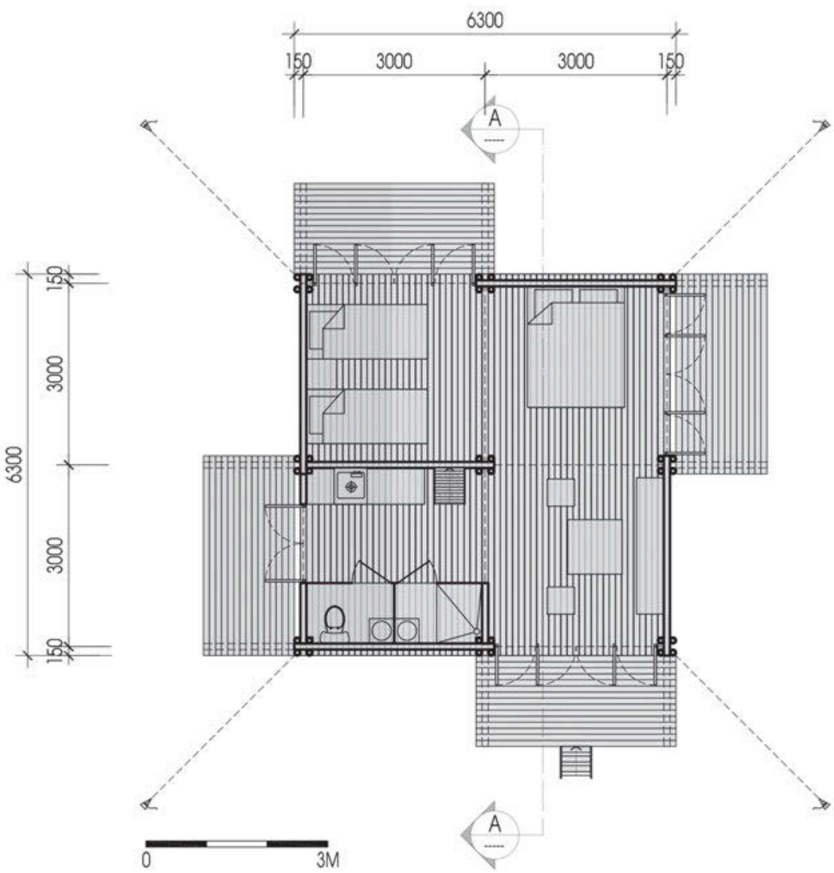
Architects and construction: IBUKU
Completion: 2012
Built area: 750 m²
Site area: 2602 m²

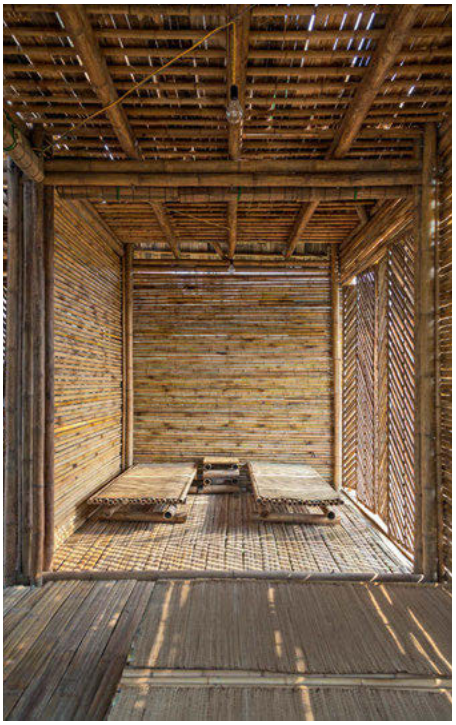
Sharma Springs Residence was the tallest bamboo structure built in Bali at the time. It is part of the masterplanned community Green Village and can be rented by visitors. Its location is at the edge of the Ayung River valley, thus affording stunning views of the scenery. The main building has six levels, four en-suite bedrooms, a spacious living room with an excellent view, and a 15 m long tunnel entrance on the fourth level. The fifth floor accommodates a private office area. Each room was customised and has a different theme. The furniture is also made of bamboo.
The residence was built within 12 months. The structure is supported by a central tower, which holds a smaller inner tower. The design was inspired by the petals of the lotus flower. The property also includes: an entry building, a guest house, a storage cave, a riverside yoga pavilion, an outdoor spa and a poolside barbecue all surrounded by beautiful permaculture gardens. The entire complex was designed and constructed by IBUKU.

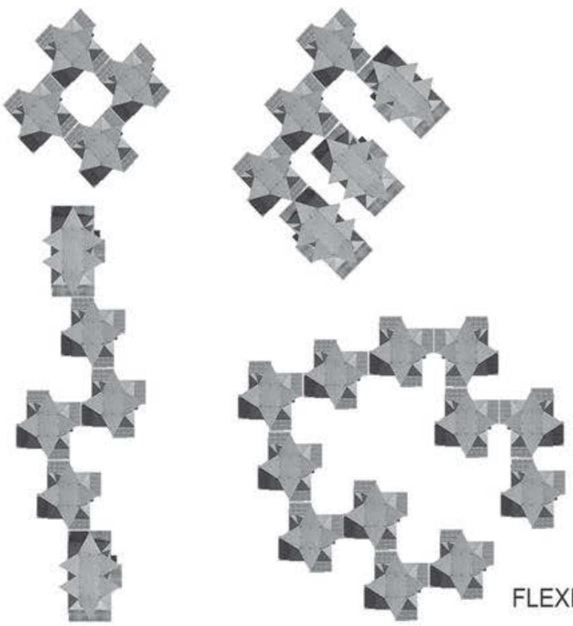
Blooming Bamboo Home
Cau Dien Town, Hanoi, Vietnam

Architects: H & P Architects (Doan Thanh Ha, Tran Ngoc Phuong)
Completion: 2013
Built area: 44 m²
Total cost: 2500 USD

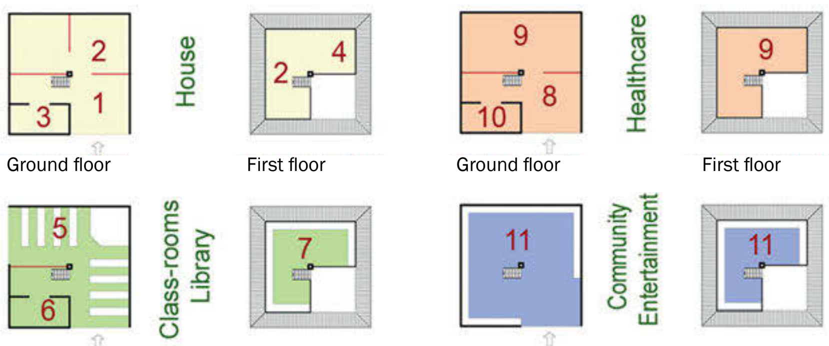
The goal of this prototype structure is to present a solution to those people in Vietnam, whose houses are threatened by sweeping floods. Elevated on stilts, the house can withstand a 1.5 m high flood. In the event of a flood, the building rises with the water level due to integrated recycled oil tanks. Anchored steel piles on all sides keep the floating structure in place horizontally, preventing it from drifting away.
The building can easily be enlarged by further modules. It not only functions as a home, but also as a medical, educational or community centre (see drawings).
The structure is mounted from modules, built of a large bamboo species of 8–10 cm diameter and a smaller species of 4–5 cm diameter. Each of the culms is 6.60 m or 3.30 m long. The cladding can be varied according to local climate and regional materials, such as thin bamboo, bamboo wattle, fibreboard or coconut leaves. Users themselves can assemble the building by bolting, binding, hanging and placing in 25 days.







FLEXIBLE USE OF BLOCK



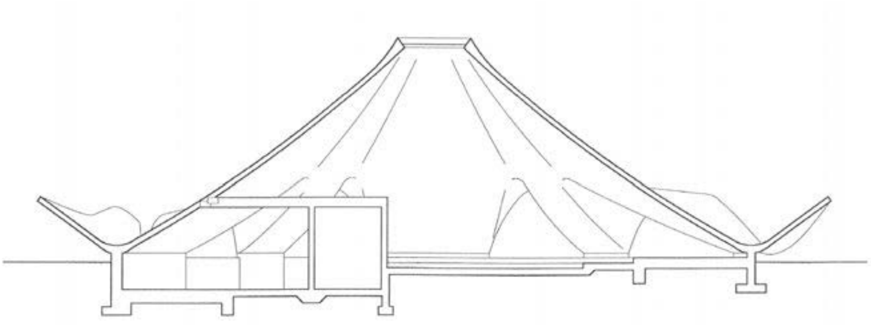
FLEXIBLE USE OF SPACE

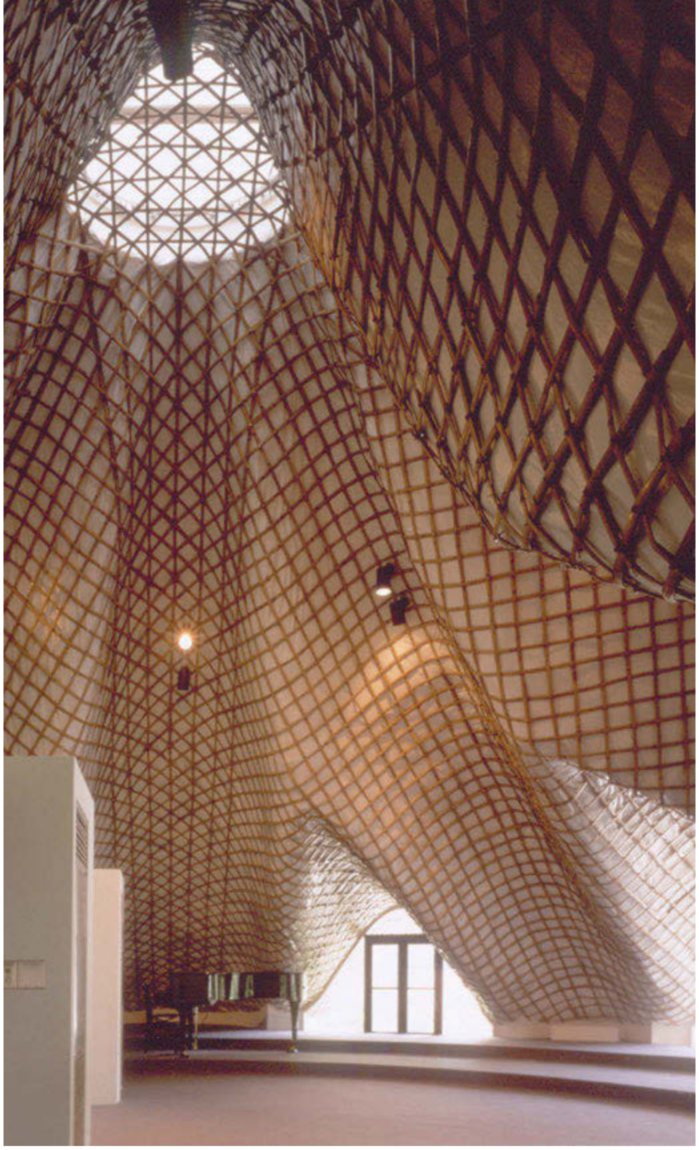
1. Living room
2. Bedroom
3. Kitchen + WC
4. Learning
5. Study room
6. For learning
7. Library
8. Clinic
9. Medical treatment
10. For healthcare purposes
11. Community space

Kindergarten and Community Centre Naiju, Japan

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

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.





Temporary Church
Pereira, Risaralda, Colombia

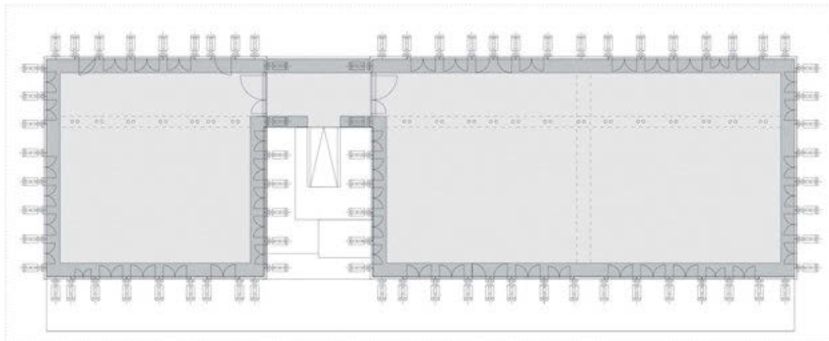
Architect: Simón Vélez
Completion: 2002
Built area: 700 m^2

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.

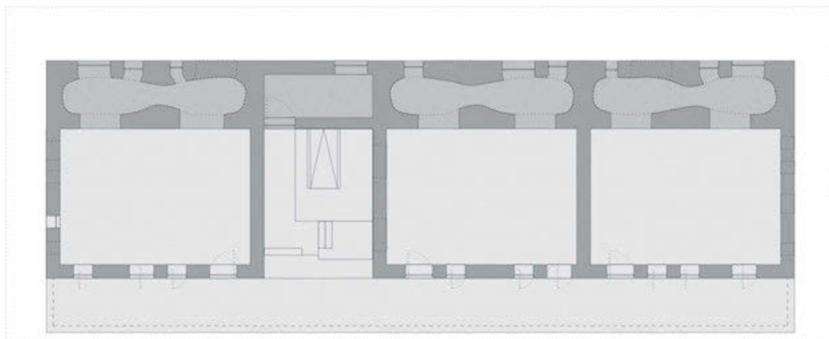
School
Rudrapur, Bangladesh

Architects: Anna Heringer, Eike Roswag
Structural calculations: Christoph Ziegert
Completion: 2006
Built area: 325 m^2

This is a self-build project using the local materials of mud and bamboo. On the ground floor there are three classrooms connected by circular openings. The walls are of cob-style earth construction. The first 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 first floor is composed of windows with wooden frames lined with bamboo shutters. The building won the Aga-Khan Architectural Prize in 2004.



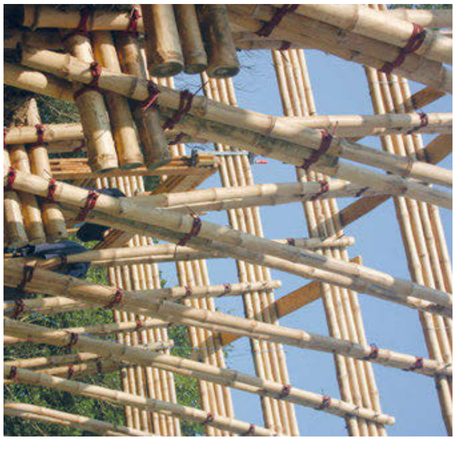
First floor plan



Ground floor plan







Nomadic Museum
Mexico City, Mexico

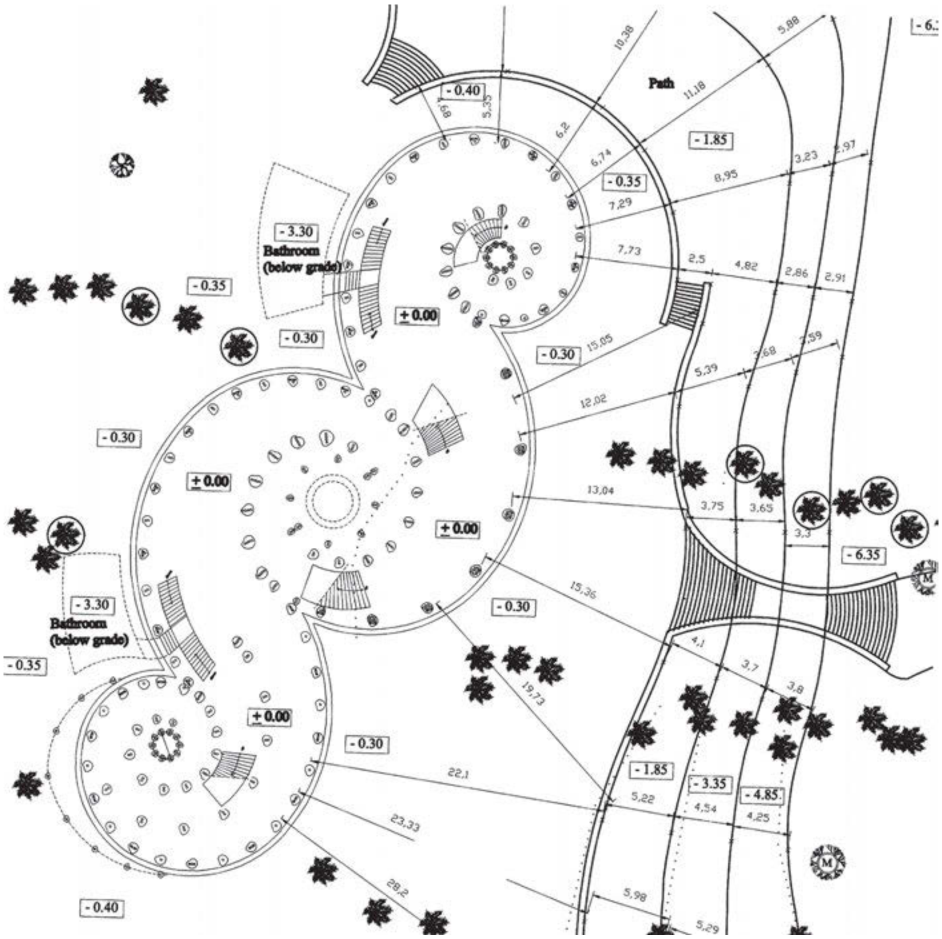
Architect: Simón Vélez
Completion: 2008
Built area: 5130 m^2

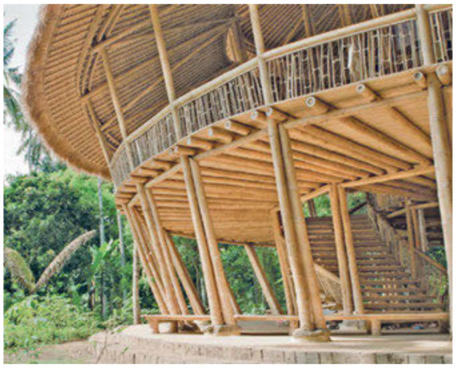
The museum, designed by Colombian architect Simón Vélez, was installed in the main square (the Zócalo) of the city, to house the photography exhibition “Ashes and Snow” by Gregory Colbert. It was a temporary structure (January until April 2008) formed of waving walls and a roof of bamboo trusses (see Chapter 10, “Beams, Trusses and Porticos”). The wall canes rested on a serpentine metal pipe, which acted as a foundation and rested on top of a layer of sandbags.

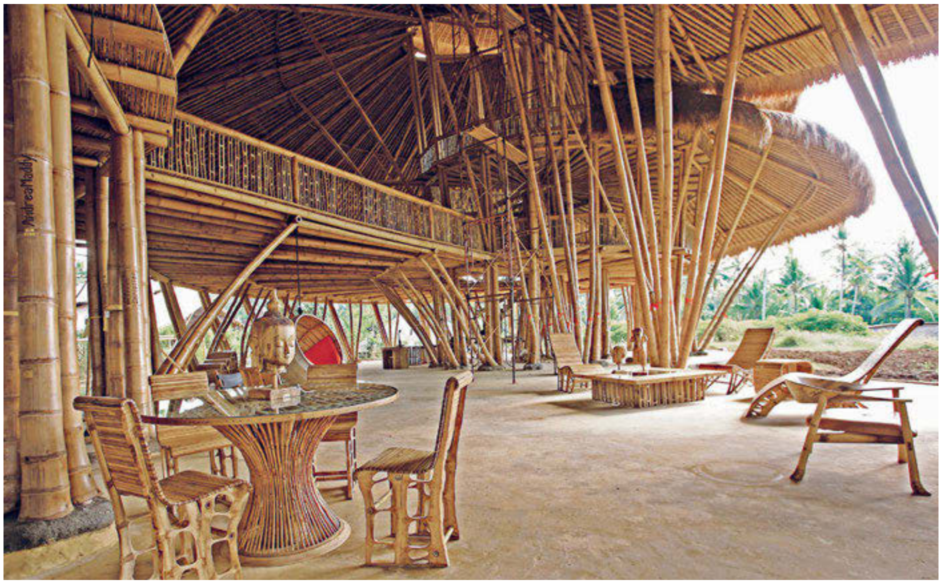
Green School Bali
Sibajang Kaja Badung,
Bali, Indonesia

Concept: John Hardy
Architects: Aldo Landwehr, PT Bambú
Bridge design: Jörg Stamm
Completion: 2008
Site area: 4.55 ha
Built area: 4350 m^2

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.







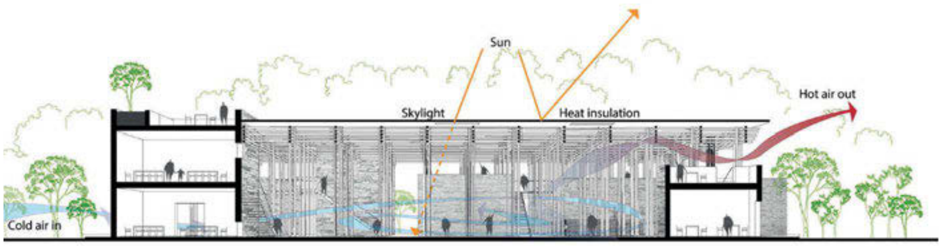
Son La Restaurant
Son La, Vietnam

Architects: Vo Trong Nghia (VTN Architects) and Vu Van Hai
Completion: 2014
Built area: 1984 m^2

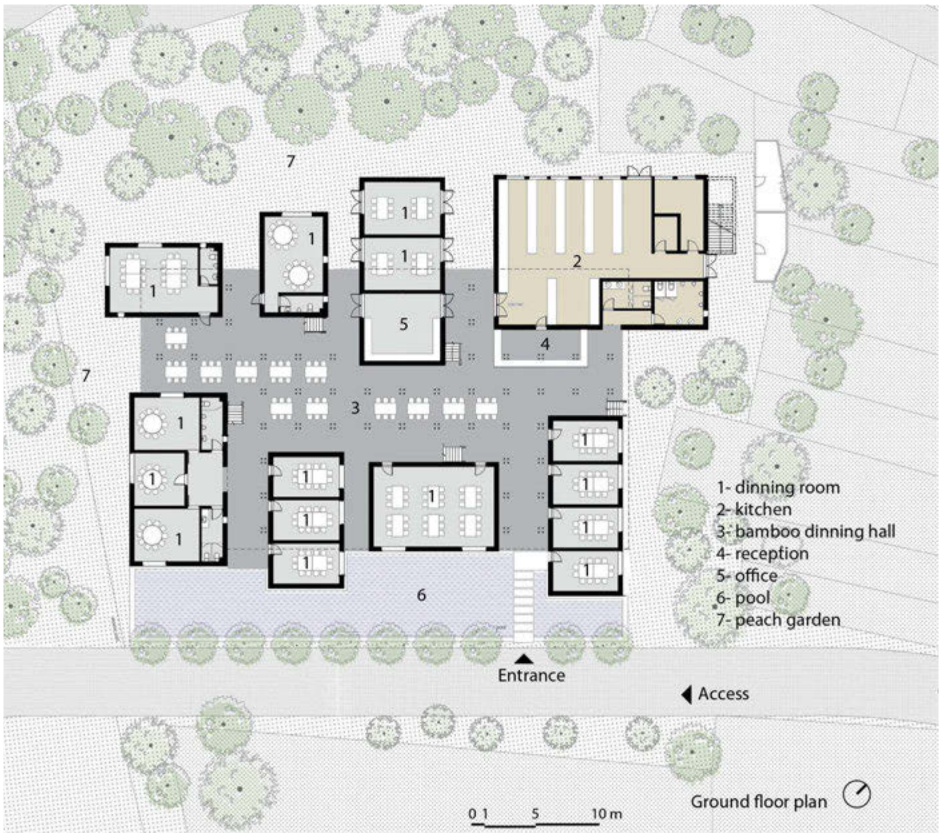
The restaurant is built of the local building materials stone and bamboo. Eight stone blocks of different size and height are arranged around a covered open-air dining hall, offering air-conditioned dining rooms as well as outdoor seating with an open view of the surrounding gardens. Supported by a bamboo structure, the large thatched roof connects the common space and the private spaces.

The roof structure is made of a local bamboo, called “luong“, which grows up to 8 m in height. The bamboo was treated by a traditional Vietnamese method, which involves soaking the canes in mud and smoking them.

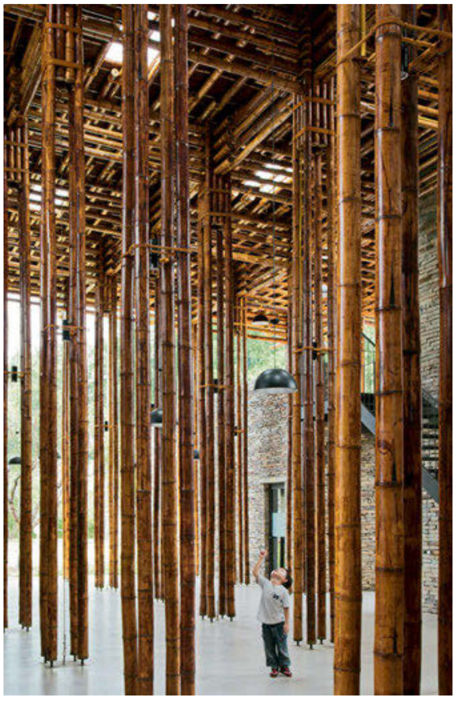
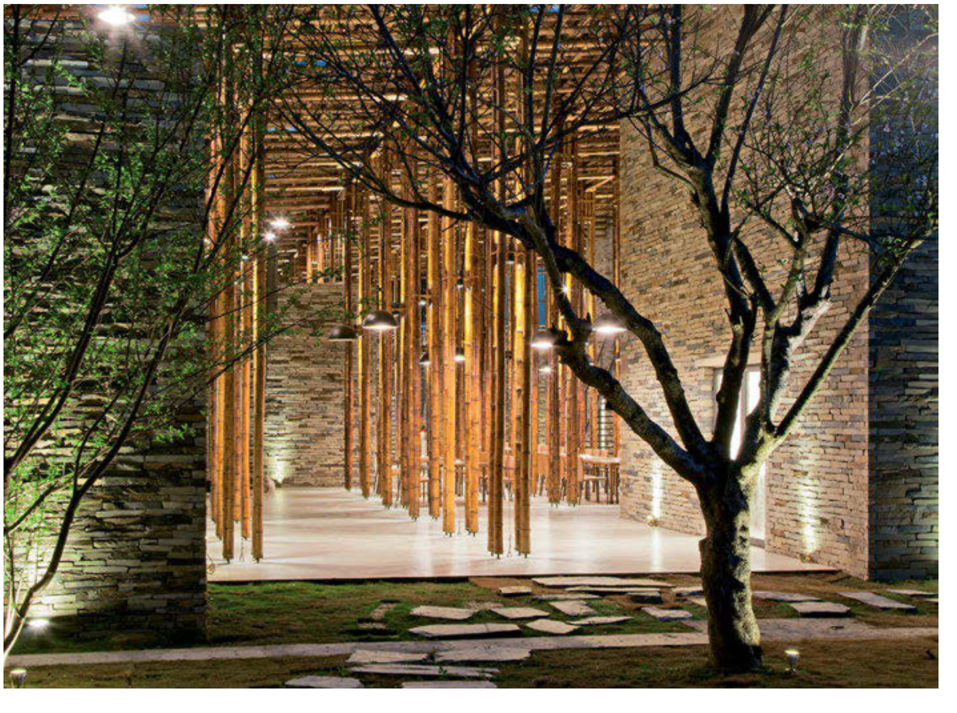
Bamboo rods of 8–10 cm in diameter are assembled with bamboo dowels and rope, creating an elegant post-and-beam structure. Each of the 96 columns is made up of four bamboo rods in a square arrangement. The beams are composed of five interlocking bamboo rods. The flat roof is covered in local thatch, called “vot”, and transparent plastic roofing sheets.

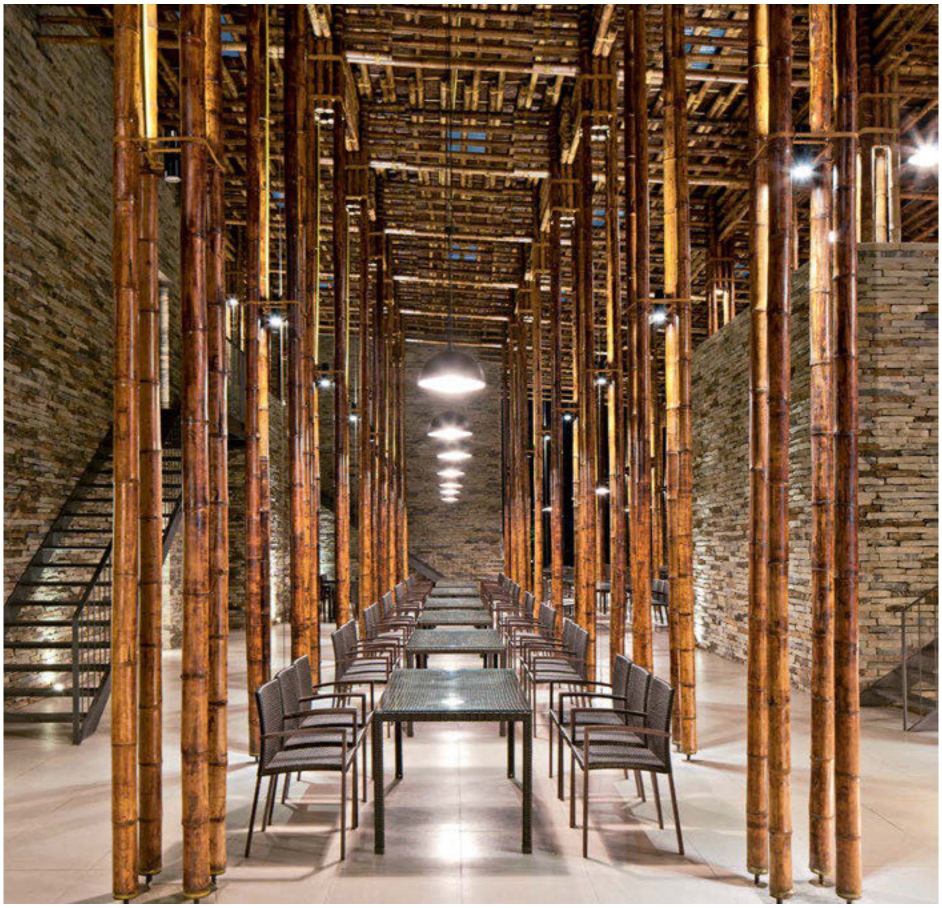


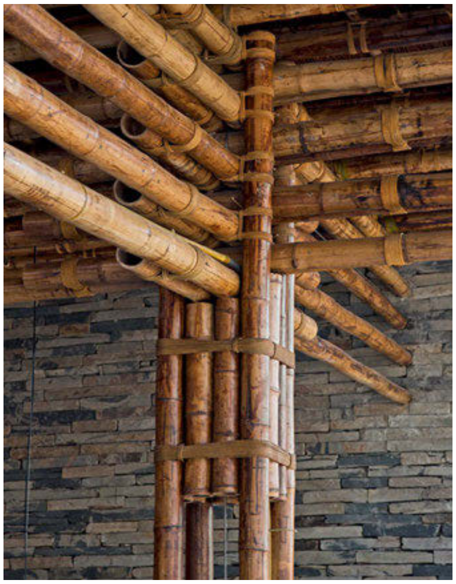
The combination of closed rooms and a semi outdoor space adapts to the tropical monsoon climate

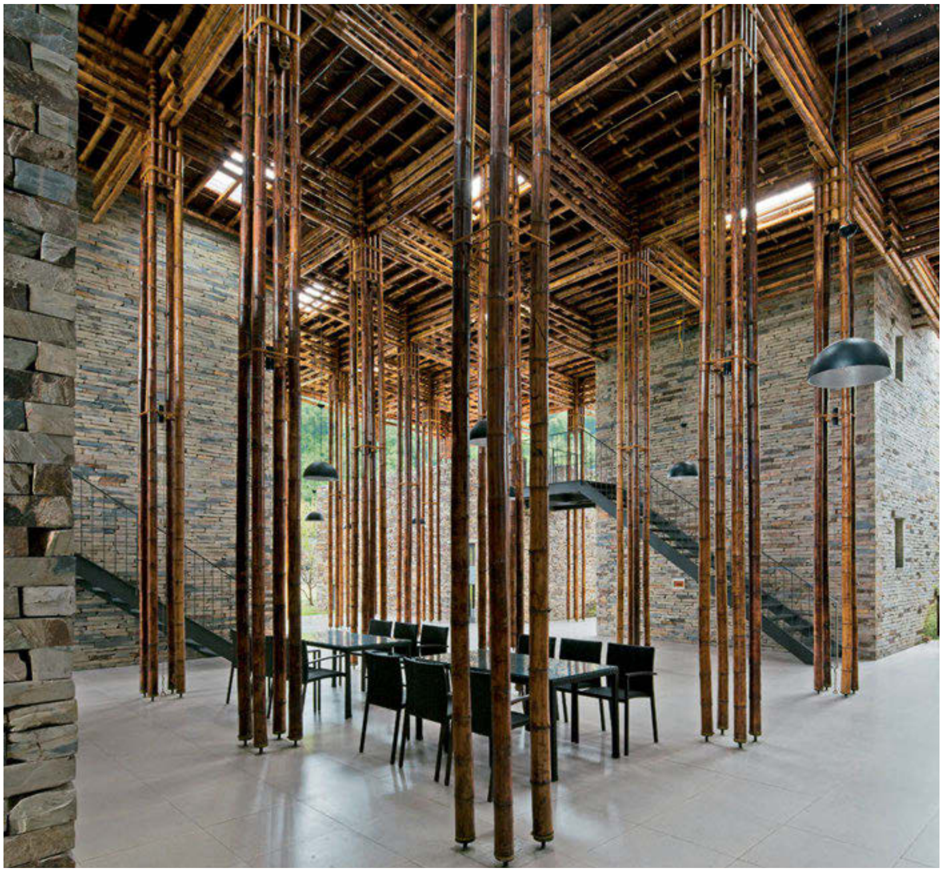






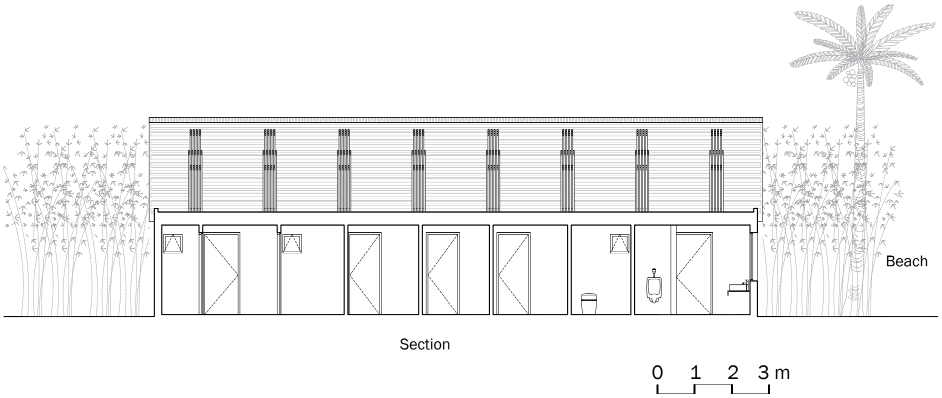




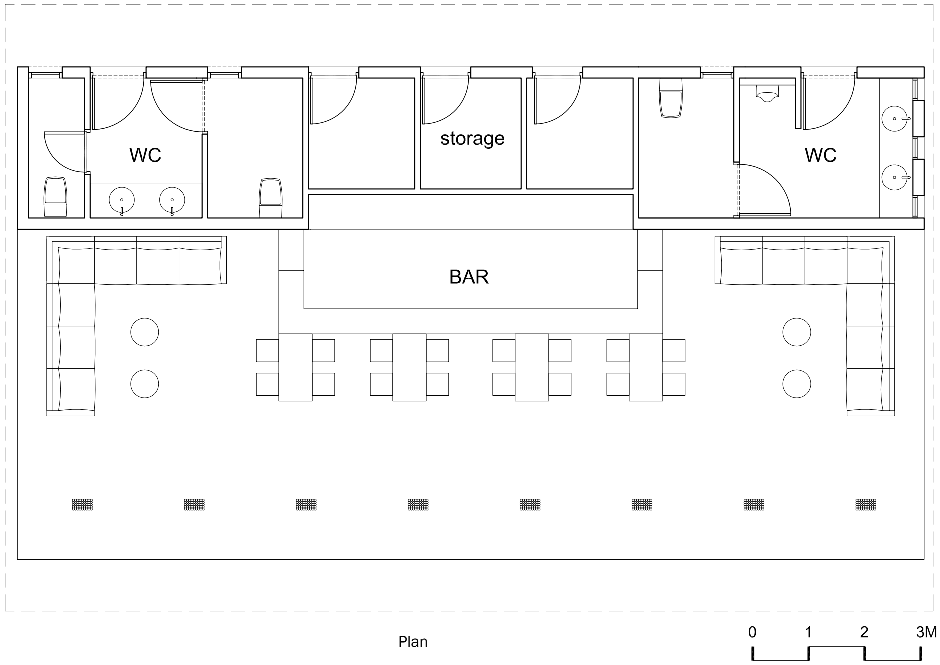
Naman Beach Bar
Danang, Vietnam

Architect: Vo Trong Nghia – VTN Architects
Completion: 2015
Built area: 143 m²

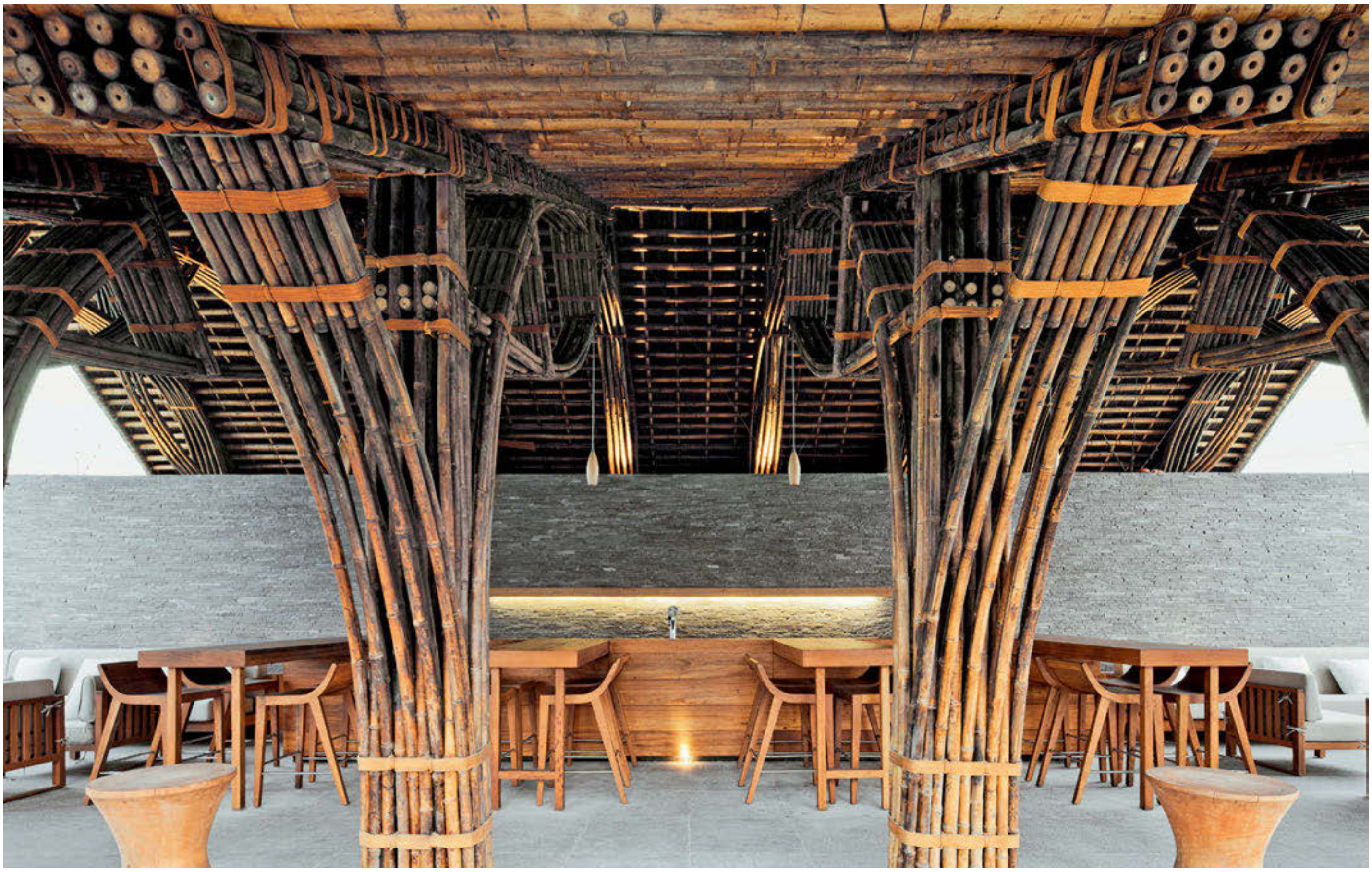
The beach bar is part of the Naman Retreat Resort, a tropical beachfront complex of hotels, bungalows and villas with restaurants and bars. The semi-open sheltered space provides an area for relaxation in front of a large pool and allows a direct view to the beach.
Constructed of bamboo and stone, the building has a pitched roof, covered with thatch. The enclosed part accommodates the service facilities and storage area. Furthermore, the stone walls function as structural support for the bamboo cover. Eight prefabricated bamboo frames, made of bent and straight bamboo rods that are interconnected by bamboo nails and ropes, carry the pitched roof.
To enhance the bamboo quality, all poles were treated in situ over a period of four months, using a process that involved bending the bamboo over fire, soaking in water and fumigating.



Section



Plan

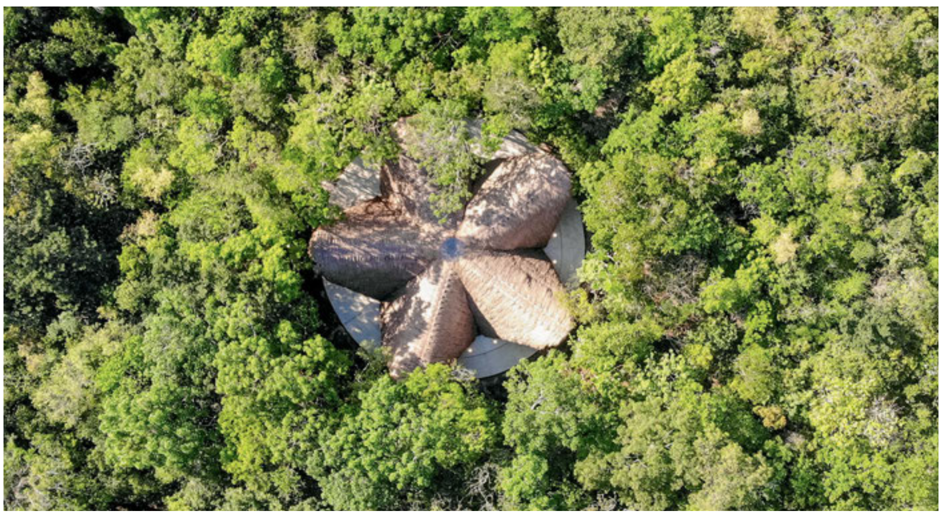


Luum Temple
Tulum, Mexico

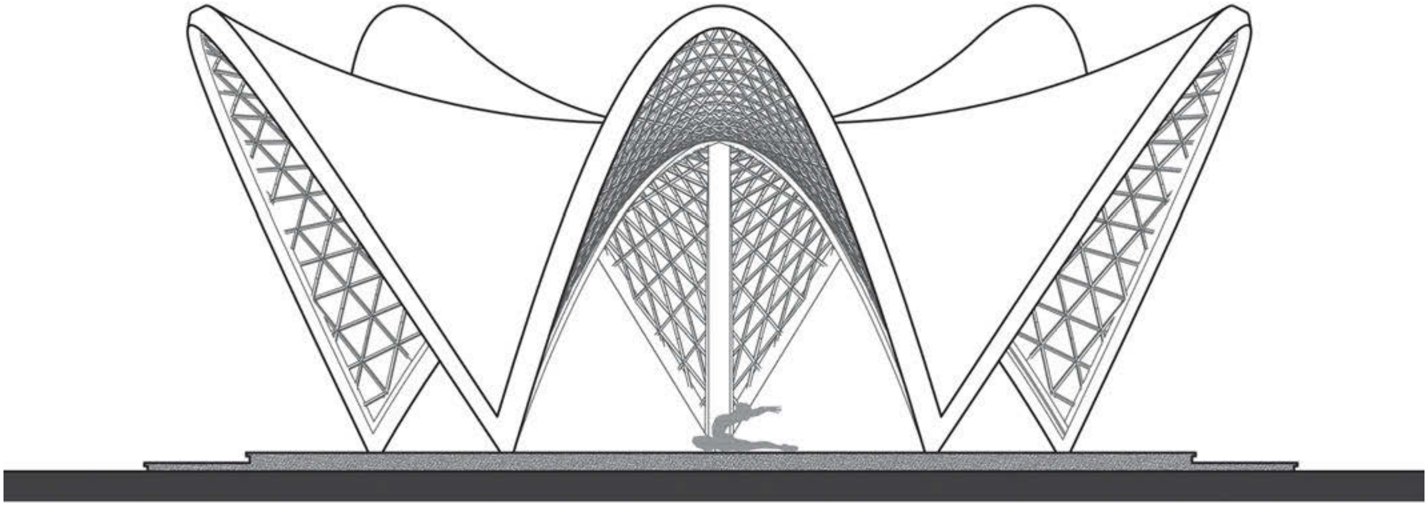
Architects: CO-LAB Design Office
Structural calculations: Esteban Morales
Builder: Arquitectura Mixta
Completion: 2019
Built area: 250 m²

Located in the emerging touristic destination of Tulum, the Luum Temple is a welcoming space for the community. Built from bamboo, the open structure hosts a variety of programmes including yoga, meditation and workshops. It is part of a new residential development called Luum Zama that sets aside 50% of its 8 hectare area for the conservation of existing vegetation while also implementing reforestation with endemic plants. Luum Zama's masterplan was also designed by CO-LAB Design Office, raising awareness for protection of the natural resources.

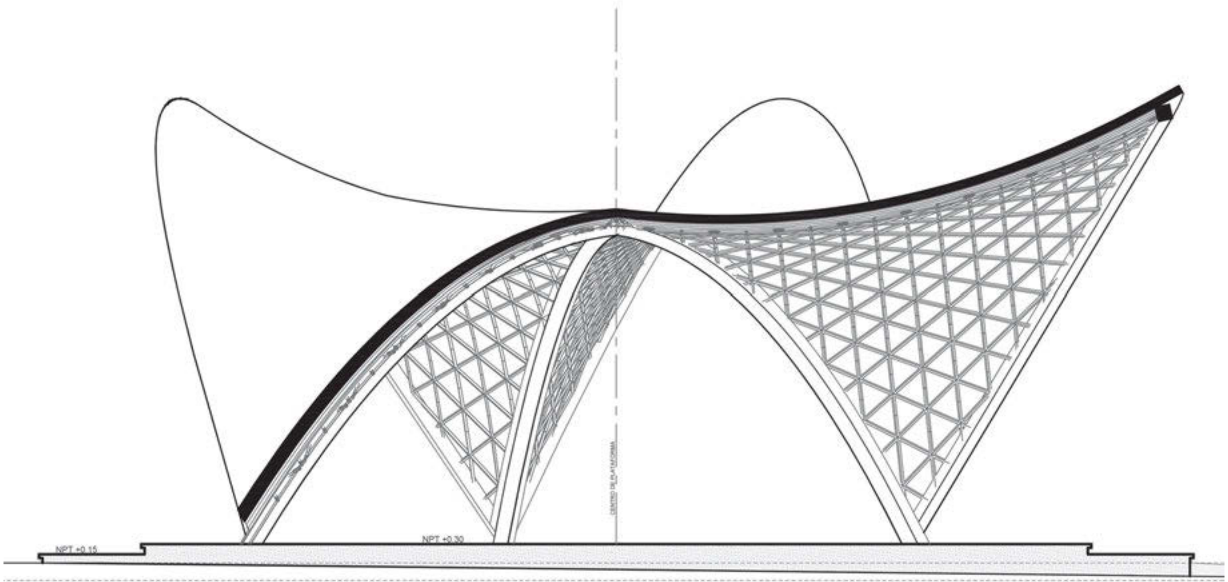
Luum Temple is nestled in a conserved area of native jungle and accessed only on foot. The open five-sided structure allows for a rich play of dappled light and shadows. Inspired by Felix Candela's reinforced concrete shells, the project is a catenary structure made from bamboo where five catenary arches support each other in structural dependency. Parametric modeling guided the construction process, creating new possibilities for one of the oldest traditional building material. The bamboo was farmed sustainably in the neighbouring Chiapas state.



CO-LAB worked in close communication with the builders and an engineer specialising in bamboo structures. The arched beams were assembled from flat sections of bamboo bent on site, cold molded on the ground, and then screwed and strapped together to work collectively as one element. Once the arches were raised they were woven together by a structural triangular pattern and then further bound by two continuous layers of bamboo lattice, interlaced in opposite directions for structural stability. The structure was designed and calculated to resist hurricane forces. On the exterior, a layer of local Zacate (grass thatch roof) typical of the region protects the structure from the rain.



Elevation



Cross section

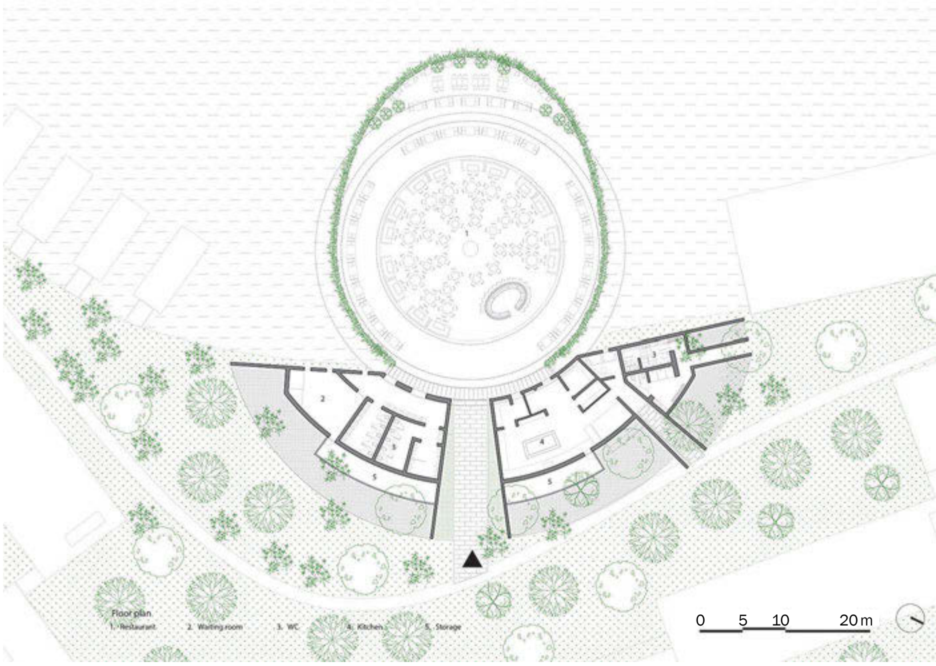
Vedana Restaurant
Cuc Phuong, Vietnam

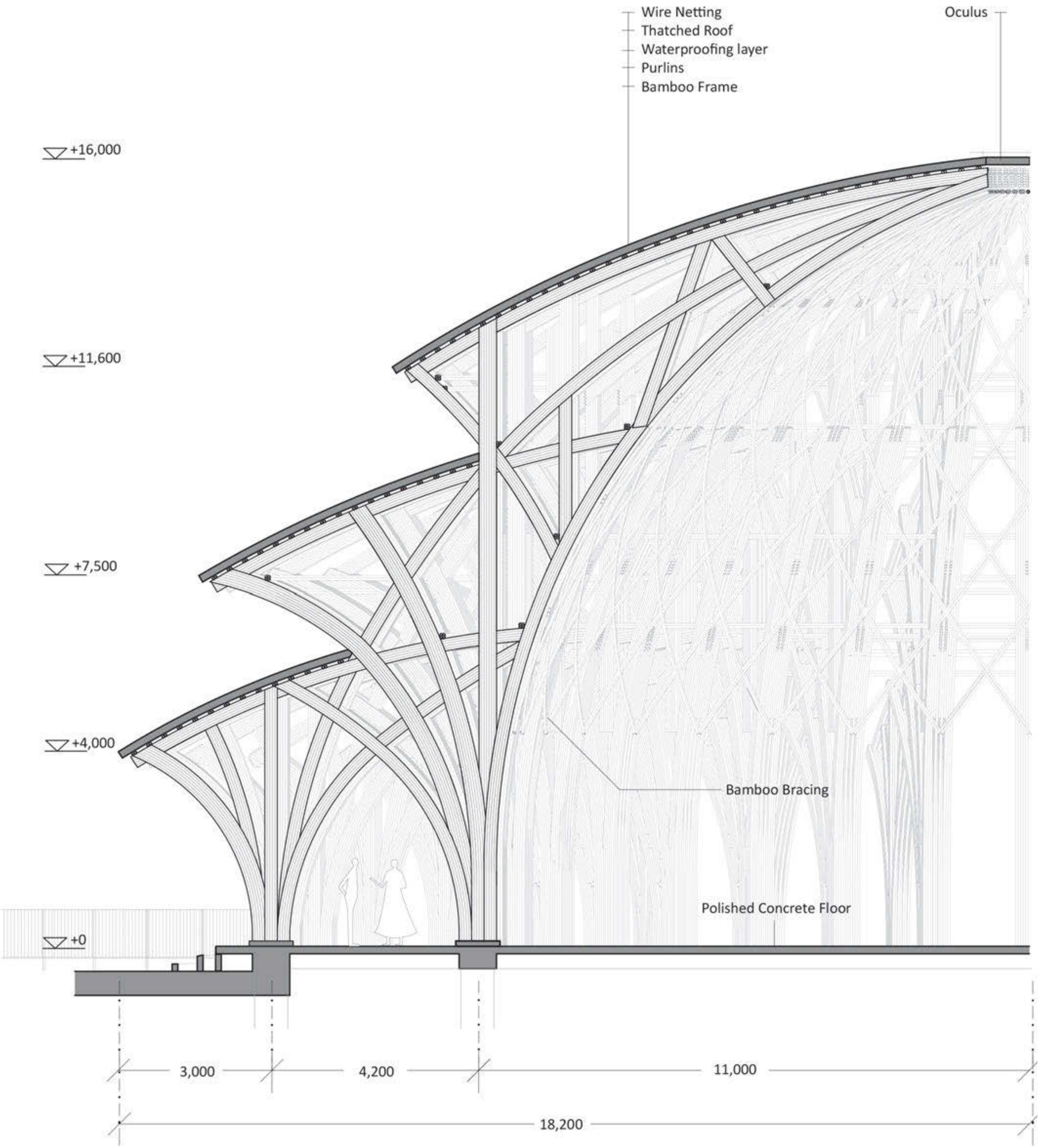
Architect: Vo Trong Nghia – VTN Architects (Design team: Nguyen Tat Dat, Nguyen Duc Trung, Tu Minh Dong, Nguyen Tan Thang)
Bamboo contractor: VTN Architects
Completion: 2020
Built area: 1000 m^2

Embedded in Cuc Phuong, a forest situated at the foothills of mountains in the Ninh Binh Province, Vedana Restaurant is a part of the Vedana Resort masterplan, also developed by VTN Architects. The resort was designed with a capacity to accommodate up to 1350 people in 135 villas, five condotels and eight bungalows. The restaurant is located in the centre of the resort. The space is used for all-day dining but can be converted to host larger events such as weddings.

The three-gabled circular roof, covering some 1050 m^2, is assembled from two stacked ring-shaped roofs and a dome roof on top, with light strips in between. The biggest radius measures 18 m while the structure height is almost 16 m. The stepped roof, inspired by traditional architecture, is made of 36 modular frames that appear like a multi-level structure, yet they are on a single floor.

The restaurant is positioned strategically next to an artificial lake that functions as a natural air-conditioner, mitigating the hot and humid weather. The lake is used for rainwater storage and for irrigation of all plants on the 16.4 hectare site. The restaurant's indoor space transitions slowly towards the exterior, creating a rich spatial experience for visitors.

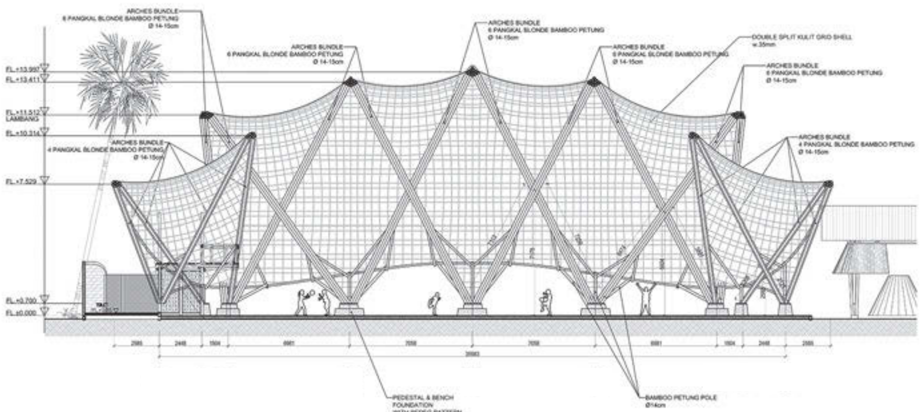


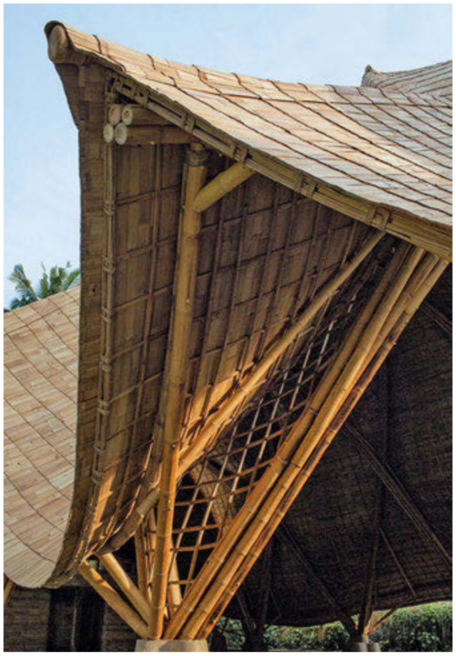

Wire Netting
Thatched Roof
Waterproofing layer
Purlins
Bamboo Frame
Oculus
+16,000
+11,600
+7,500
+4,000
+0
Bamboo Bracing
Polished Concrete Floor
3,000
4,200
11,000
18,200

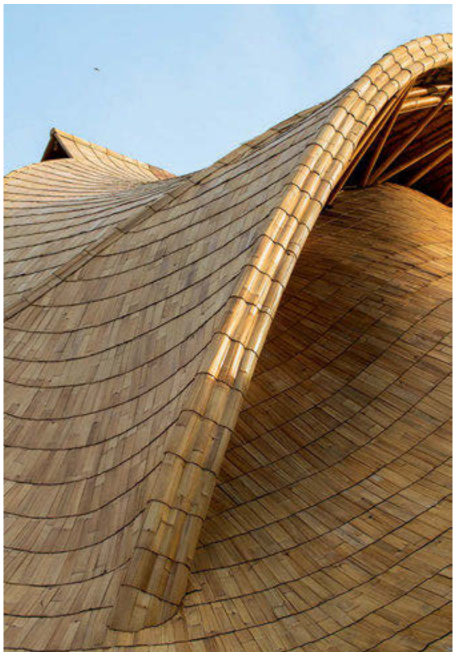
The Arc, Green School Bali
Sibajang Kaja Badung, Indonesia

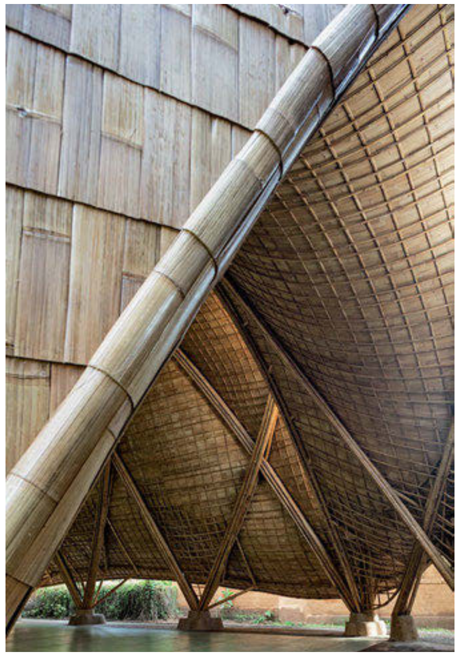
Architect: IBUKU
Concept: Jörg Stamm
Structural calculations: Atelier One and Ketut Yasa Bagiarta
Construction: Bamboo Pure, Jules De Laage
Completion: 2021
Built area: 760 m²

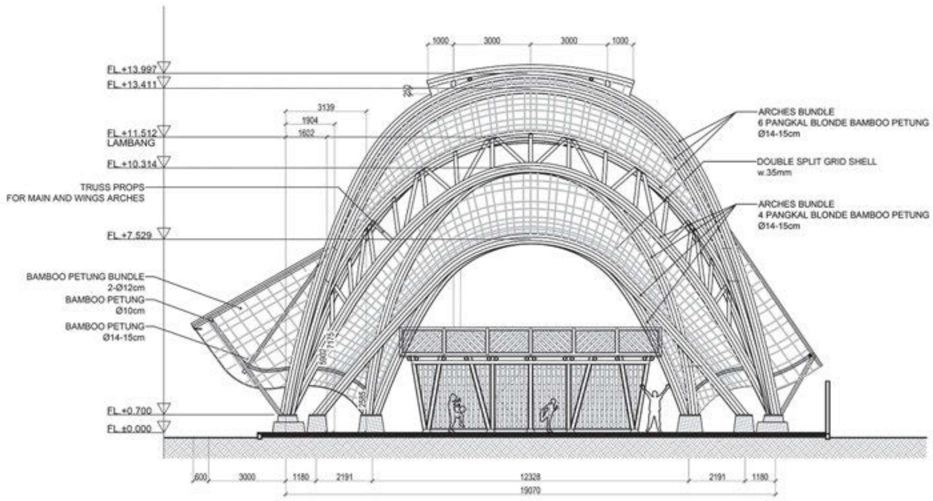
The Arc is a large hall that is part of the campus of the Green School in Bali, Indonesia. It is used as a gym and also acts as space for workshops and recreation activities. It was built from a series of intersecting 14 m tall bamboo arches spanning 19 m, which are interconnected by an anticlastic gridshell of bamboo strips. The gridshell itself is covered and stabilised by two continuous layers of bamboo lattice, interlaced in opposite directions for structural stability. While the gridshells appear to hang from the arches, they actually hold them up. Using shape stiffness, the gridshells form the roof enclosure and provide buckling resistance to the parabolic arches. The two systems together create an efficient lightweight structure with minimalised use of material, able to flex under load and allowing the structure to redistribute weight, thus easing localised forces on the arches. Bamboo shingles cover the whole structure to provide shelter from the elements and imbue the building with aesthetic elegance.







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FL +13.411
FL +11.512
LAMBANG
FL +10.314
TRUSS PROPS
FOR MAIN AND WINGS ARCHES
FL +7.529
BAMBOO PETUNG BUNDLE
2-Ø12cm
BAMBOO PETUNG
Ø10cm
BAMBOO PETUNG
Ø14-15cm
FL +0.700
FL ±0.000
ARCHES BUNDLE
6 PANGKAL BLONDE BAMBOO PETUNG
Ø14-15cm
DOUBLE SPLIT GRID SHELL
w.35mm
ARCHES BUNDLE
4 PANGKAL BLONDE BAMBOO PETUNG
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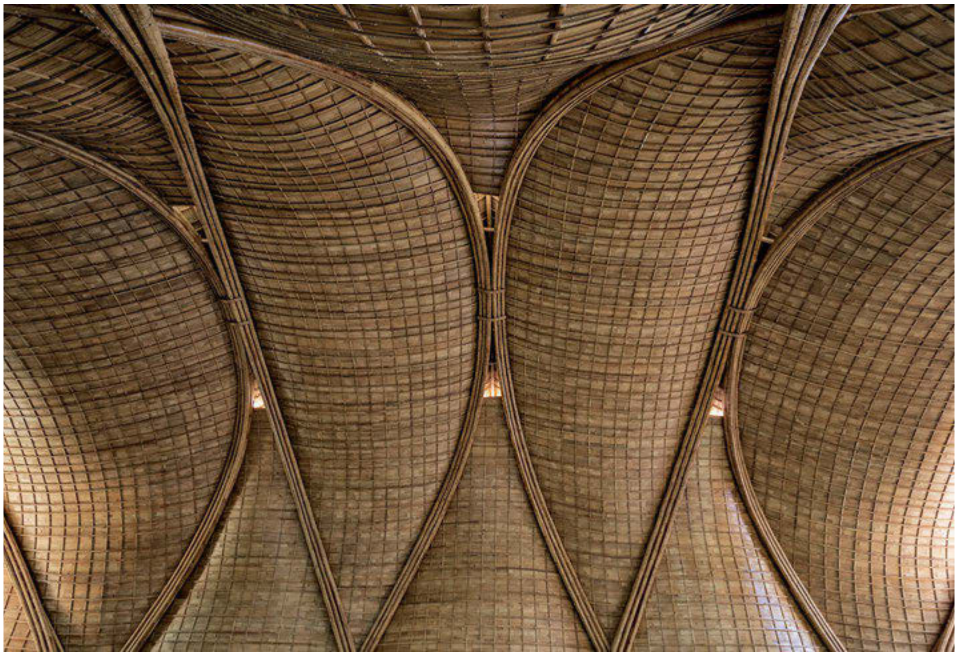
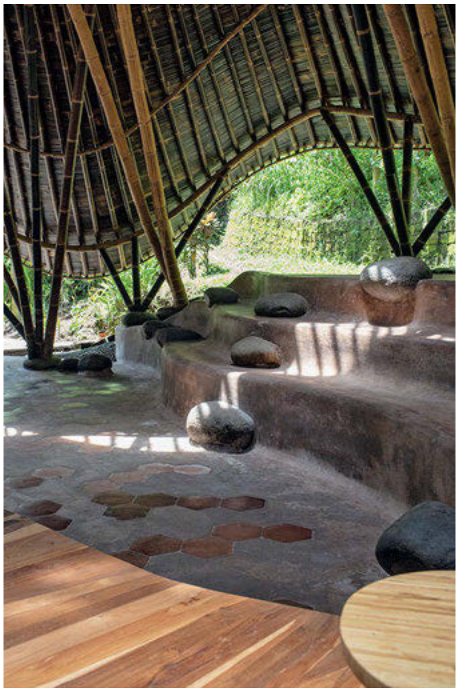


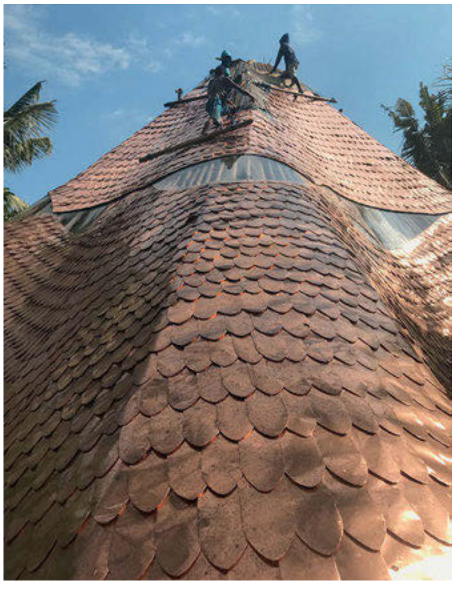
Dining Hall, Green School Bali
Sibajang Kaja Badung, Indonesia

Architect: IBUKU – Jules de Laage, Orin Hardy
Concept: Jörg Stamm
Structural calculations: Atelier One with Ketut Yasa Bagiarta
Construction: Bamboo Pure
Completion: 2022
Built area: 200 m^2

The hall called Dapur Naga (The Dragon Kitchen) is situated on the Bamboo University campus next to the Green School, founded and built in 2008 and documented on pp. 106–107 in this book. The Green School is a private school attended by some 500 students. The campus is set in a lush jungle and most buildings are wall-less. The experimental bamboo structure of the Dining Hall was built as part of a Bamboo U Build and Design course. It is a place to share meals together in harmony with nature. The design and construction process was a collaboration between the Bamboo U and the design firm IBUKU. The structure is held up by a central hyperbolic tower that has been splayed out over the existing terraces of the site to achieve maximum floor space for up to 100 people to enjoy a casual indoor-outdoor dining experience. It has a natural floor made of lime and recycled brick powder. The roof is clad with hand-made copper scales that are intended to look like dragon scales.



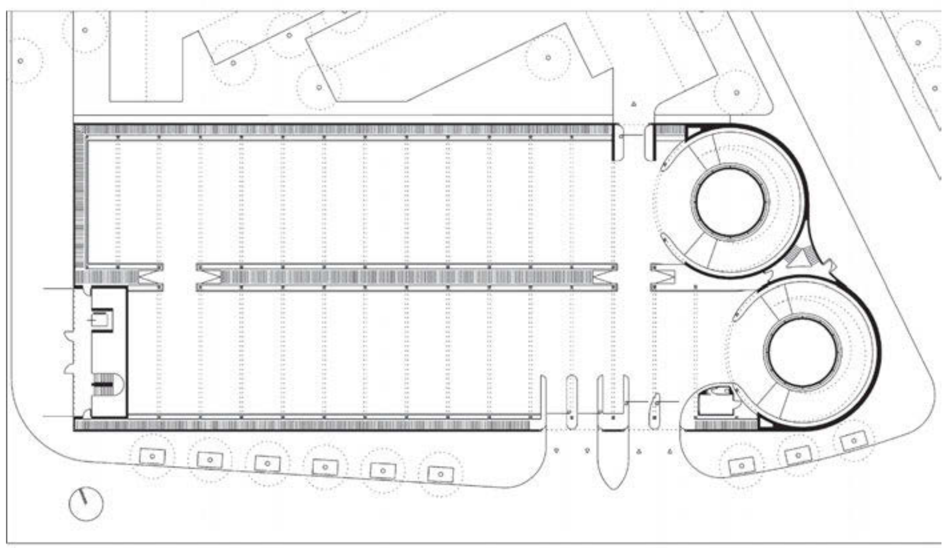


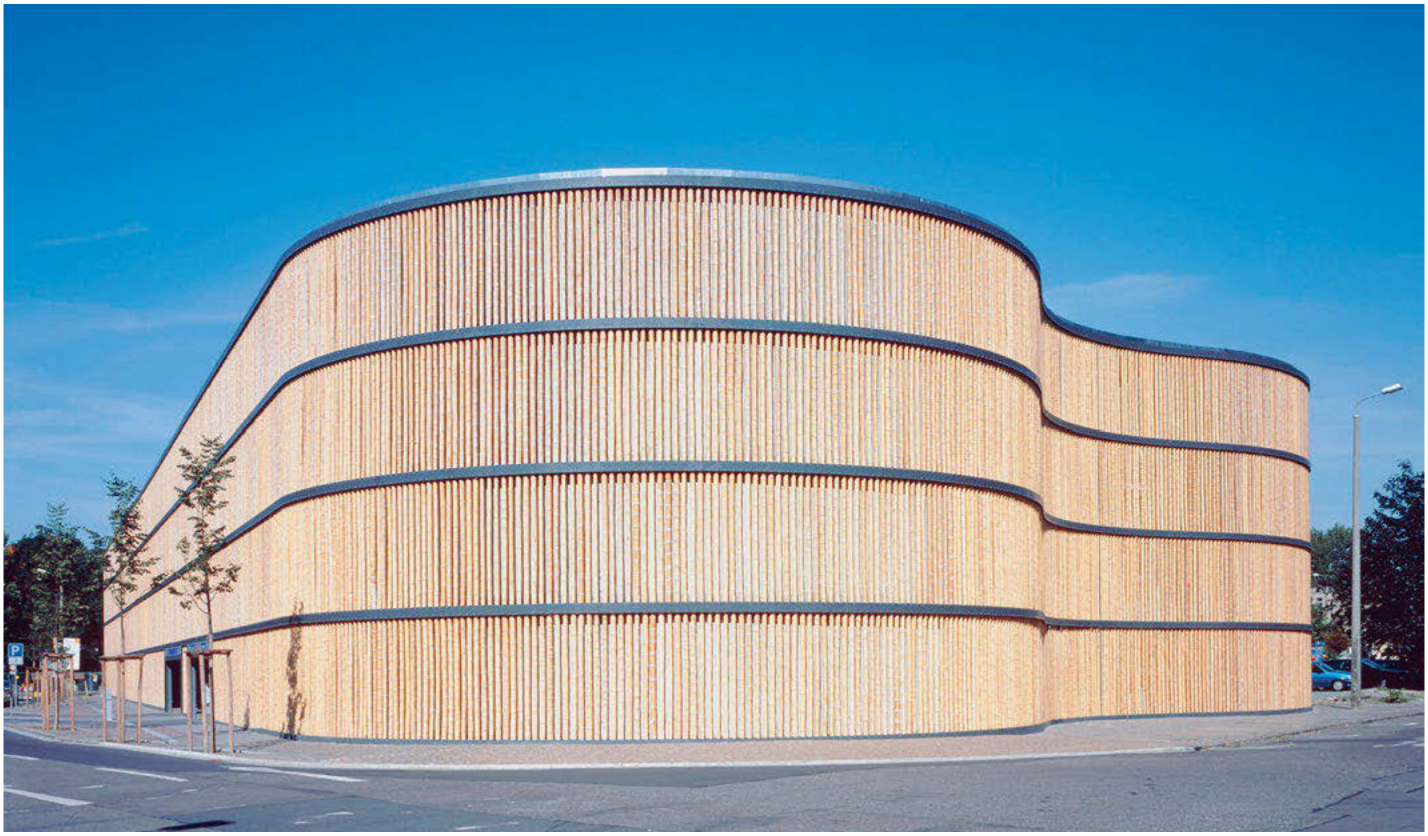


Multi-Storey Car Park Façade
Leipzig, Germany

Architect: Hentrich-Petschnigg & Partner (Gerd Heise)
Completion: 2004

The 4000 m^2 façade of the three-storey parking structure is clad with 7700 *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 towards the outside and furthermore guarantee sufficient light and air for the interior. In 2012, an extension of the car park was built and also clad with bamboo.

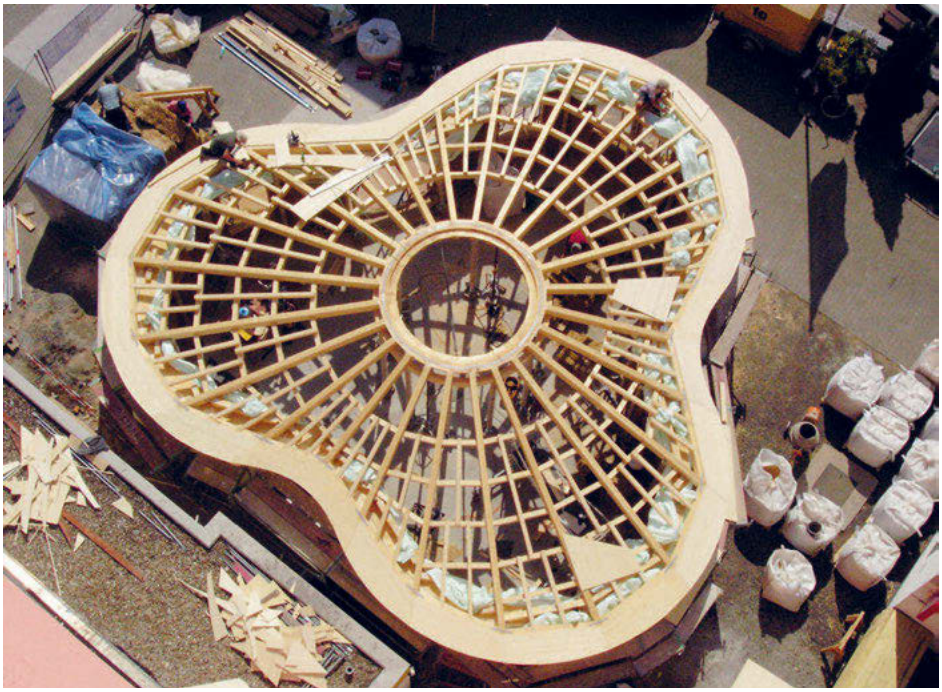




Office Building
Darmstadt, Germany

Architects: Susanne Körner, Tilman Schäberle
Structural calculations and bamboo construction: Christoph Tönges
Completion: 2005
Built area: 85 m^2

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. Engineer Christoph Tönges developed a conical rod connection (similar to the one shown in *9.61*) that connects the bamboo columns with the timber roof. The detail received a Specific planning approval (ZiE – Zulassung im Einzelfall) by the building authority.
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.



Tollgate
Pereira, Colombia

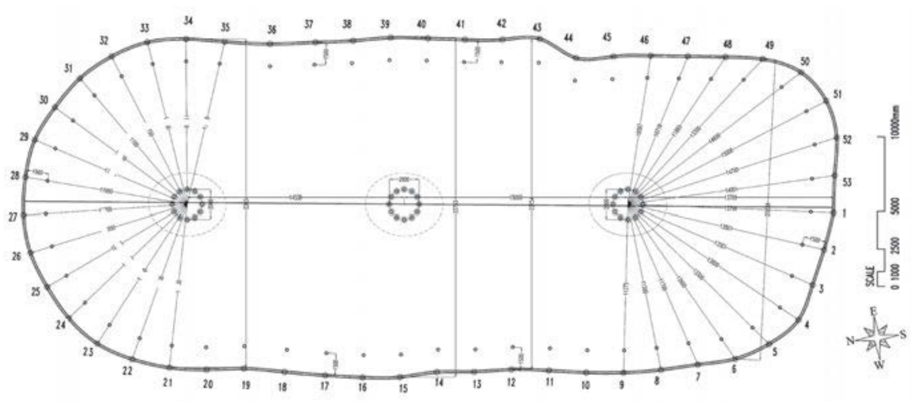
Architect: Simón Hosie
Owner and executor: Odinsa Group
Structural calculations: Herbert Ramírez
Completion: 2006
Built area: 600 m^2

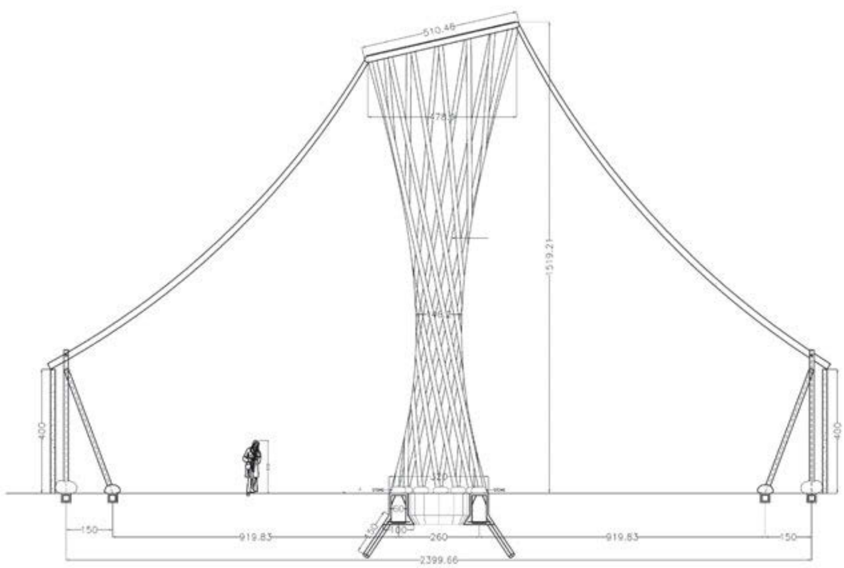
The tollgate has a bamboo roof of *Guadua angustifolia,* 26 m long with four support points. Each point divides the span into two sections: the outer span is 8 m and the main inner span is 18 m, below which the services and functional elements of the tollgate are housed. The anchorages are of steel,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

Jewellery Factory
Ubud, Bali, Indonesia

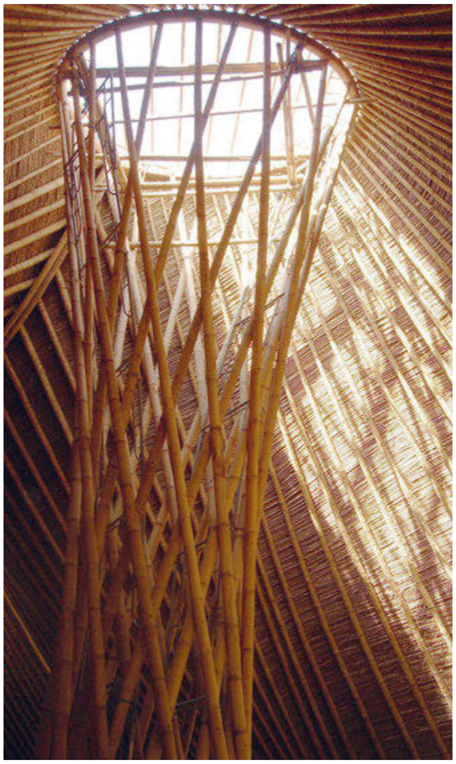
Architect and supervisor: Jörg Stamm
Structural calculations: F. T. Althoff
Completion: 2007
Built area: approx. 1700 m^2
Total cost: 50,000 USD

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.





Section 0 1 2.5 5 10 m



Footbridge
Cúcuta, Norte de Santander, Colombia

Architects: Jörg Stamm, Xavier Pino
Structural calculations: Gerardo Castro
Completion: 2008
Built area: 400 m^2
Total cost: 150,000 USD

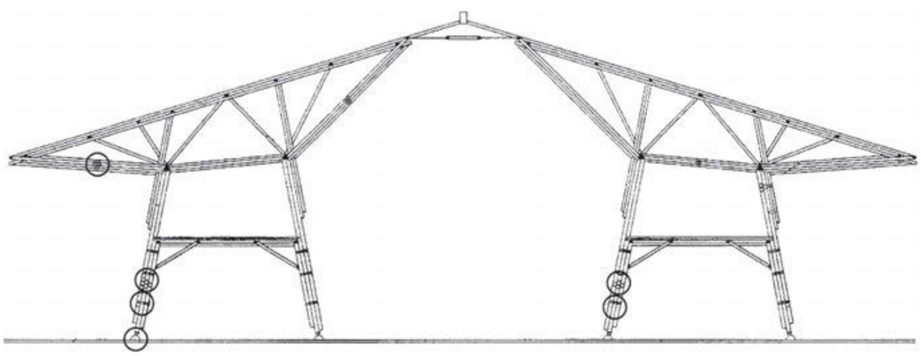
The bridge has a 30 m span and a free width of 3 m. It was built with 600 canes of *Guadua angustifolia* bamboo, with a section of 10–14 cm. Canes with natural curvature were selected for the arches. The compressive forces were transferred to a massive concrete foundation. The floor of the bridge is concrete; the roof has a covering of terracotta tiles. The arched elements consist of five bent bamboo canes that are held together in a permanent curve with timber nails. A membrane roof was installed as protection against the weather. The bridge was calculated for a load of 500 kg/m^2 and a 30-year life span.

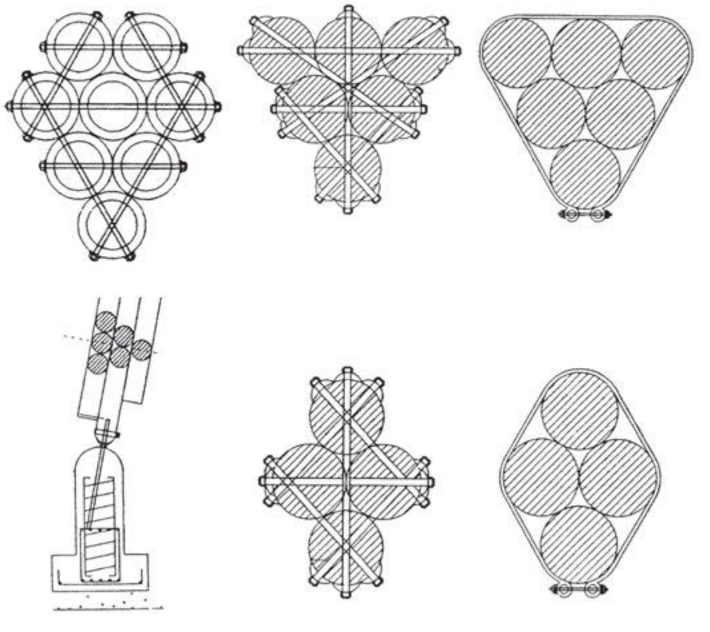



ZERI Pavilion, EXPO 2000
Hanover, Germany

Architects: Simón Vélez, Marcelo Villegas
Structural calculations: Aicher, Lindermann, Steffens
Completion: 2000
Built area: 1650 m², plus gallery of 500 m²

In order to obtain the building permit for this pavilion, a 1:1 scale model was constructed in Manizales, Colombia, see p. 25. 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 ten corners, a diameter of 40 m and eaves of 7 m. The columns have a height between 8 m and 14 m. On the first floor there is a 500 m² gallery. For this structure, 3500 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.





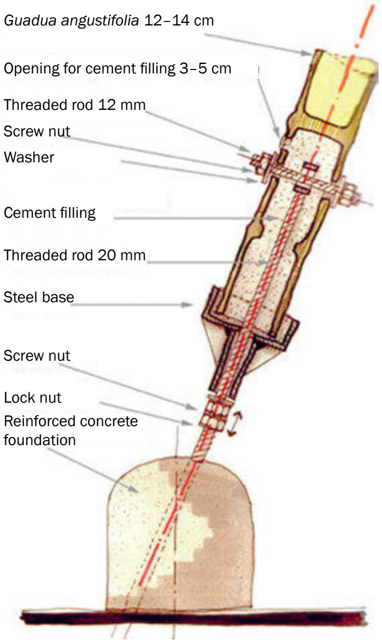
Pavilion
Vergiate, Italy

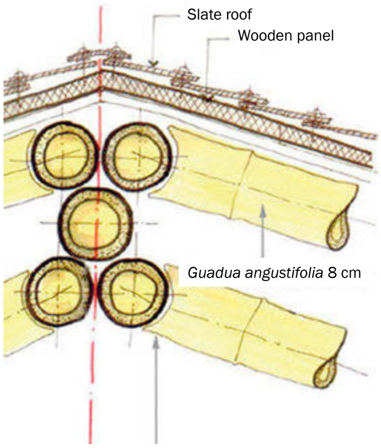
Architects: “emissioni zero” under the direction of Valeria Chioretto and Neri Baulin
Completion: 2003
Built area: 512 m^2

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.








Restaurant Roof
Coburg, Germany

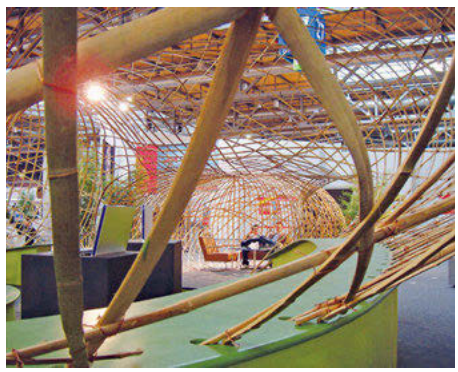
Architect: Auwi Stübbe
Realisation: Students of Coburg University of Applied Sciences
Completion: 2006
Built area: 300 m^2

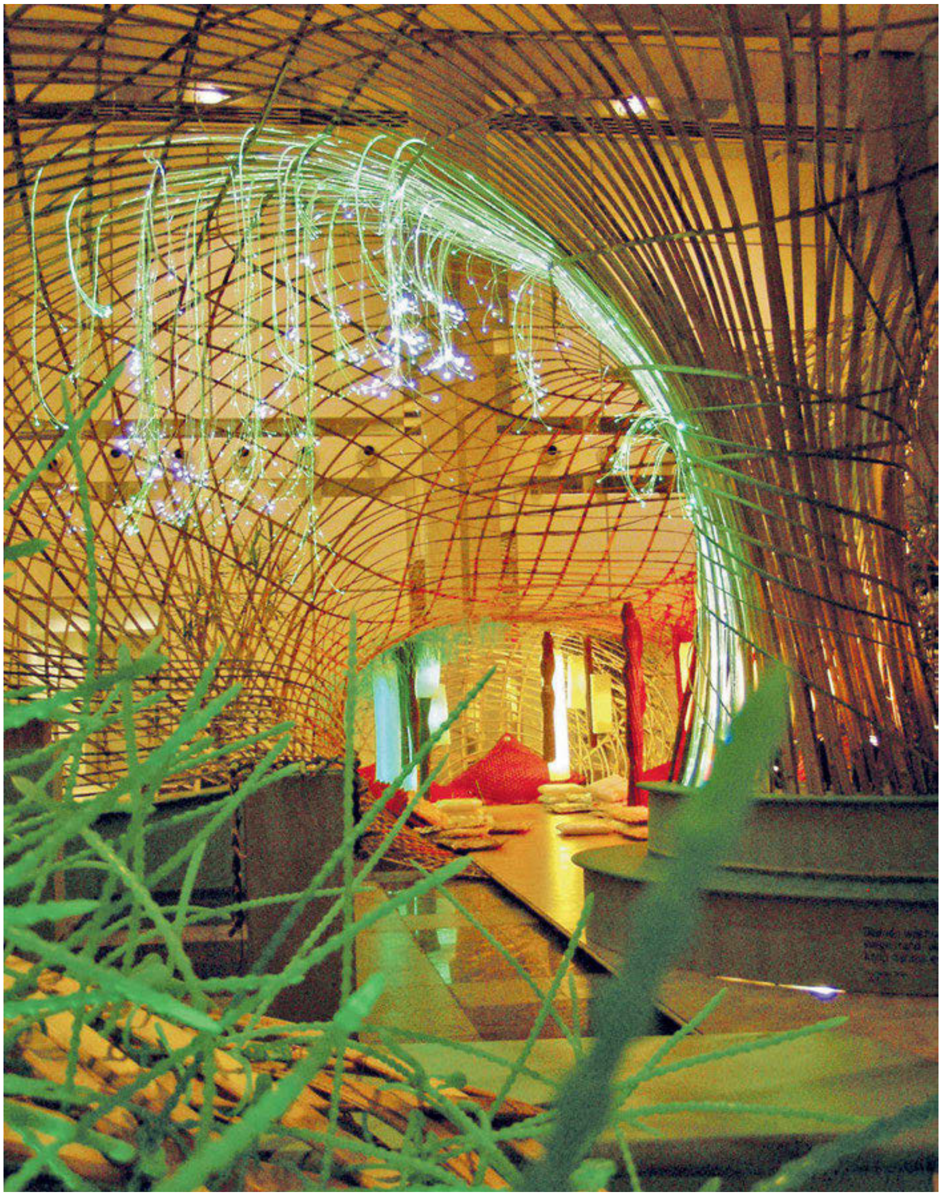
Auwi Stübbe and his students at the Coburg University of Applied Sciences, Germany, built a roof with a network of bamboo laths for a "Design Fair" held by their university. Slats made of split bamboo with a length of 6 m form a triangular mesh structure. Where they meet at their ends, the slats overlap 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.

Exposition Roof
Cologne, Germany

Architect: Auwi Stübbe
Realisation: Students of Coburg University of Applied Sciences
Completion: 2006
Built area: 140 m^2

A roof over a rest space, consisting of the same construction as an earlier realised Restaurant Roof (see pp. 144–145), was built by Auwi Stübbe and his students for the furniture exhibition "IMM Cologne 2006". The area has different braided furniture and illumination objects.





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

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

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. In 2008 and 2009 Heinsdorff built various pavilions on city squares in Chongquing, Guangzhou, Shenjang and Wuhan. Each pavilion was composed of several elements that could be combined for different forms. They are dismountable after 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 *9.43* to *9.46* and *10.24*),

Indian Pavilion, EXPO 2010
Shanghai, China

Concept: Sanjay Prakash & Ass., Pradeep Sachdeva, Ass., Environmental Design Solutions, New Delhi; Integrated Design, Bangalore
Dome design: Pradeep Sachdeva, Simón Vélez
Structural calculations: Prem Krishna
Completion: 2010
Built area: 980 m^2

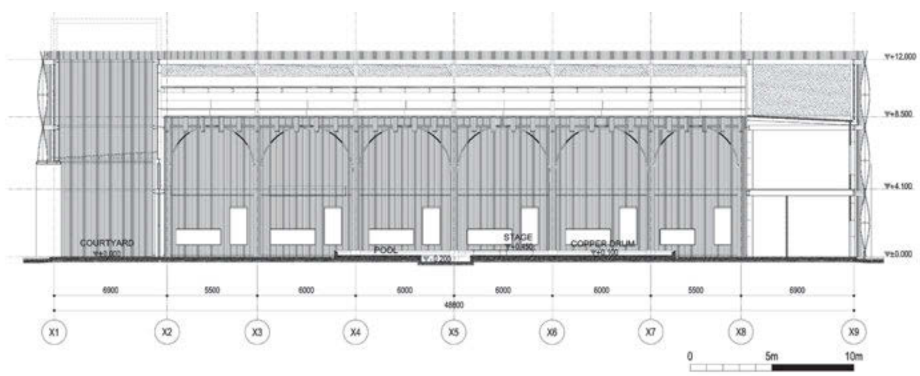
The pavilion has a domed form, 35 m in diameter and 17 m high. The structure consists of 36 arches, each one formed with a triangular section of six bamboo canes, with secondary horizontal and vertical elements. This dome supports a micro-concrete shell; a membrane functions as moisture barrier. The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

Vietnamese Pavilion, EXPO 2010
Shanghai, China

Architect: Vo Trong Nghia – VTN Architects
Completion: 2010
Floor area: 1000 m^2

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.

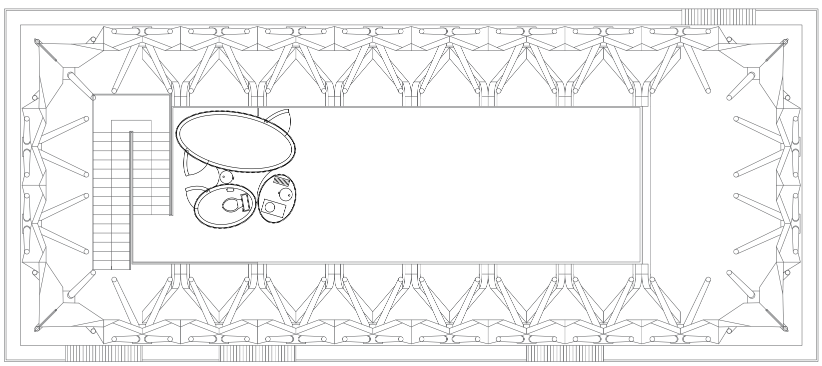


German-Chinese House, EXPO 2010 Shanghai, China

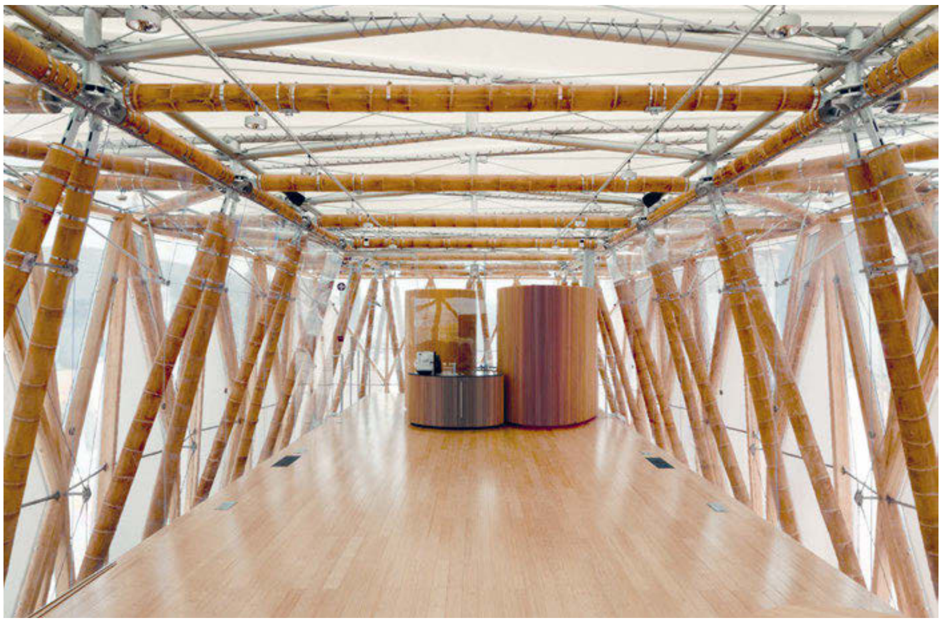
Architect: Markus Heinsdorff
Organisation and realisation: MUDI Architects, Shanghai
Structural calculations: Chair for Timber Engineering and Wood Technology, TU Munich; Institute of Solid Construction and Institute of Materials and Mechanics in Civil Engineering, TU Darmstadt; Tongji University, Shanghai
Completion: 2010
Built area: 330 m^2

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.

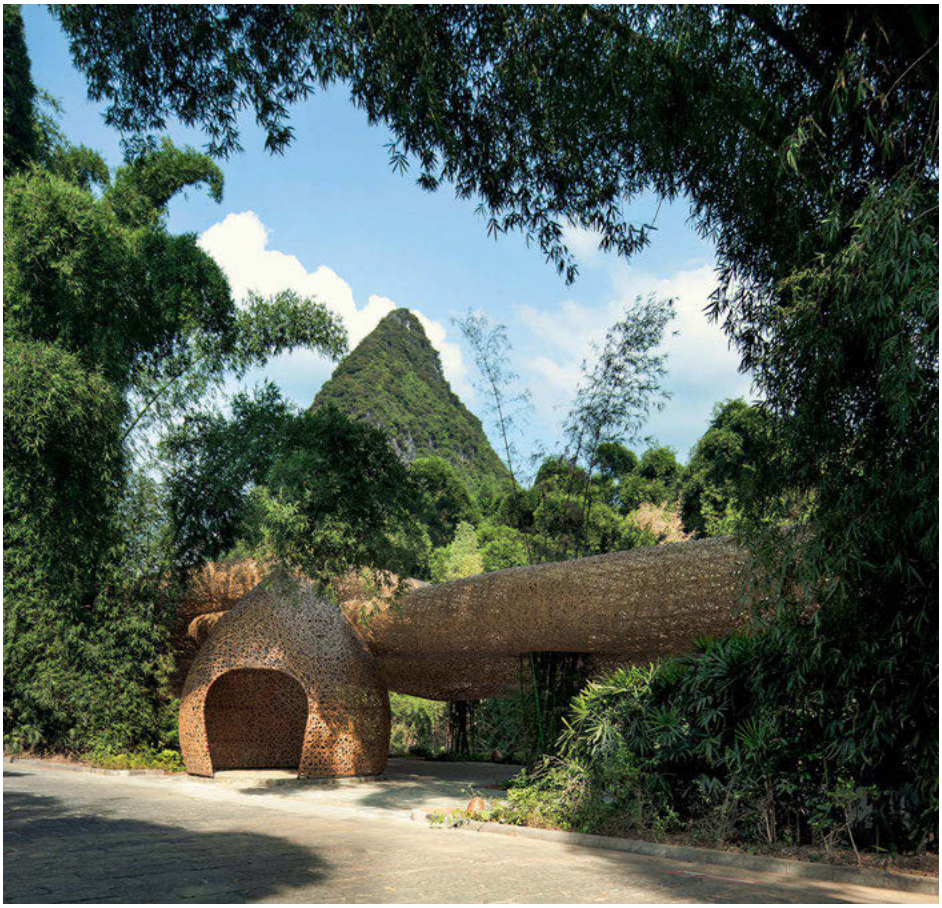
The ends of the bamboo canes were first soaked with polyurethane resin and a further layer of polyurethane-resin-soaked grit to provide a good mechanical key. The ends were then filled with a concrete mixture made with a high proportion of fly ash, which ensures that the concrete adheres firmly and without 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 (see *9.43* to *9.46*). The façade of the pavilion is covered with a lightpermeable 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

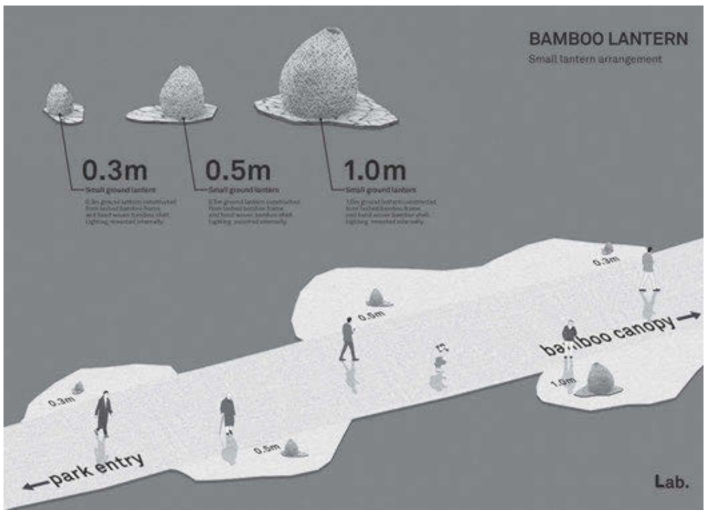


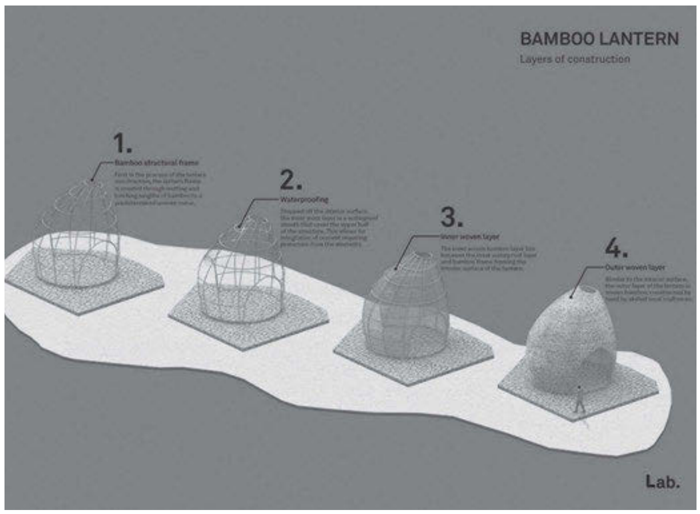
Bamboo Canopy and Pavilions, Perfomance Space "Impression Sanjie Liu" Yangshuo, Guilin, China



Architects: IILab. (Design team: Hanxiao Liu, Henry D'Ath, Lexian Hu, Alyssa Tang, Chaoran Fan, Luis Ricardo, David Correa)
Structural calculations: Lalu Partners Structure Consulting
Bamboo lantern, bamboo weaving and structure installation: Shanghai JD Bamboo Architectural Design & Engineering Ltd.
Completion: 2020
Site area: 90,000 m^2
Built area: 1900 m^2

The performance space for the show “Impression Sanjie Liu”(Impression of the Third Sister Liu) is located in one of the most dramatic landscapes in China. Endless greenery surrounds the site dominated by large karst towers of rock. The bamboo canopy and pavilions were to be added carefully to the existing site, in deference to the overwhelming landscape. Large clusters of bamboo plants cover most of the area, thus creating natural structures of mingling pipes and leaves. The structures were inspired by these bamboo groves and try to blend in with them.
The show has two main areas at either end of the island. The entry and pagoda form the arrival zone for the guests and the main stage provides the performance space, perched at the bank of the Li River at the other end. Between these two functions, there was little interaction so far. The two interventions, lantern and canopy, were introduced in this middle part of the island. The first, woven bamboo lanterns, are scattered where guests circulate and they guide and intrigue them. The second structure is a woven canopy amongst clusters of bamboo that provides an ambulatory to walk sheltered from the regular rainfall.
Upon entering the site, small lanterns line the pathway and cast a dappled light. As visitors walk further, the lanterns become drastically larger to a point where the guests can walk into the lantern. Each lantern consists of a structure of bamboo lengths encased in lashed bamboo on either side. The bamboo framing shows markings of how it is bowed with fire to create the curved lantern silhouette. Teams of local craftsmen have threaded numerous strips of bamboo in an intricate pattern that requires no glues or nails. These pieces of handicraft are therefore all slightly different. In the daylight, the lanterns appear solid. At night, the lantern becomes porous. While diffusing light, it plays games of scale and light.
Further along, at the edge of the island, the canopy shrouds itself within the large masts of bamboo. At first glance, it appears to have no support, only the columns of bamboo going up through the circular openings. The columns twist upwards from their footing and outwards, mimicking the indecisive growth path of the bamboo to meet the structure above. The hand-woven layer obscures what is in front and what lays behind. Stretching 140 m, the woven ceiling takes on a shape of an inverted landscape, undulating between different levels of surfaces. The stepped surface of the canopy is pieced together entirely with the same irregular hand-woven bamboo as the lantern, but on a larger scale. During the day, light streams through the woven fabric of the canopy, creating patches of light on the ground below. The entire canopy gives off a temperate glow. At night, lighting orchestrates the movements of the visitors making their way to the stage.
Inspired by the spirit of Impression Sanjie Liu, theatrical moments made its way into many parts of the design: The hand-weaving of the bamboo; the topography of the canopy dancing between columns of bamboo as if unsupported and even the way guests can move from lantern to lantern, in a narrative of interaction – everything acts together to create a festive and dramatic mood, readying the visitors for the performance.


BAMBOO LANTERN
Small lantern arrangement
0.3m
0.5m
1.0m
0.3m
0.5m
0.3m
0.5m
1.0m
bamboo canopy
park entry
Lab.


BAMBOO LANTERN
Layers of construction
1.
2.
3.
4.
Lab.

Digital Bamboo Pavilion
Venice Biennale, Italy

Architect: Digital Building Technologies at ETH Zürich
Completion: 2020
Built area: 40 m^2

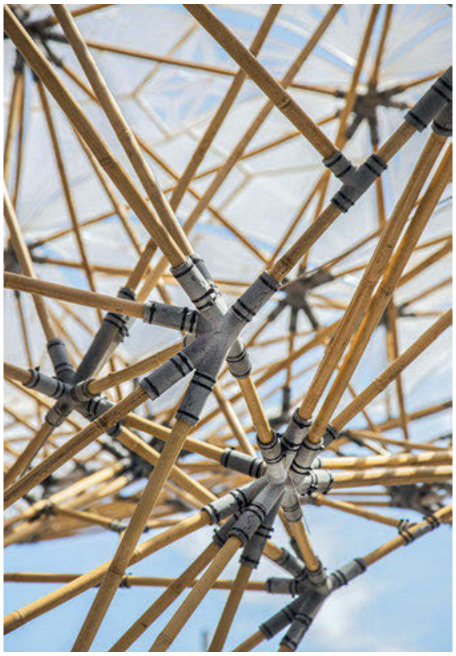
The Digital Bamboo pavilion, planned by the chair of Digital Building Technologies at ETH Zürich, under the supervision of Prof. Benjamin Dillenburger, represents the combination of a biologically based material with digital fabrication. The goal was to create a novel sustainable constructive system.

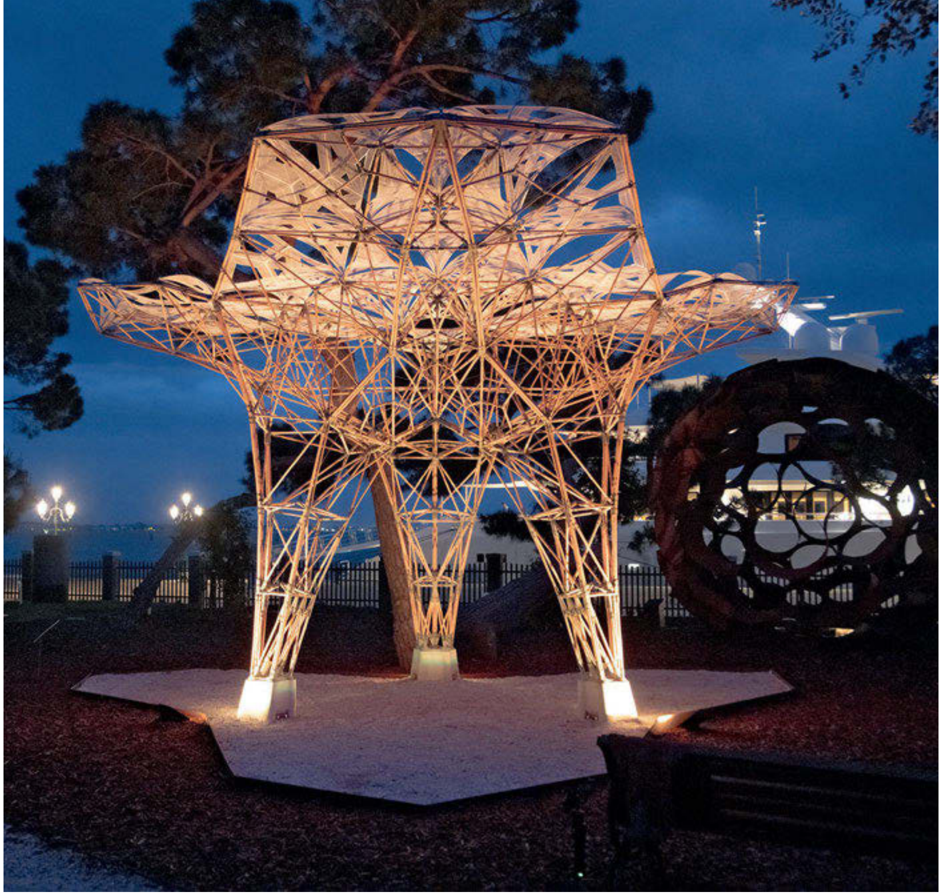
The ultralight structure is a space frame that covers an area of 40 m^2 and has a total weight of only 200 kg. It is composed of 930 bamboo poles connected with 381 3D-printed joints and covered by lightweight 3D-printed shading panels. The geometry of the pavilion is rotationally symmetric, consisting of three wings supported by three columns; the wings cantilever almost 5 m in three directions while requiring minimal support. The main load-bearing system is defined by a spatial truss reinforced by post-tensioned cables. It was designed using customised computational tools that allowed the seamless integration of design, structural validation, research development and fabrication constraints.

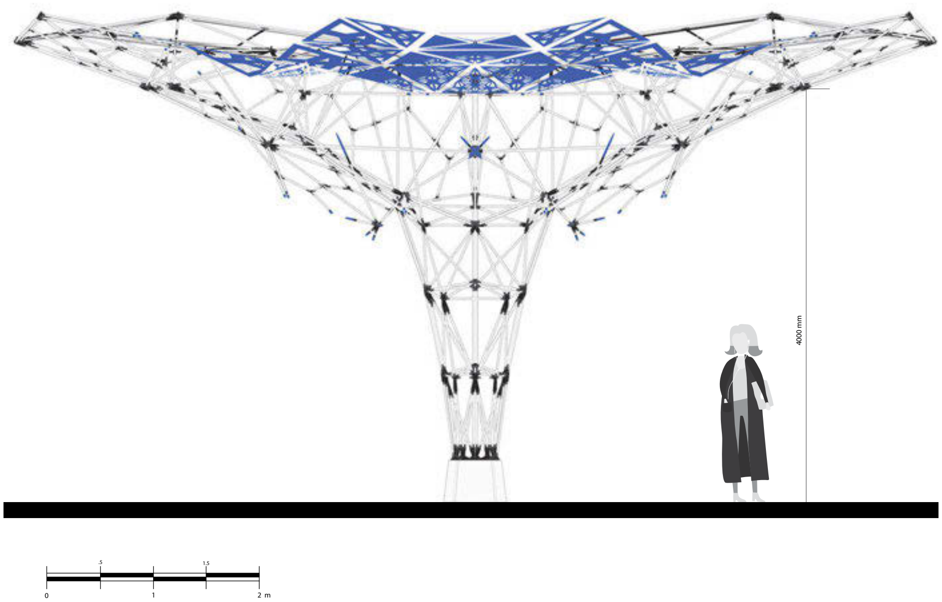
The bespoke connection system was developed specifically for bamboo and is based on the 3D-printing technology MultiJet Fusion. It is a fully reversible dry connection system tailored to ease assembly and minimise the use of material.

The shading panels of the pavilion are fabricated through a method called add-on 3D printing of a recyclable UV-resistant thermoplastic on a lightweight Lycra textile. 3D printing stiffens and shapes the fabric into flexible bespoke panels. The composite elements are locally reinforced.

The construction system developed for the pavilion aims to reduce the logistical efforts of construction while exploiting the advantages of digital fabrication. Following the principle of decentralised prefabrication, the complexity of the structure is encapsulated in small parts that can be fabricated all over the world using available 3D printing machines. These custom parts can be used to build high-performance structures in combination with local materials.






4000 mm
0
1
2 m

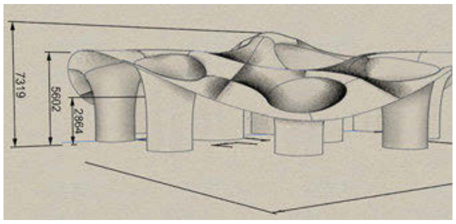
Canopy at Terra Botanica Park
Angers, France

Architects: L'atelier Déambulons, Louise Rué
Structural calculations: Aurea structure
Realisation: L'atelier Déambulons
Completion: 2020
Built area: 600 m²

For the tenth anniversary of the Terra Botanica park, it was decided to create a new landscaped area called the Oasis. The objective was to provide an installation at the visitor's entrance to make the existing restaurant terrace more attractive.

The structure consists of 12 shafts from which the slats radiate outwards, crossing each other to form a lace pattern. The crossings were fixed by rivets. The fractal design was developed using the parametric method via Rhinoceros software. This computer design method made it possible to obtain the desired curves. The 3D modeling was done by Hugo Pont – SD4B.

About 1300 bamboo culms, split into more than 5000 strips with a total length of 20 km, were needed to cover the 600 m² surface and to achieve the height of 7 m. The assembly was done by ten people within three months.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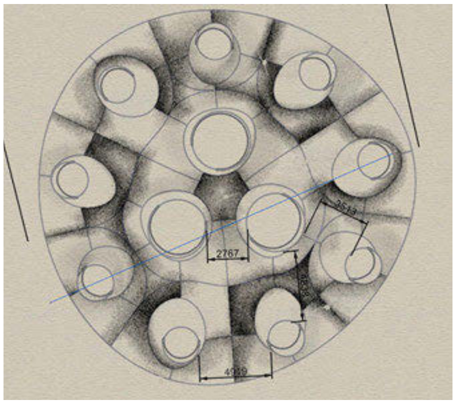
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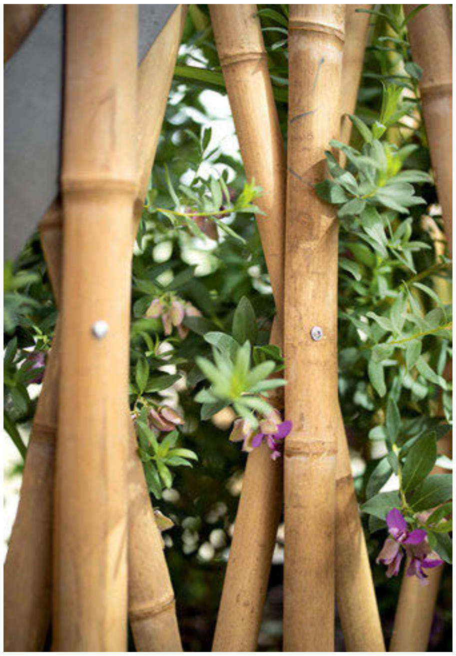

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About the Author

In 1974, Gernot Minke founded the Building Research Laboratory (FEB) at the University of Kassel, devoted to the exploration of natural building materials. At this laboratory, he directed more than 40 research and development projects in the field of building with bamboo, earth, straw bales, green roofs and low-cost housing. He taught at the University of Kassel for more than 35 years and was the invited speaker at more than 60 international conferences. Minke is also an independent architect and worldwide advisor for building ecology as well as the author of numerous articles and several technical books, among them *Straw Bale Construction Manual* (2020) and *Building with Earth* (fourth and revised edition, 2021).

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