# Bamboo As Building Materials In Rural Area-Greenhouse Design

## Master degree Thesis


POLITECNICO DI MILANO

Master degree in Architectural and Urban Design
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# Abstract

Bamboo is a cultivated material that can be planted in anywhere. At the same time, it can grow fast and can be constructed easily by simple techniques. Therefore, in rural area like Castiglione Della Pascaia, it is a perfect to plant bamboo and build a greenhouse and other creative spaces, because of affability and feasibility. Most of materials can be collected from local inhabitants, such as paper, bamboo, bio-waste, plastic, clothes. Greenhouse will provide fishes, vegetables for local. This kind of project also can create space for local education on agriculture and for kids to play.

There are more than 1600 species of bamboo and most of them are growing at the tropical area. In Italy, there is no endemic species but many projects that tried to introduce bamboo to Italy, such as Castiglione Della Pascaia, Parma, Ivrea. As building material, bamboo can be structure elements like beams and pillars, trusses. It also could become nonstructural element, such as strips and waving, different sorts of cutting for walls, windows, and roofs. It can be intertwined and reinforced with concrete or laminated and compressed as dense blocks.

Bamboo can grow fast with different size according to species. The upper part of culm includes more fibers, so it is more elasticity and can be used as leaders or sticks. The middle part usually can be transferred to structures like roof purlins, scaffoldings, and pillars. The testing on five main species in Italy shows that Bambusoides and Iridescens have good mechanical property on compression and tension. Planting bamboo optionally uses 5 x 5 meter spacing. After 3 to 8 years during mature period, it can be harvested and treated with Boucherie method or Borax acid immersion method.

Bamboo can be flexibly connected by tight rope, bamboo strips or rattan, or it is possible to use plugin and bolt connection. Interlocking connection frequently applies to more complicated structures. The foundation always uses the way to integrate with concrete and bamboo. Floor, roof, wall, door, and window can be constructed by different techniques. Meanwhile, rod shaped building structures, like straight rods, curved compression rods, curved tension rods are the main approaches to frame building stably.

There are many cases that could be referred, from Walter Lise projects for Vergiate Bamboo Pavilion and ZERI Pavilion for EXPO 2000, to Atelier cnS's project in China, such as Changqi Stadium Bamboo Corridor and Huanglong Waterfront Bamboo Pavilion, for which they design bamboo structures with umbrella shape and jointing together, integrating with steel skeleton and special waving techniques.

Therefore, the design proposal will concentrate on sustainable approaches of reusing local waste and bamboo, creating spaces serving for local community from indoors to outdoors, applying aquaponic systems and collecting rainfall and sunlight. The greenhouse is placed on the top of existing underground parking lots, so bamboo is an ideal building material not only for feasibility and low money, but also for light structure.

# Acknowledgement

I am really grateful to my dear supervisor- Professor Clementi Matteo for helping me to improve my thesis and design project by explaining with understandable ways. During each step, he provided lots of very useful advice for me and I learned so much knowledge from him, not only on architectural design, construction ways, sustainable strategies, but on the ways to solve the problems confidently. I did so many versions for final design with different ways in the last half years, speeding so much time on it. I was kinds of nervous and misunderstanding on the way how to improve my projects properly. Thanks to my professor for his hard work and explaining patiently. I am so satisfied with my result of design proposal, trying to apply a reasonable, stable structural systems. Also, I would like to thank Polimi to provide this amazing studying atmosphere and platform to share knowledge. I learned a lots of knowledges and experiences form my colleagues and teachers, which expended my horizons.

Thanks again to all who helped me!

07th July, 2022 in Milano

# Contents

# 1.About Bamboo

Bamboo, as a cultivated material, has more than 1600 species all over the world. Some of them can be used as decoration or structural elements for buildings. Bamboos are distributed mainly on tropical area, particular south-east-Asia. Also it can grow in different environments according to different species, which can be divided to neotropical woody bamboos, north temperate woody bamboos, paleotropical woody bamboos, and herbaceous bamboos. Even though in Italy, there is no endemic species. Nowadays, bamboo was farmed around Italy, such as the Labyrinth of Masone in Parma, Ivrea, Castiglione della Pescaia. The species growing in this areas mainly belong to phyllostachys bambusoides, phyllostachys edulis, phyllostachys iridescens, phyllostachys vivax, and Phyllostachys violascens. While many institutes are working to use bamboo as building materials. Studio Cardenas was trying to combine bamboo with contemporary technologies. EMISSIONIZERO applied Guadua bamboo poles to build pavilion in Europe.

# 1.1 Bamboo species

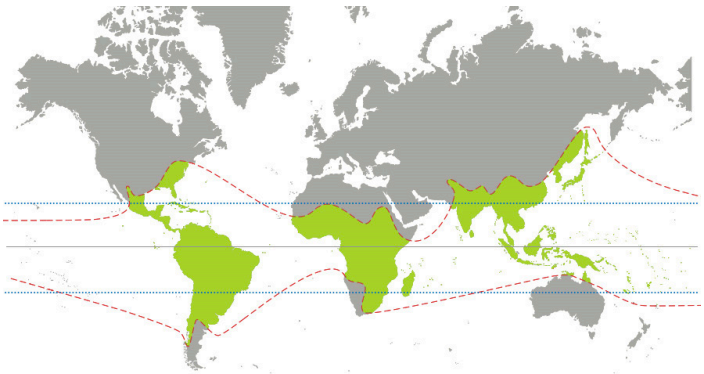
### Several bamboo species

There are many different opinions on how many species of bamboo that there are. Some experts say there are approximately 1000 species of bamboo, while others say there are more than 1600 species on the planet growing naturally. Of course, all these species of bamboo are both decorative and useful when they are used in the **homes and businesses** in countries around the world.[1,Bamboogrove]

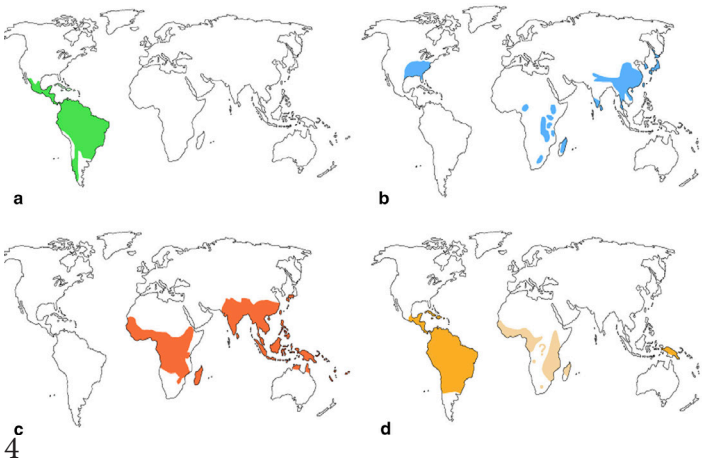

1. Phyllostachys aurea
2. Chimonobambusa quadrangularis
3. Phyllostachys nigra
4. Phyllostachys bambusoides " Violascens"
5. Phyllostachys nigra f. boryana
6. Phyllostachys viridis " Robert Young"
7. Phyllostachys bambusoides

(2,Xiaobing Yu)

# 1.2 Geographical distribution



(National Geographic,1980)




### Global Natural Bamboo Habitat

The main area of distribution are the **tropics**, in particular, South-East-Asia. Bamboo grow at sealevel and can be found at altitudes of up to **3800m**.
Most bamboo species grow at temperatures from **-28°C to +50°C**. Bamboos grow mainly on sandy loam to loamy clay soils. They prefer well drained soils but grow also in wet and even marshy locations. They do not tolerate saline soils. [3,Dunkelberg]

-a Neotropical woody bamboos
-b north temperate woody bamboos
-c paleotropical woody bamboos
-d herbaceous bamboos
(4,Yeasmin)

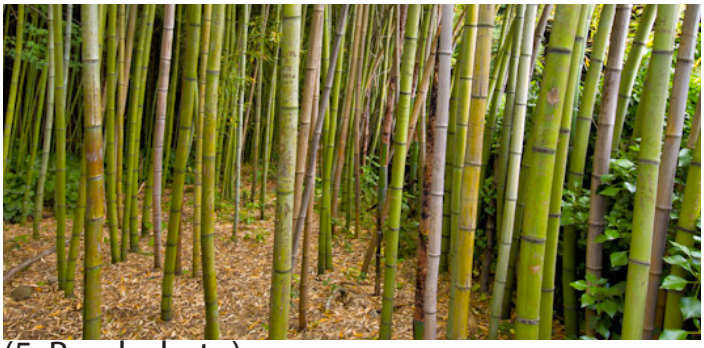
**Worldwide distribution of bamboo**

**Herbaceous bamboo** constitutes about 110 species which are mainly concentrated in the Neotropics of Brazil, Paraguay, Mexico and West Indies. The natural bamboo forest covers approximately 600,000 ha area across Brazil, Peru and Bolivia, which is known as "Tabocais" in Brazil and "Pacales" in Peru. The Bambuseae tribe includes about 1,290 species worldwide and constitutes three major groups. The **Paleotropical woody bamboo** is distributed in the tropical and subtropical regions of Africa, Madagascar, Sri Lanka, India, Southern Japan, Southern China and Oceania. The **Neotropical woody bamboo**s are distributed in Southern Mexico,Argentina, Chile and West Indies. The **north temperate woody bamboos** are found in the North Temperate Zone and a small amount at a higher elevation of Madagascar, Africa,India and Sri Lanka.[4,Yeasmin]

## 1.3 Bamboo in Italy


There are close to 2,000 known varieties of bamboo, native to Asia, Africa and the Americas. That makes Europe one of the only continents with **no endemic species** of this prolific grass. But the region certainly has its share of bamboo enthusiasts. And now efforts are finally under way to begin farming bamboo in Europe.[5,Bambubatu." Bamboo Farming and Industry in Europe in 2022."]

**Three bamboo forests in Italy:**

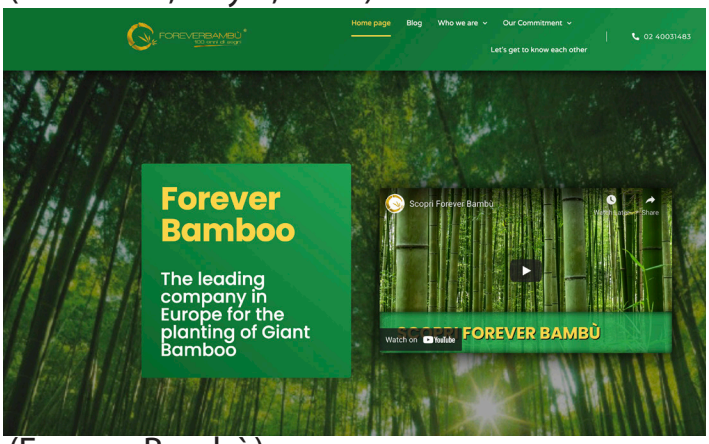

(5. Bambubatu)

In the province of **Parma, the Labyrinth of Masone** is the largest existing labyrinth of bamboo plants between 30 centimeters and 15 meters high, belonging to 20 different species, for a total of 200 thousand specimens. **Phyllostachys bissetii** was most used for the Labyrinth. [6,Claudio Cafarelli]


(5. Bambubatu)

The first bamboo natural park was born in **Ivrea** and will extend over 15 hectares with the aim of promoting educational paths to discover the properties and benefits of this plant. [6,Claudio Cafarelli]

(Facebook, July 3, 2021)




(Forever Bambù)

(http://casavacanze.poderesantapia.com/)


(www.museidimaremma.it)

## Castiglione della Pescaia

103 hectares of **Phyllostachys edulis bamboo**,they will be used to build the largest Italian forest a Castiglione della Pescaia, in the province of Grosseto. In Toscana, the Italian company **Forever Bambù** will plant the first 40 hectares by this spring, while the remaining 63 in 2022. The forest, of 100 thousand giant bamboo plants, will be able to absorb 27.500 tons of carbon dioxide in just one year. [6,Claudio Cafarelli]

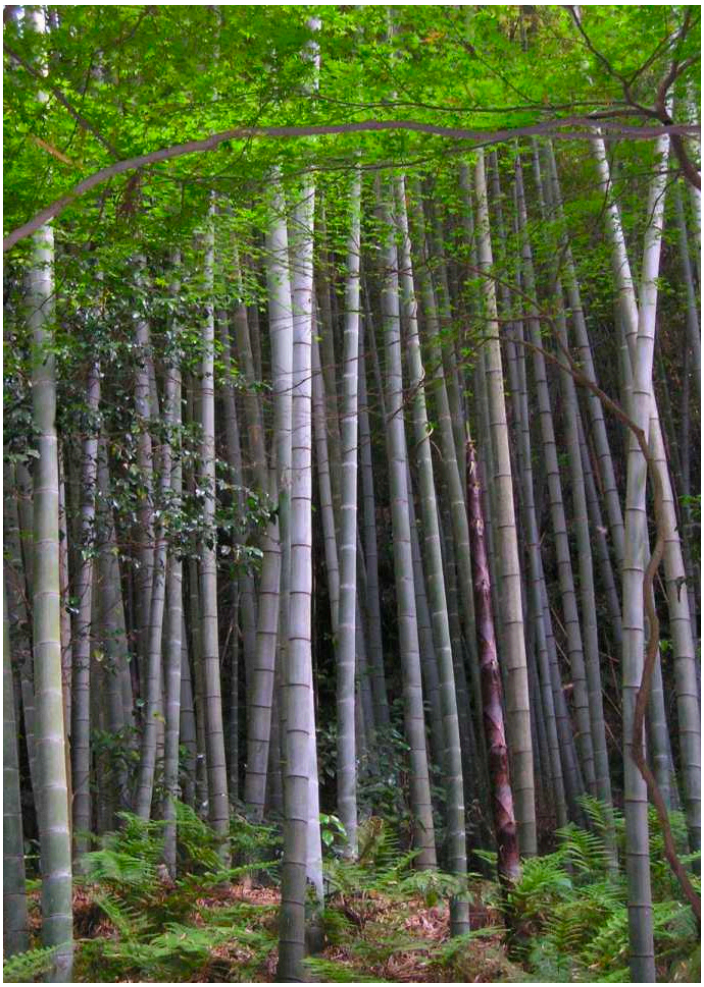
**Forever Bambù** is the first Italian initiative that combines a structured supply chain with attention to the planet and the territories through the cultivation of **Giant Bamboo**: a versatile, resistant and sustainable material used in the food and industrial sectors, which absorbs 36 times more CO2 than any traditional forest and can replace many polluting resources such as plastic. (https://www.foreverbambu.com/)

While the giant bamboo in Maremma is highly **invasive species**.The giant bamboo is in fact an allochthonous plant species, highly invasive and capable of seriously altering the plant and animal biocoenoses of the areas where it spreads.The serious impact of the diffusion of this species outside its range has already been amply demonstrated in the case of Japan, where the problem has now become more evident.Equally well known and evident is the difficulty or, better, the impossibility of proceeding with an eradication of the species where it has now established itself.If we then consider that the project in question would insist on an area of exceptional naturalistic value such as the **Grosseto plain** and in particular it would be located a short distance from the **Diaccia Botrona swamp** , a site of community importance, a wetland of international importance and an area of exceptional natural values, as well known, the unsustainability of the initiative is even more evident. [7,Toscana Chianti Ambiente]

**Five species mainly existing in Italy:**

## Phyllostachys bambusoides

Phyllostachys bambusoides is a "running" (monopodial type) evergreen bamboo which can reach a height of roughly **20 m** (66 ft) and a diameter of **10 cm** (3.9 in). The culms are dark green, with a thin wall that thickens with maturity, and very straight, with long internodes and two distinctive rings at the node.The species is thin-skinned, easily split lengthwise, has long fibres, and is strong and highly flexible, even when split finely.Leaves are dark green, and the sheaths are strong and hairless. New stalks emerge in late spring and grow at a rate of up to 1 m (3 ft 3 in) a day; one specimen produced culms growing a remarkable 120 cm (47 in) in 24 hours.The flowering interval of this species is very long, lasting roughly 120 years. [8,Wikipedia]



## Phyllostachys edulis

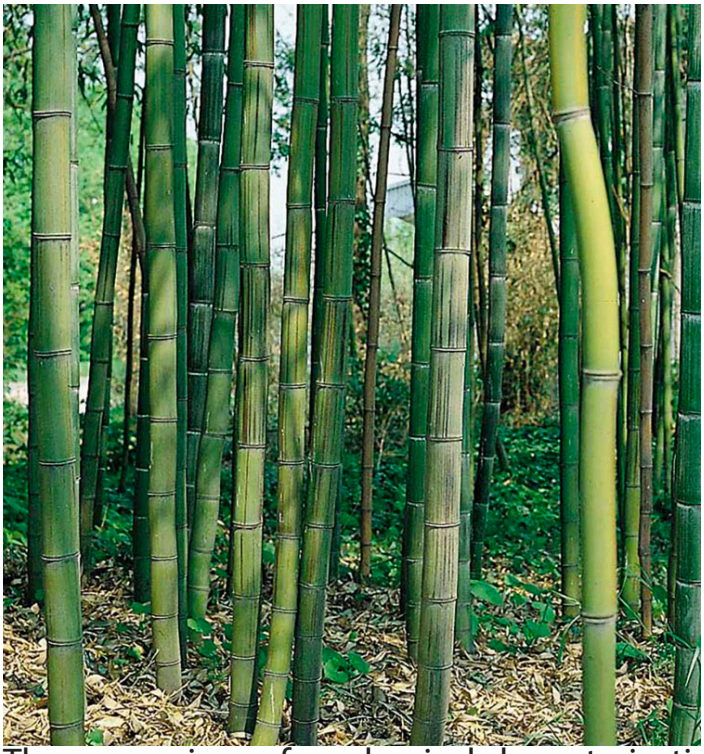
Phyllostachys edulis, the mōsō bamboo, or tortoise-shell bamboo, or mao zhu is a temperate species of **giant timber bamboo** native to China and Taiwan and naturalised elsewhere, including Japan where it is widely distributed from south of Hokkaido to Kagoshima.The edulis part of the Latin name refers to its edible shoots. This bamboo can reach heights of up to **28 m** (92 ft).This particular species of bamboo is the most common species used in the bamboo textile industry of China and other countries, for the production of rayon.The diameter could be up to **18cm.** [9,Wikipedia]

## Phyllostachys iridescens

Maximum Height: **12+ m**(40+ feet)
Diameter: **8.9 cm**(3.5 inches)
Hardiness: -5º F
Phyllostachys iridescens is one of our largest, fastest growing, and strongest bamboos. The culm walls are very thick and are used for timber. Many of the canes have light yellow striping and a bright white band beneath the node. Some also have graceful bends in the lower internodes. The culm sheaths when the new shoots emerge are a very attractive reddish-brown, with long, colorful sheath blades (see photo on left). This bamboo makes a nice specimen or grove and is very cold hardy and reliable. [10,Bamboo Garden]

## Phyllostachys vivax

Phyllostachys vivax, the Chinese timber bamboo, is a species of flowering plant in the bamboo subfamily of the grass family Poaceae, native to China.It is a tall, robust evergreen plant growing quickly to 8 m (26 ft) or more, with strong green canes to **12 cm** (4.7 in) in diameter, and topped by drooping leaves. Sources vary as to the maximum size, with one source quoting **21 m** (69 ft). Mature canes turn yellow.Initially forming clumps, the plants will eventually establish large thickets via underground running rhizomes, unless artificially restricted. The form P. vivax f. aureocaulis from eastern China is frequently found in cultivation, and has more vivid yellow canes striped with green. It is suitable for parks or large gardens, and is hardy down to at least −15 °C (5 °F). It has been given the Royal Horticultural Society's Award of Garden Merit.The Latin specific epithet vivax means "long-lived". [11,Wikipedia]

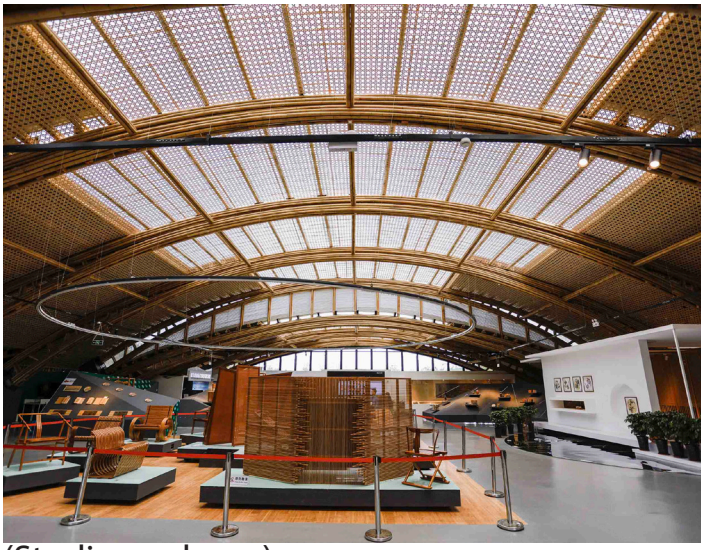


**Phyllostachys violascens**

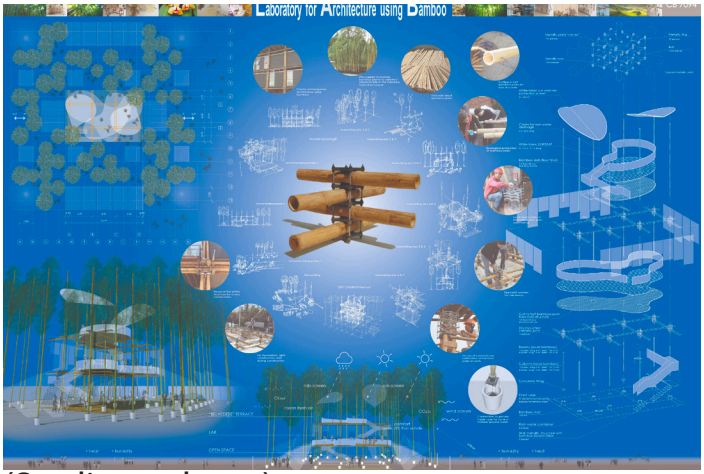
Height: **9.14 m**(30 feet)
Diameter: **5.08 cm**(2 inches)
Hardiness: 0º F
This bamboo is an enigma. Sometimes striped with brownish purple. Sometimes striped with gold or yellow. And, sometimes just plain green. It spreads vigorously but its wood is not very strong so in an average winter expect several canes to break under the weight of the snow. [12,Bamboo Garden]

The comparison of mechanical characterization of five species in terms of compression and tensile properties will be descriped at the chapter 3.

## 1.4 Research institutions



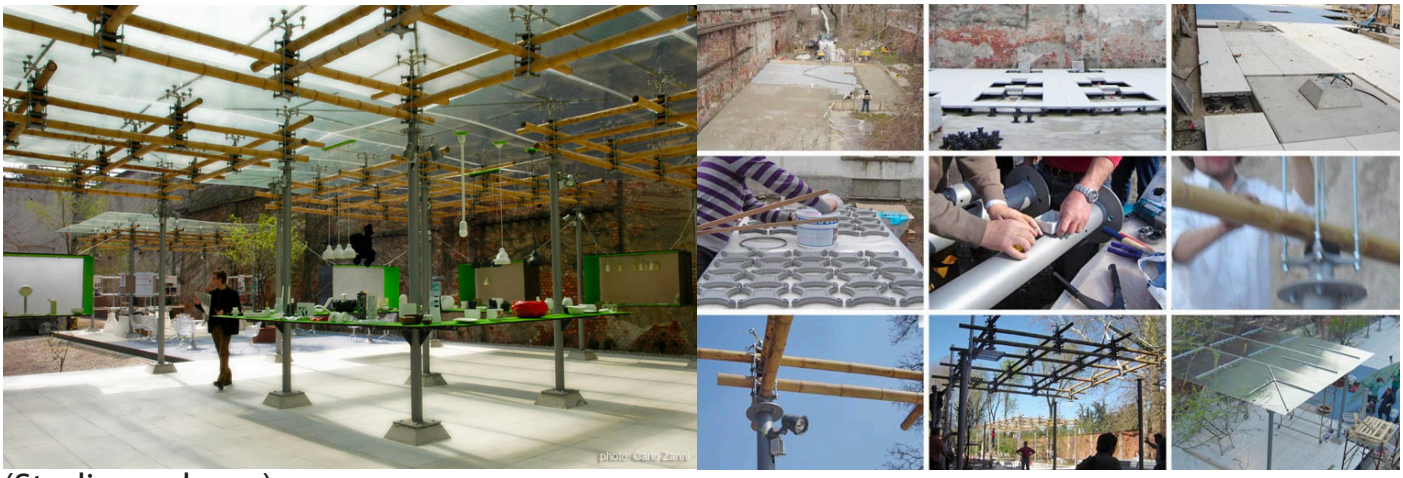
(Studio cardenas)




(Studio cardenas)

**Studio Cardenas**

Studio Cardenas, which opened in Milan in 2004, is an expanding Architectural studio that develops a great variety of issues: from public areas to poly-functional spaces, from commercial areas to those set aside for leisure, from showrooms to dwellings and general design.The design process is always supported by a in-depth research: a constant striving directed at facing present day issues such as the use of sustainable materials and technologies as well as the development of innovative construction techniques.(https://www.studiocardenas.it/index.php/it/)

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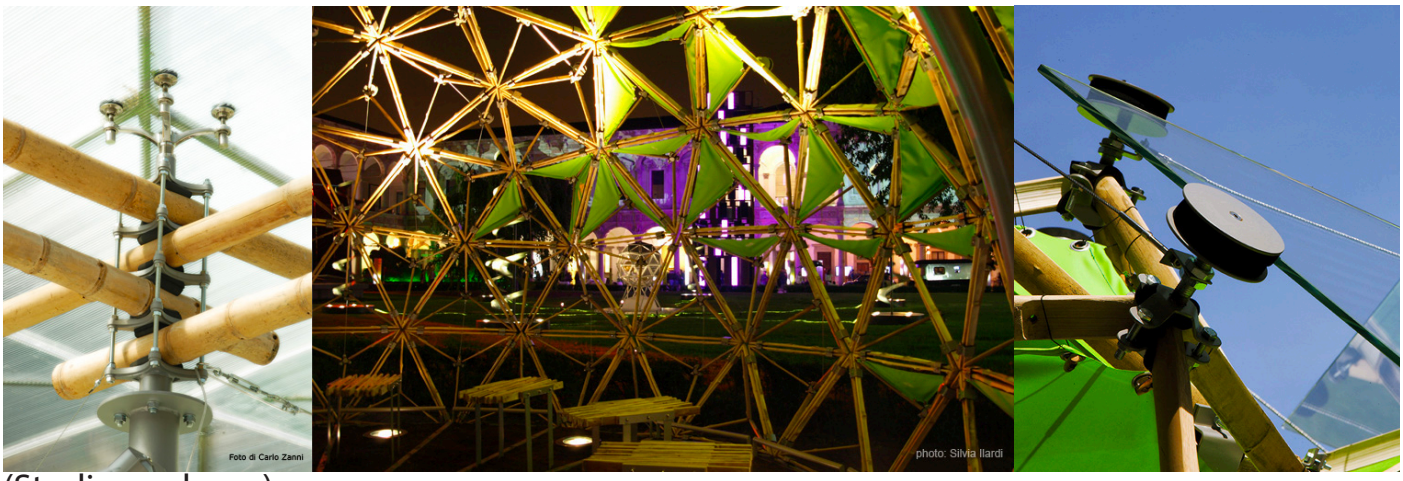


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**Founder:**
**MAURICIO CARDENAS**

Born in Bogotá, Colombia in 1969. Cárdenas graduated with the Degree of Bachelor of Architecture from the Universidad de Los Andes (Bogotá, Colombia) in 1993. In 1994 he obtained a Master of Architecture from Syracuse University in New York and began collaborating with leading architectural firms such as Studio Meiji Watanabe & Associates in Tokyo and Renzo Piano Building Workshop in Paris.

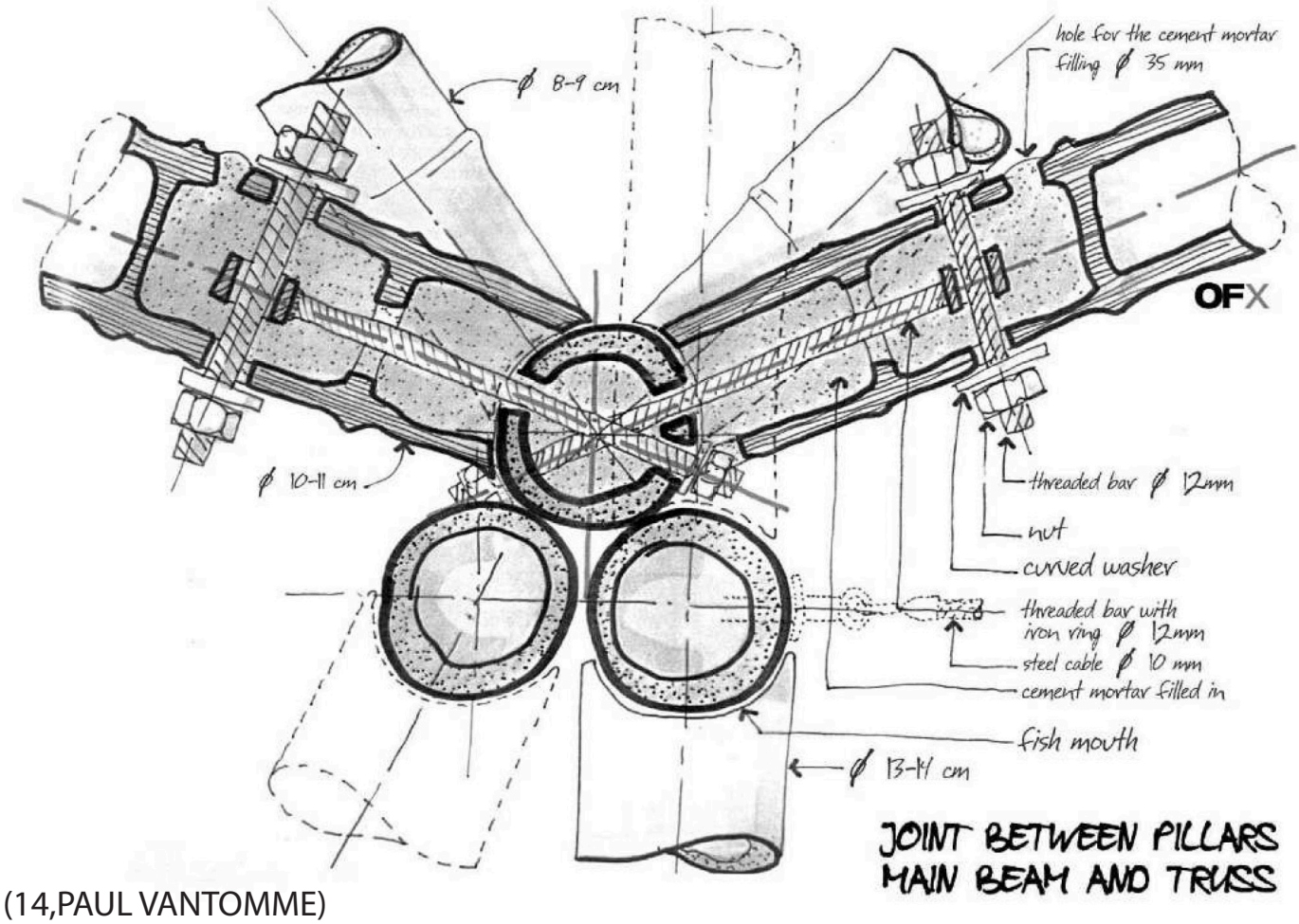
In 2002 he obtained a Ph.D. from the **Politecnico di Milano School** of Interior Architecture with a dissertation on the design of environmentally sensitive work spaces. (https://www.studiocardenas.it/index.php/it/)

(13,Piero Orlando)

**Prof. Walter Liese**
**-The Vergiate Bamboo Pavilion**

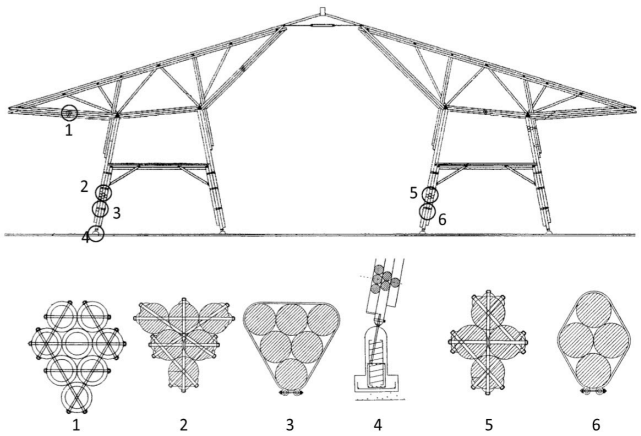
The Vergiate Bamboo pavilion is a public building entirely made of bamboo,whose design and implementation were commissioned to the Italian non-profit association **EMISSIONIZERO** by the Municipality of Vergiate to build a new structure to regenerate an area traditionally destinated to public recreation.

The technological process was a semi-prefabricated one: the trusses were made on the ground and then lifted on scaffoldings in the right position and height,and then joined together at the rigde and at the main beams.And then, the precut pillars were fixed to the trusses and foundations in concrete.The construction started in September 2002, with **400 Guadua bamboo poles imported from Colombia.** [14,PAUL VANTOMME]




(14,PAUL VANTOMME)

(Architizer)




(16,Gernot Minke)

## Zero Emissions Research and Initiatives -ZERI Pavilion for EXPO 2000

ZERI Pavilion in Manizales, Columbia. Design by Simon Velez, built on land provided by the Caldas Committee of the Coffee Federation, and funded by the Manizales Chamber of Commerce, chaired by Dr. Mario Calderon.
The Global ZERI Network participated in the World Expo in Germany in 2000, designing and building a bamboo structure that has become a landmark in sustainable architecture. The pavilion was designed by Simon Velez of Colombia and underwent a series of scientific tests in collaboration with several academic institutions: University of Braunschweig, University of Stuttgart, and Science University of Bremen. The building was erected first in Colombia, then in Hannover and received 6.4 million visitors during the 5 month Expo. [15,Zeri]

The floor plan has 10 corners, a diameter of 40 m and eaves of 7 m. The columns have a height be-tween 8 m and 14 m. On the second floor there is a 500 m2 gallery. For this structure, 3,500 rods of **Guadua angustifolia bamboo** from Colombia were used, installed by 40 specialised workers from Co-lombia. 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. [16,Gernot Minke]

# 2.Bamboo Application

Bamboo as building materials can be applied as structural elements for beams and pillar. Usually, bamboo can work as triangle structure or trusses for pavilions. Meanwhile, non-structural elements are also important for constructing bamboo buildings. Bamboo strips might be woven together. Horizontal cutting bamboo can merge as windows or walls. Vertical cutting bamboos can frame a special shape. Also in China, arraying bamboo as transparent walls are very popular. And bamboo can work for roofing systems, like thatch roof combined with Congo grass, halved bamboo roof placed in an interlocking sequence, flattened bamboo roof, and copper roof cladding of hand-cut copper tile shingles. At the same time, people found that bamboo is also a preferable material to replace steel in reinforced concrete system, which was inspired from traditional intertwined raw bamboo splits techniques. While swelling and shrinking would destroy bamboo reinforced structures. Engineered bamboo is another treatment for reusing bamboos. After process of splitting, resin, compression, heat cured, bamboo scrimper was made as panels. Another is laminated bamboo, for which bamboo culms can be spited, planed, bleached, caramelized, glued, pressed, and striped as panels.

## 2.1 Structure elements

(Archdaily)

**Pavilion for Beijing Design Week -Rising Canes**

It is a structural system made entirely of bamboo and ropes. Bamboo was chosen as the main construction material for its long traditional roots in China and fantastic structural capability, as well as part of a desire to fight its current obscurity as a construction material.[https://www.archdaily.com/]

(Archdaily)

**Wind Pavilion / Tongji CAUP**

With fully explored bamboo's potential structure of composite and information, they proposed originally a composite configuration of **string-supported bamboo beam and side arches**, which greatly reduces the amount of frames landing on the ground and realizes a curved surface with lithe and coherence. When the wind blows, the eventual space seems like a expensive canopy, evoking people's initial feeling of being protecting from nature.[https://www.archdaily.com/]

(Archdaily)

**Bamboo Sports Hall for Panyaden International School / Chiangmai Life Construction**

Chiangmai Life Architect's Bamboo Sports Hall for Panyaden International School combines modern organic design, 21st-century engineering, and a natural material – bamboo. The innovative structural design is based on newly developed **prefabricated bamboo trusses** with a span of over 17 meters without steel reinforcements or connections. These trusses were prebuilt on-site and lifted into position with the help of a crane.[https://www.archdaily.com]

## 2.2 Non-structural elements

(14,Anastasia Maurina)

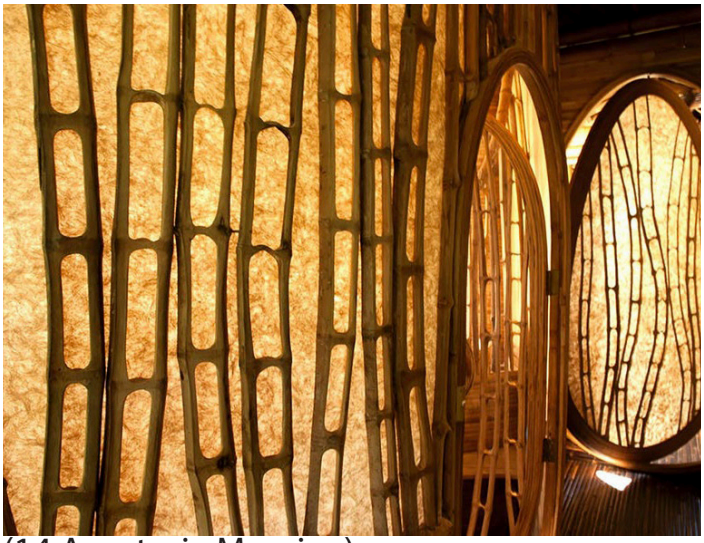
### Bamboo strips and waving

Bamboo weaving is a type of bambooworking in which two distinct sets of **bamboo strips** are interlaced at normally right angles to form an object. The longitudinal lengths of bamboo are called the warp and the lateral lengths are known as the weft (also known as 'woof', an archaic English word meaning "that which is woven"), or filling. The method in which these strips are woven affects the characteristics of the finished piece.Bamboo is typically **hand-woven**, with a number of bamboo weaving traditions having developed globally over time, particularly in Southeast Asia and East Asia, where bamboo suitable for weaving is particularly abundant.[https://en.wikipedia.org/wiki/Bamboo_weaving]

(14,Anastasia Maurina)

### Horizontal cutting bamboos

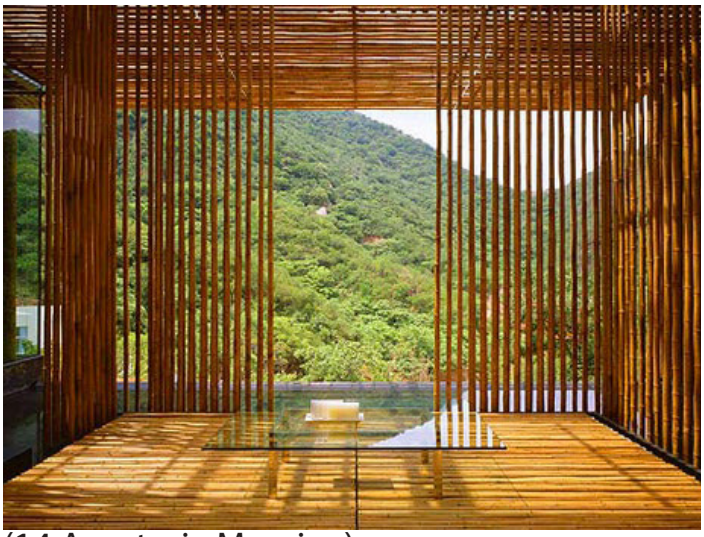
The benjamin garcia saxe designed a project- **a forest for a moon dazzler**,in which they used module pieces to create an internal garden between both and as a way to prove the possibilities of expansion of the concept. Overall 5,000 pieces 15cm pieces of bamboo were manually cut an placed to create what has been considered a beautiful way to rethink bamboo as a space making material.[https://www.archdaily.com/]



(14,Anastasia Maurina)

**Vertical cutting bamboos**

**Sharma Springs** was designed for the Sharma family as a jungle fantasy escape. It is a 6-level, 4-bedroom 750sqm home overlooking the Ayung river valley, built almost entirely of bamboo. The house was decorated by veetical cutting bamboos.[https://www.archdaily.com/]

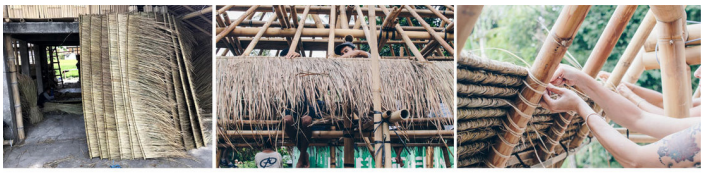


(14,Anastasia Maurina)

**Bamboo filter wall**

In Great (Bamboo) Wall project,they designed the walls as filters formed of bamboo. They found the material's weakness charming. The Great Wall, built of solid stone and brick, was once used to sever the civilized world from the world of savages; the **bamboo filter** would on the other hand allow light and wind to pass through. It could also represent a connection between two worlds.[https://www.archdaily.com/]

**Four roofing Systems**

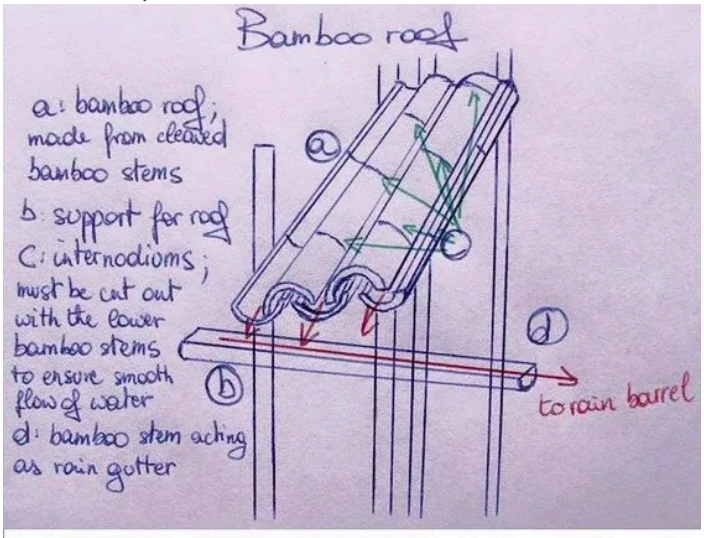


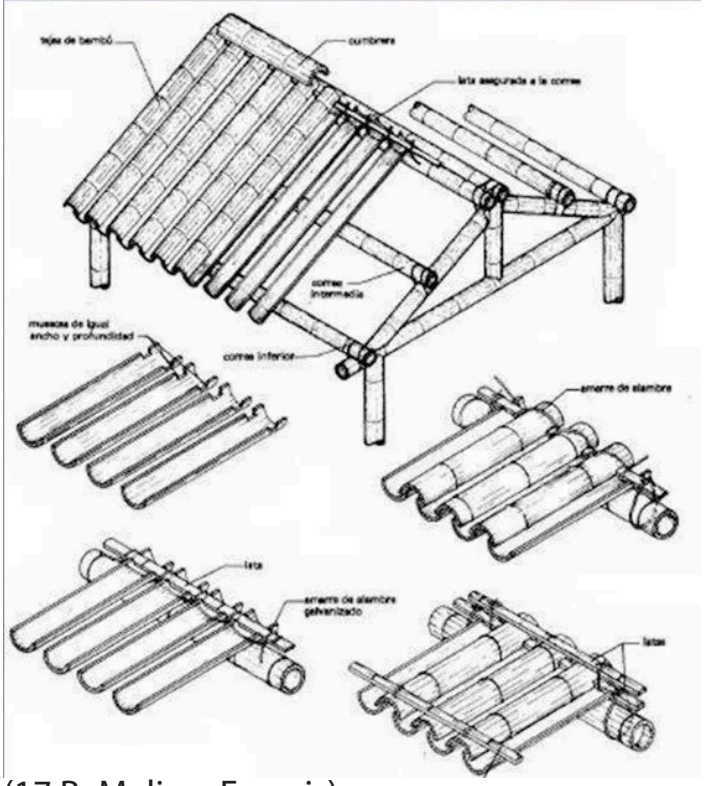
(Archdaily)

**Thatch Roof (known locally as alang alang)**

Alang-Alang roofs are a traditional thatch roofing technique used in Indonesia. **The Congo grass** (Imperata cylindrical) is harvested when mature and dried. Then, thatch panels of a maximum of 3 meters in length are made by folding the dry grass over a bamboo split and **threading it onto the split using palm fiber**. The bamboo split gives structure to the grass turning it into a panel whilst also acting as a roofing batten. When installed the alang alang panels are tied to the rafters using a lashing technique with **bamboo rope**.[https://www.archdaily.com/]

(Archdaily)



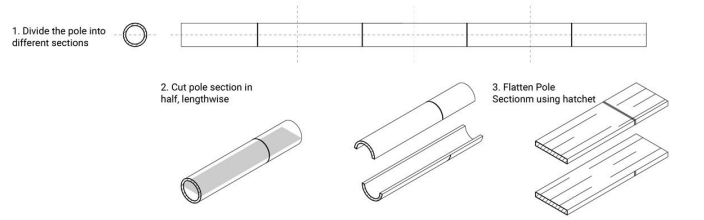



(17,ByMelissa Francis)

**Halved Bamboo Roof**

The halved bamboo roof is made up of freshly harvested bamboo poles split into **two halves and placed in an interlocking sequence** similar to a Spanish tile roofing technique. For a well-designed bamboo building using halved bamboo, the roof needs a minimum roof pitch of 40 degrees and the rafters should not be placed further than 60 cm apart from one another. Finally, the roof ridge should be covered properly. [https://www.archdaily.com/]

This Bamboo Poles Rain Gutter Roof Tiles Project is a great way to use a quick growing natural resource that cools naturally through convection and channels rain to a reservoir. The use of bamboo rain gutter roofing is basically one inexpensive way to drain water off buildings and homes. Apart from being highly efficient, they tend to provide a kind of rustic charm to the exterior décor that is quite difficult to obtain from any other material. Just so you know, they can be used to efficiently **collect rainwater from the roof and at the same time ensure proper drainage**.[17,ByMelissa Francis]




(Archdaily)

## Flattened Bamboo Roof (known locally as pelupuh)

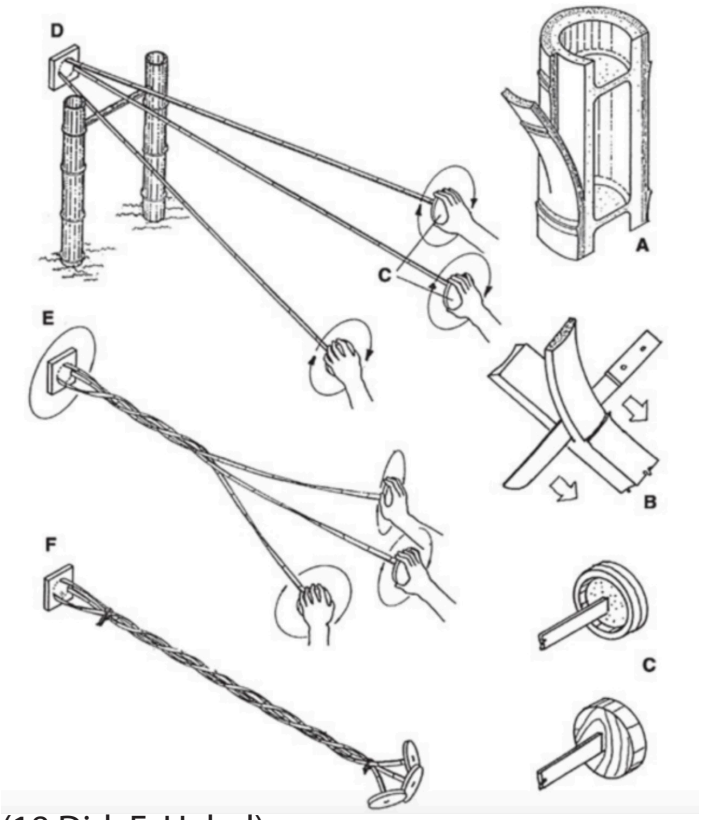
Pelupuh is handwrought flattened bamboo made into roofing shingles and it is made by cutting a Gigantochloa apus bamboo pole in **half lengthwise**. Then **a cut** is made into the culm wall from the inside out using a **hatchet**. The cuts do not pierce through the entire culm wall, just enough so that the section of the culm is **flattened out**. The cuts should be made at an angle to prevent splitting in the structure of the bamboo. The nodes are then shaved off using a bamboo knife or hatchet. We use this processed bamboo material in a **3 layered hybrid roofing technique** where we first **place treated pelupuh over the rafters** for interior aesthetics, then an asphalt linear (**synthetic waterproofing membrane**) and **pelupuh** which is cut to size as roofing shingles as a final layer. All layers are attached using a nail gun.[https://www.archdaily.com/]

(Archdaily)

## Copper Roof

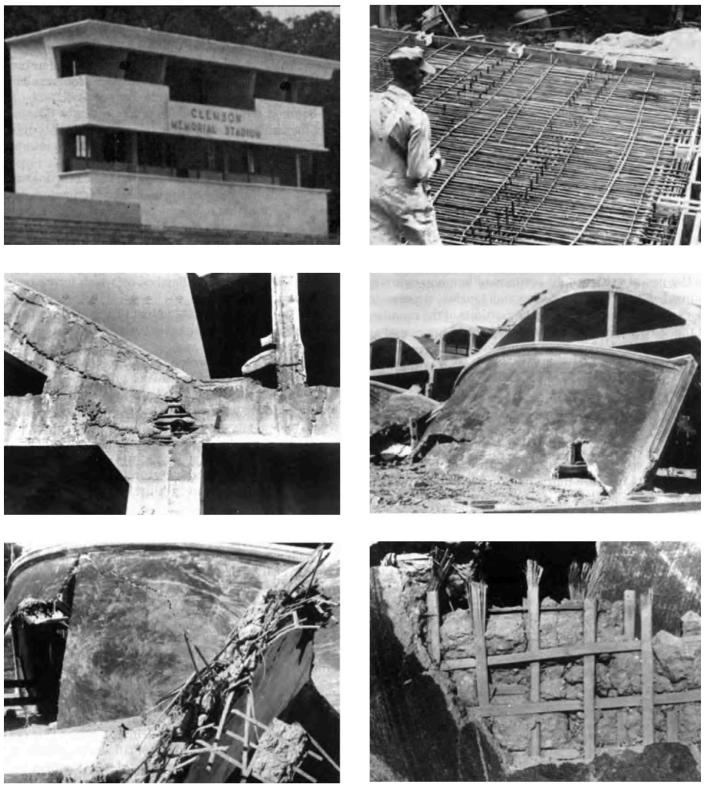
Copper roofing is a recent experiment for bamboo structures pioneered by John Hardy and IBUKU. It is durable but very costly. The copper sheets are customised as tile shingles on the ground by hand and put in place on the roof. When constructing a copper roof, **pelupuh are first placed over the rafters** for interior aesthetics, an **asphalt liner** is then attached using a nail gun, and cladding of customised **hand-cut copper tile shingles** are placed as a final layer.[https://www.archdaily.com/]

## 2.3 Bamboo reinforced concretes



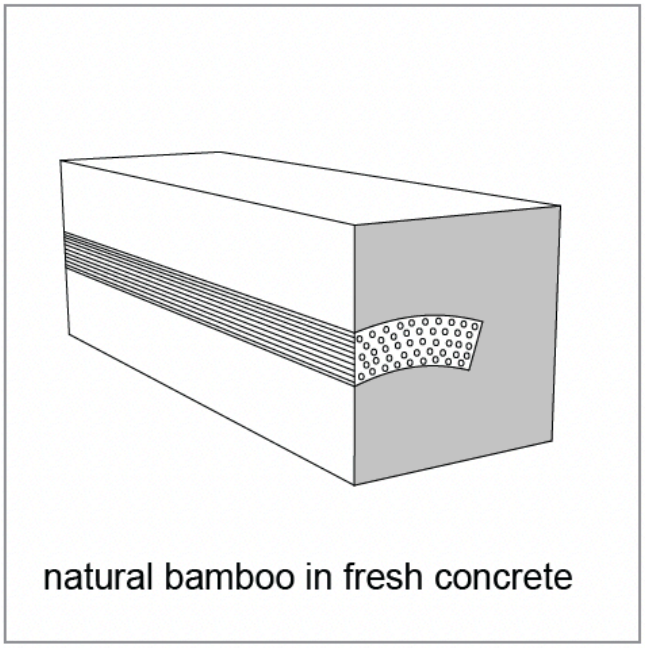

(18,Dirk E. Hebel)

**Intertwined raw bamboo splits** were already used as tensile cables in suspension cables and maritime applications in China around 300 AD. Tension cables made from woven strips of only the outer layer of bamboo were used in shipbuilding and for the construction of suspension bridges, the most famous of which,Zhupu bridge, was reportedly built around 300 AD.This 261-metre-long bridge crosses the Minjiang River and connects the famous Erwang Temple and the well-known Dujiang Dam . For its construction,builders used 500-metre-long bamboo cables,twisted from three or four towing cables with a diameter of 5 centimetres each. Columbian bamboo expert Oscar Hidalgo-Lopez displays their potential as concrete reinforcement in his book Bamboo: The Gift of the Gods. [18, Dirk E. Hebel]

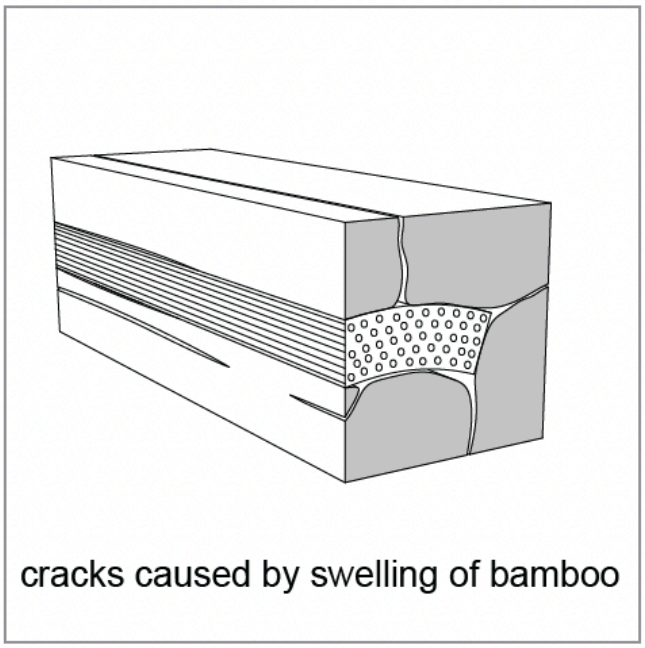


(Oscar Hidal-go-Lopez in Bamboo: The Gift of the Gods in 2003)

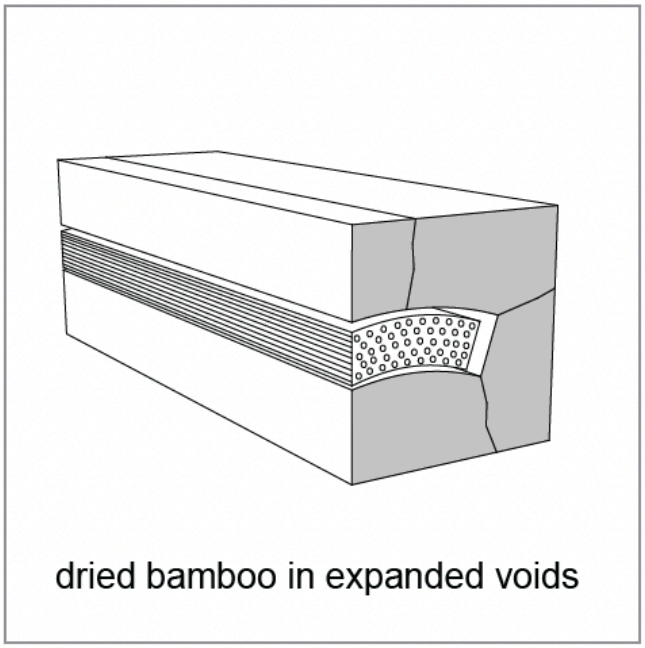
Used in the construction of military hangars in Korea, **raw and untreated bamboo splits de-bonded from the concrete** matrix due to **swelling and shrinking** of the organic material and caused the structures to collapse. Based on these results, in 1970, Helmut Geymayer and Frank Cox from the US Army Engineer Waterways Experiment Section studied the application of a local bamboo species from Mississippi, Arundinaria tecta, for reinforcing concrete beams and slabs.Concrete beams with a reinforcement ratio of three to four per cent were prepared, using bamboo splits that were either coated with an epoxy and polyester resin or pre-soaked for 72 hours before placing into the concrete matrix.The results showed that bamboo-reinforced concrete beams could develop about three to four times the maximum flexural strength of unreinforced beams of the same cross sections. [18, Dirk E. Hebel]



natural bamboo in fresh concrete



cracks caused by swelling of bamboo

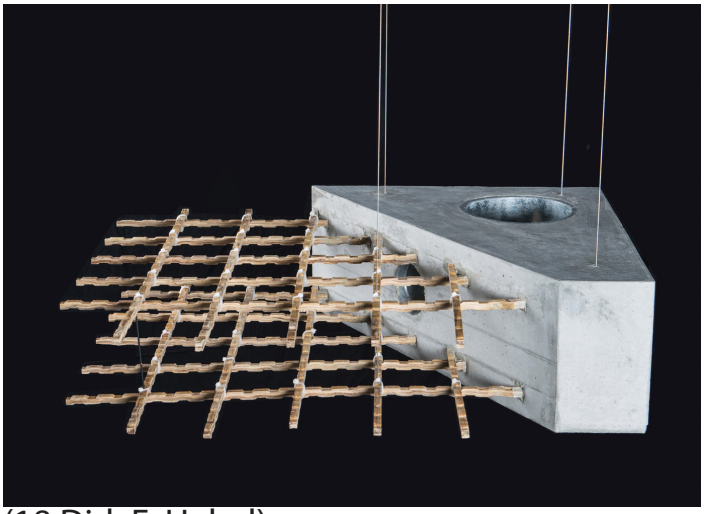


dried bamboo in expanded voids

(18,Dirk E. Hebel)

Effects of **swelling and shrinking** and the resulting de-bonding of untreated bamboo when used as a reinforcement system in concrete applications.As to cracking and failure, the results confirmed the conclusions by Glenn on the bonding behaviour of bamboo-reinforced concrete beams: due to different **thermal expansion coefficients** of bamboo and concrete and the ensuing thermal strains, **cracking** seemed unavoidable. This points at an important fact: while bamboo offers very high tensile strength, the low bonding strength between concrete and bamboo as a result of continuous swelling, shrinking, and differential thermal strains impedes the extensive application of bamboo as reinforcement for concrete elements. [18, Dirk E. Hebel]

Bamboo as concrete reinforcement must be **soaked, dried and covered with a waterproof coating**. This is intended to prevent the action of absorbing each other between bamboo and concrete. Water absorption occurs in two stages. The first phase of wet concrete will be absorbed by bamboo and after the concrete has hardened, the water in the bamboo will be absorbed by the concrete. This process is called the hygroscopic and hydrolysis process which lasts for an infinite amount of time. If bamboo is not coated with a waterproof layer, it will absorb each other and the bamboo will shrink. [19,Muhtar Muhtar]



(18,Dirk E. Hebel)

**Engineered bamboo as a reinforcement system in concrete applications.**Steel-reinforced concrete is the most common building material in the world. At the same time, very few developing countries have the ability or resources to produce their own steel or cement, forcing them into an exploitative import relationship with the developed world. Bamboo is in principle available in those areas of the planet which are expected to have the highest share of construction activities in the decades to come, including Africa. [18, Dirk E. Hebel]


1 (18,Dirk E. Hebel)

**Composite bamboo material tensile test conducted by Future Cities Laboratory.**

1-Tension test of the newly developed bamboo composite material, performed in accordance to Eurocode and the standards of the American Society for Testing Materials, ASTM International.

2-Newly developed bamboo composite material at the SEC/FCL Advanced Fibre Composite Laboratory.

3-Bamboo composite reinforcement system as tested at the SEC/FCL Advanced Fibre Composite Laboratory.

4-Bone-shaped test sample of the newly developed bamboo composite material.

5-Test samples before testing

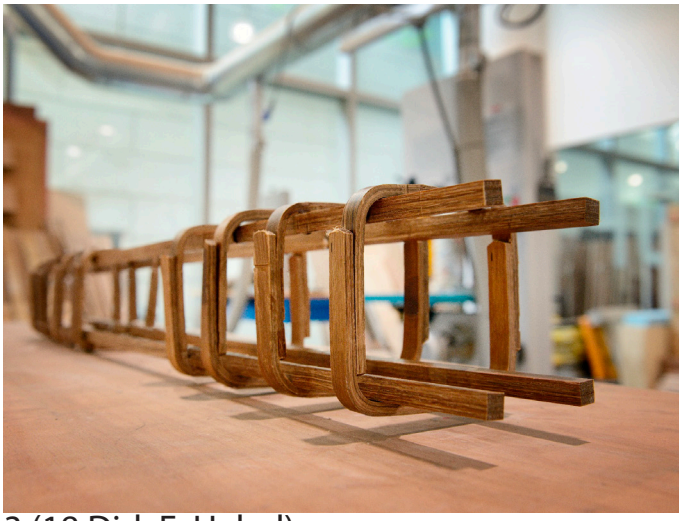
6-Microscopic investigation of test samples and their behaviour at the SEC/FCL Advanced Fibre Composite Laboratory

7-Four-point bending test of the newly developed bamboo composite material

8-All test samples of various test series at the SEC/FCL Advanced Fibre Composite Laboratory are documented,catalogued, and stored at the facility

9-Investigation of material behaviour

2 (18,Dirk E. Hebel)

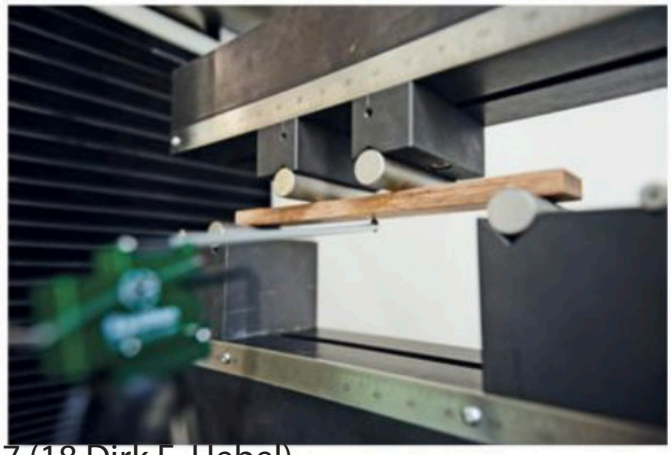


3 (18,Dirk E. Hebel)

4 (18,Dirk E. Hebel)

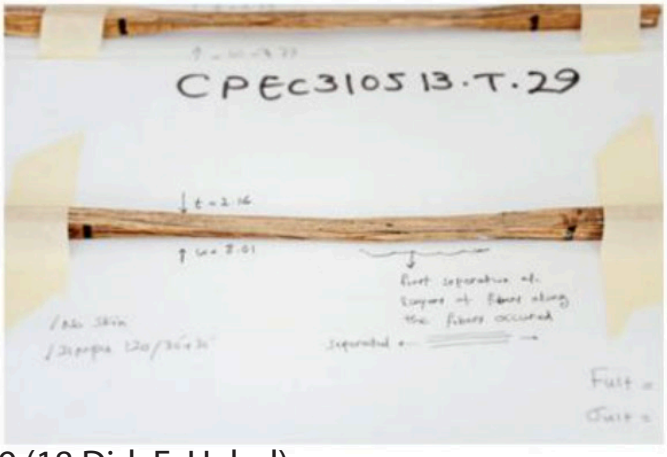

5 (18,Dirk E. Hebel)

6 (18,Dirk E. Hebel)



7 (18,Dirk E. Hebel)

8 (18,Dirk E. Hebel)



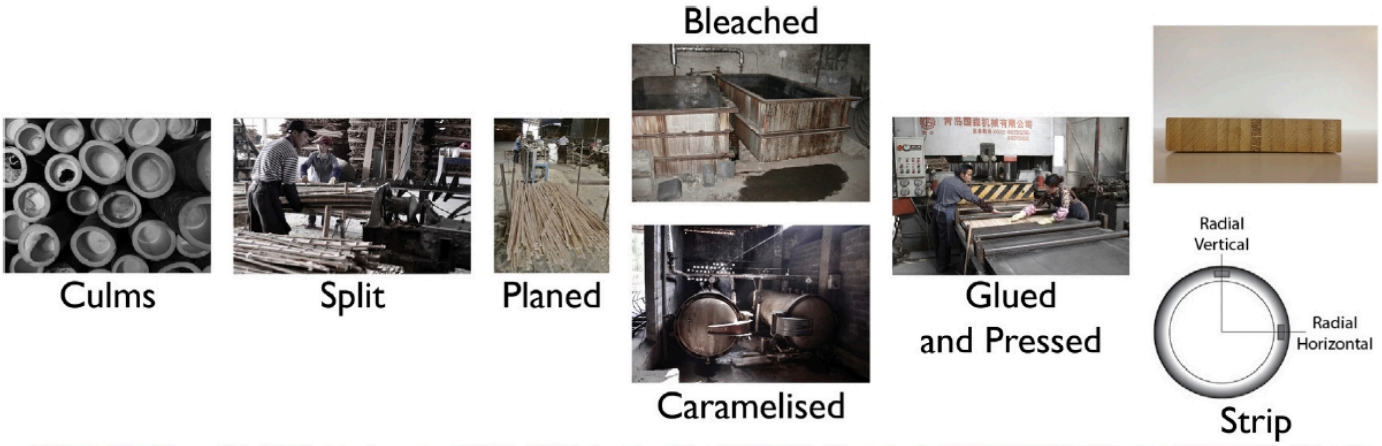

9 (18,Dirk E. Hebel)

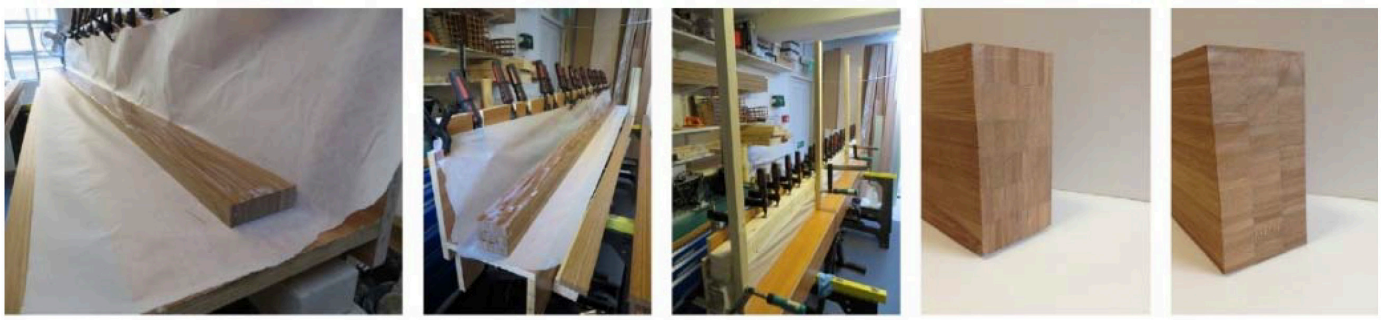
## 2.4 Engineered bamboo elements

### Bamboo scrimber


Bamboo scrimber, also referred to as strand woven or parallel strand bamboo, consists of crushed fibre bundles saturated in resin and compressed into a dense block.The process is materially efficient, utilising approximately 80% of raw inputs, and produces a product with a Janka hardness that is acceptable for external applications such as deck flooring. The process maintains the longitudinal direction of the bamboo fibres and utilises the resin matrix to connect the fibre bundles. [20,Bhavna Sharma]

### Laminated bamboo




Laminated bamboo maintains both the longitudinal fibres as well as a portion of the original culm matrix. The bamboo culm is split, planed, processed (bleached or caramelised),laminated and pressed to form the board product. The orientation of the strip within the board, and therefore the direction of the radial fibre density, is randomly placed within in the board. The final products use only approximately 30% of raw material input due to large losses of material when the strips are planed to form the rectangular section. The sheet product is primarily used indoors for surface applications or furniture. While both materials are currently used for surface applications, both maintain the inherent strength of bamboo by maintaining the longitudinal fibre orientation and the engineered product creates a uniform section for connections and joints in structural applications. [20,Bhavna Sharma]

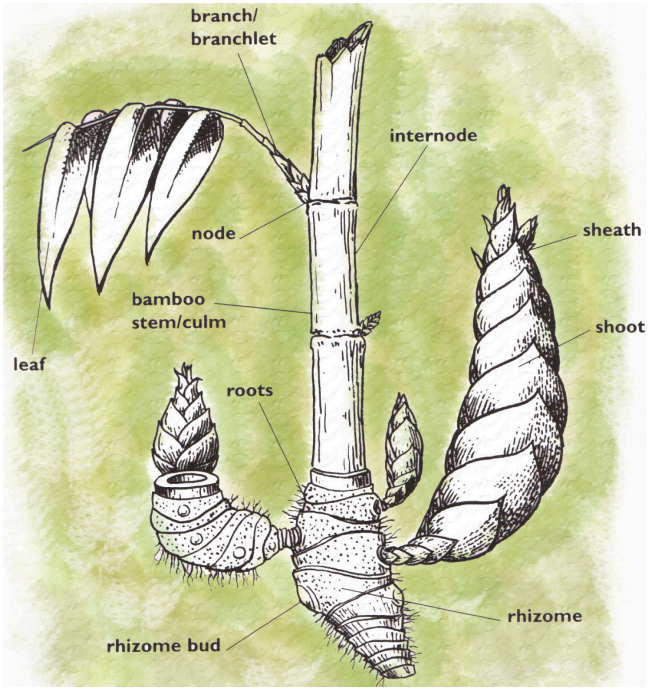
# 3.Bamboo Mechanical Property

Bamboo has an excellent mechanical property of tension and compression, because of its biological attributes. In the roof part, stem grows out of a net kind root system and reaches already after one year its total tallness. The growth of the culm begins from the buds on the rhizomes. And rhizomes can be divided to monopodial bamboos and sympodial bamboos. Bamboo fibers consist of three layers, the skin outside, the main part bamboo timber with tissues, and the pith inside. And bamboo growth types are varied from tree forms, straggler forms, reed forms, and shrub forms. Different parts of bamboos can be used as differences. The top parts can be leaders and sticks because of lightness and flexibility. The middle parts tend to be as structural elements like beams, pillar, roof purlins. When testing the mechanical property of five bamboo species in Italy, Bambusoides and Iridescens have good result in compression and tension property under the same condition of other attributes.

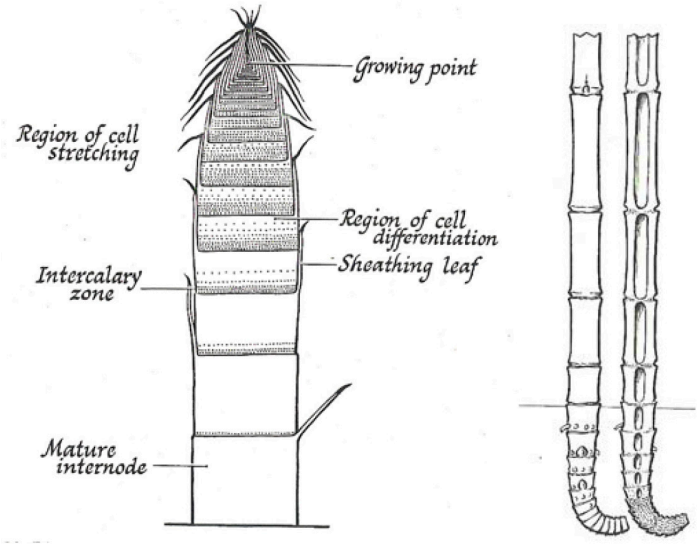
## 3.1 Biological attributes

The growth pattern of the bamboos is a singular combination of grass, leaf-bearing tree and palm.Like the grasses they have tubular blades, lancetshaped cover leaves and panicular flowers and from a subterranean rootstock branch extensively to form dense to loose bushes. The following characteristics distinguish bamboos from grasses: the longevity of their canes, their branching and the lignification. Like leafbearing trees they increase their crown every year by throwing out new branches and also shed their leaves each year.The growth pattern of the trunk is similar to that of the palm tree. Emerging with its definitive circumference from the soil without increasing in diameter later. The species "Guadua angustifolia" will reach lenth of up to 20 - 25 m with a diameter of 12 cm. [21,Bauen mit Bambus]

**01-bamboo root**




(22,Bamboo Construction Source Book)



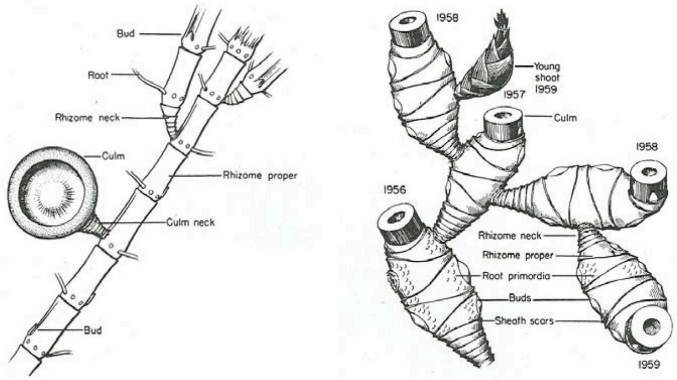

(24,Xiaobing Yu)

**Bamboo root**

Each stem grows out off a netkind rootsystem and reaches already after one year its total tallness. After that the [leitsysteme] start to lignify and in the next 6-8 years it gains harness and strength because of the silification of the outer tube wall. So bamboo can also be titled as a lignifying giant grass. [23,Bauen mit Bambus]

**Bamboo culm**

The culm consists of internodes and nodes. It is the visible part of bamboo which makes bamboo so unique as a material and a plant. It is also where bamboo differs from grass and tree. The growth of the culm begins from the buds on the rhizomes: the buds grow at this position for several years before they become bamboo shoots and emerge out of the soils. The later structure of culms (the internodes and nodes) has already been totally defined during this phase. The overground growth of bamboo is like the shift of telescope tubes from bottom to top. The culm diameter tapers also from bottom to top, like the wall thickness. [24,Xiaobing Yu]




(24,Xiaobing Yu)
Left:Laptomorphs (monopodial);
Right: Pachymorphs (sympodial)

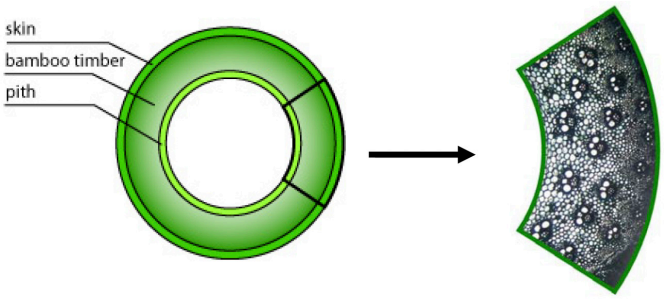
## Rhizomes

The bamboo rhizomes can basically be divided into two main groups:

**- Laptomorphs or also called monopodial bamboos** that have long and thin rhizomes from which the buds produce single and regular shoots. The bamboo species Phyllostachys pubescens belongs to this group.

**- Pachymorphs or also called sympodial bamboos** that have short and thick rootstocks from which the canes grow up. The bamboo species Guadua angustifolia belongs to this group. [24,Xiaobing Yu]

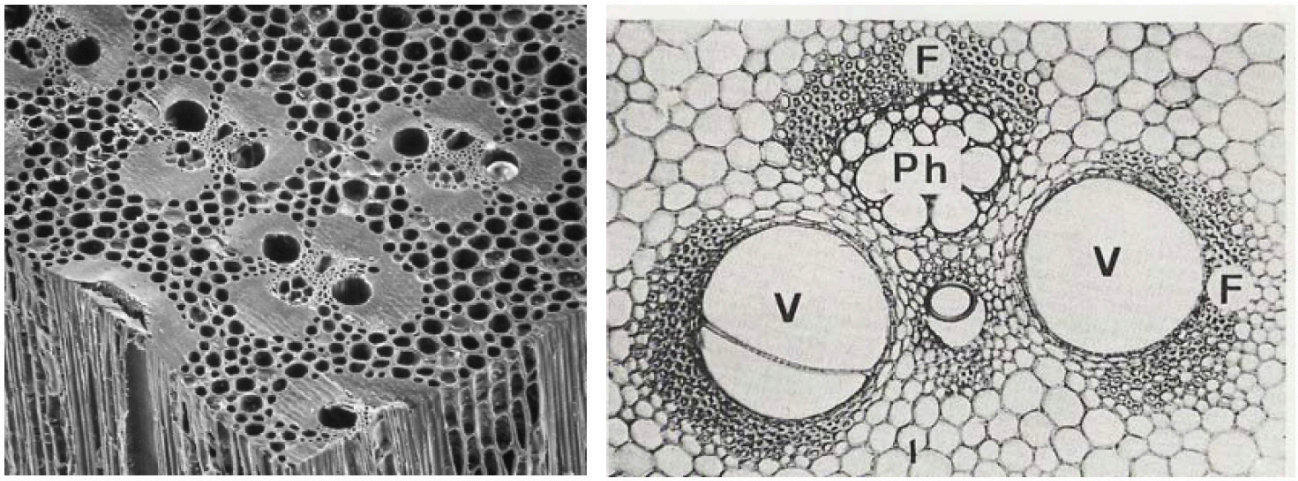
## 02-bamboo fibres




- **The skin:** the cortex of the bamboo culm cross section. Watertight layer which protects bamboo against moisture lost from inside and invasion from outside. No vascular bundles fund in this section.
- **The bamboo timber:** between the skin and the pith, with vascular bundles and parenchyma tissues. It is the main structural and functional part of the culm.
- **The pith** is the inner surface of the bamboo cavity. It is a parenchyma tissue, without vascular bundles (24,Xiaobing Yu)

Under the microscope the cross section of a culm shows a very special arrangement of the cells and demonstrates a harmony of the function and construction in nature. Kratzsch (1933) has divided the bamboo culm cross section from outer to inner into four sectors to demonstrate the gradual anatomical changes. For a better understanding of the processing of the bamboo culm, here the division created by Zhang (2001) will be used, in which the bamboo culm cross section is divided into three sections. [24,Xiaobing Yu]

**The bamboo culm has a much more elegant and finer structure: the outer third of the culm has a much higher percentage of fibers than the inside and at the peripheral zones the vascular bundles are also smaller and more intensive than those of the inner parts.** Two functions account for that: firstly the tube structure always has its largest tensile and compression at the peripheral zones when it is bended, so the distribution and arrangement of the cells guaranty the highest strength at this part. The second is, the harder and denser the peripheral parts, the better the culms are protected from outer invasions. Also bamboos have in their upper part of culm much more fibers so that the bamboo has more elasticity on its upper part; this property prevents that bamboo is destroyed in strong wind or heavy rain and snow. [24,Xiaobing Yu]




V: Vessel of xylem. Ph: Phloem. F: Fiber cap

(24,Xiaobing Yu)
3D view of the bamboo culm (left) and the vascular bundles of bamboo culm (right).

## 03-Bamboo Growth & Forms

Tree forms

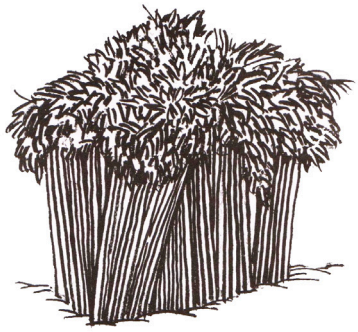
Straggler forms

### Tree forms

These are bamboos up to 35 metres in height, and with large or medium-sized, usually thick-walled, culms.

### Straggler forms

These are medium-sized bamboos up to 15 metres tall, with the tip of the culm arching or drooping down or climbing on adjacent trees.



Reed forms

Shrub forms

(22,Bamboo Construction Source Book)

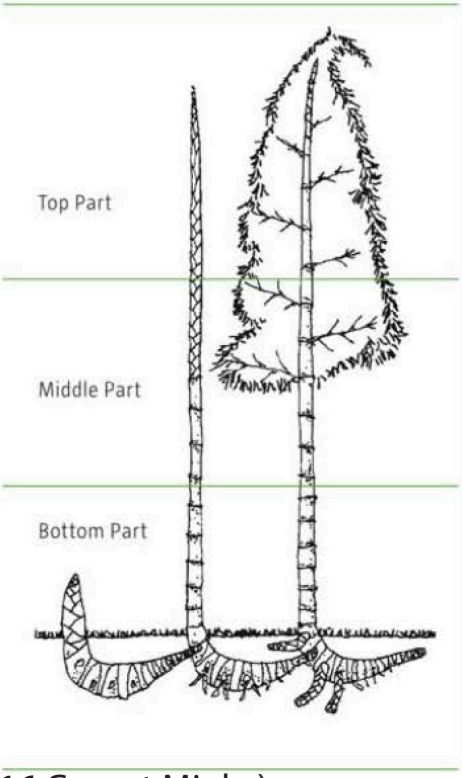
### Reed forms

These are medium-sized bamboos, which commonly grow as reed brakes, They have thin-walled culms up to 9 metres in height with long internodes.

### Shrub forms

These are erect short forms of bamboo found in temperate species. They mainly occur at high altitudes, and have very thin culms that rise to a height of up to 5 metres. [22,Bamboo Construction Source Book]

## 04-Bamboo different uses




| | 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 | |

(16,Gernot Minke)

The use depends on the type of bamboo, its age and the part of the plant. The figure describes the uses for the bamboo **Guadua angustifalia 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 Bang la Desh over 70% and in Guayaquil, Ecuador, 50% of the population uses it in construction. In seismic zones bamboo construction is preferred due to its lightness and flexibility. In humid tropical zones bamboo is used in construction since it is a local, cheap and easily handled material; furthermore in these areas it allows walls with low thermic mass. [16,Gernot Minke]

# 3.2 Mechanical characterization of five species of Italian bamboo

## 01-Methodology and materials

**Nomenclature**

| Symbol | Description |
|---|---|
| $A$ | cross-sectional area of the culm calculated as $(\pi/4)[D^2 - (D - 2\delta)^2]$ ($mm^2$) |
| $\delta$ | the wall thickness (mm) |
| $b$ | width of tension test specimen in gauge region (mm) |
| $D$ | outer diameter of the bamboo culm (mm) |
| $E_{c,o}$ | compressive modulus of elasticity parallel to fibers (MPa) |
| $E_{t,o}$ | tensile modulus of elasticity parallel to direction of fibers (MPa) |
| $F$ | load applied in test (N, kN) |
| $F_{ult}$ | maximum (ultimate) load applied in test (N, kN) |
| $\sigma_{c,0}$ | compressive stress in the direction of the fibers during compression test (MPa) |
| $\sigma_{c,0\,20}$ ; $\sigma_{c,0\,60}$ | $\sigma_{c,0}$ at 20% and 60% of the ultimate force, respectively (MPa) |
| $f_{c,o}$ | compressive strength parallel to direction of fibers (MPa) |
| $\sigma_{t,0}$ | tensile stress in the direction of the fibers during tension test (MPa) |
| $\sigma_{t,0\,20}$ ; $\sigma_{t,0\,60}$ | $\sigma_{t,0}$ at 20% and 60% of the ultimate force, respectively (MPa) – |
| $f_{t,o}$ | tension strength parallel to direction of fibers (MPa) |
| $\varepsilon_z$ | longitudinal strain in the direction of the fibers (-) |
| $\varepsilon_{z\,20}$ ; $\varepsilon_{z\,60}$ | $\varepsilon_z$ at 20% and 60% of the ultimate force, respectively (-) |
| $\varepsilon_t$ | circumferential strain (-) |
| $\varepsilon_{t\,20}$ ; $\varepsilon_{t\,60}$ | $\varepsilon_t$at 20% and 60% of the ultimate force, respectively (-) |
| $L$ | length of test piece (mm) |
| $m_i$ | initial mass of test specimen (g) |
| $m_0$ | oven-dry mass of test specimen (g) |
| $\rho$ | density (kg $m^{-3}$) |

(25,Luisa Molaria)

## Methodology

The experimental investigations are carried out, as far as possible,according to **the standard ISO 22157-1:2019 "Bamboo structures -Determination of physical and mechanical properties of bamboo culms -Test methods"** Carrying on the tests, it was clear that the compression test suggestedby ISO standard was effective and easy to perform while tensile test was not effective and hard to perform.
In general, and in particular in bamboo specimens, tension tests (parallel to the fibers) are more difficult than the compressive characterization since several issues can affect the tensile test results. Fiber gradation across the thickness and ancorage conditions of the specimens influence the strength and the failure. Moreover, the geometry of the specimen is always very complex (being a curved shell) oftenpresenting natural flexure and twist; further, the friction coefficient of the outer and inner surfaces of the culm are considerably different,due to both the higher hardness of the outer surface and to the
presence of a sort of natural polymeric vax covering it . Moreover,great tensile longitudinal force needed at failure, may not be associated with a sufficient strength in the radial direction, required to sustain the compressive force generating by the jaws often leading to a premature crushing in the grip area.
The paper is organized in two parts. The first part shows the results of the mechanical characterization, in compression and tension, of five bamboo Italian species:
**(i) The compression tests are carried out following ISO 22157:2019,strictly.**
**(ii) For tension test a set-up, suitable for thin-thickness Italian bamboo,is proposed.**
The second part of the paper is dedicated to:
**(i) discuss critically some aspect of the methodology proposed in ISO 22157:2019 for tensile tests;**
**(ii) describe the modifications of the experimental rig we adopt to improve the execution of tension test;**
**(iii) compare the results obtained following the different set-up.**
[25,Luisa Molaria]

## Materials

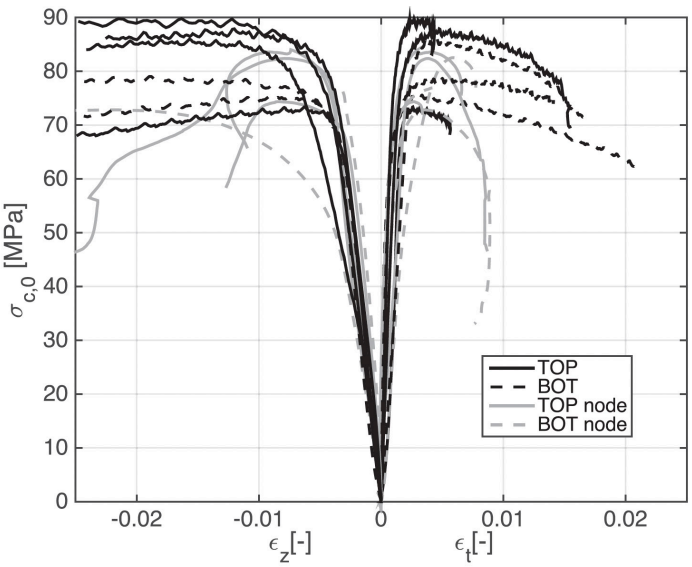
This study enrolls five species of Italian bamboo of the family of Phyllostachys: **Bambusoides (BAM), Edulis (EDU), Iridescens (IRI), Vivax (VIV) and Violascens (VIO)**. All the tested bamboo culms were cultivated in Italy, in particular Bambusoides, Iridescens, and Vivax in Langhe (Piemonte region, north-west part of Italy), Edulis in Pordenone, (FriulinVenezia Giulia, north east part of Italy), and Violascens in Bologna,Emilia Romagna.
Two parts of one meter length are cut from the culm: the first one from **0.5 to 1.5 m** from the ground (identified as **'BOT'**) and the second one from **2.5 to 3.5 m** from the ground (identified as '**TOP**'). From each of the two parts of a culm, 4 specimens are obtained: two **cylinders for the compressive test**, one with node and another one without node and two **sticks of rectangular cross section for the tension test**, one with node and one without node. Three culms for each species are examined.The cylindrical specimens for compressive test are cut from the culm using a circular saw. The stick specimen for the tensile test are obtained using a splitter.

## 02-Compression test

Left:specimen equipped with a bidirectional strain gauge.
Right: set up.(25,Luisa Molaria)

| Species | | $D$ [mm] | | $\delta$ [mm] | | $\rho$ [kg m$^{-3}$] | | n. culms |
|---|---|---|---|---|---|---|---|---|
| | | *Mean* | *St.Dev* | *Mean* | *St.Dev* | *Mean* | *St.Dev* | - |
| BAM | TOP | 58.06 | 3.25 | 4.70 | 0.55 | 875 | 6 | 6 |
| | BOT | 58.67 | 2.96 | 5.95 | 0.41 | 891 | 43 | 6 |
| | ALL | 58.36 | 2.98 | 5.33 | 0.80 | 883 | 29 | 12 |
| EDU | TOP | 62.42 | 3.88 | 5.81 | 0.59 | 918 | 67 | 6 |
| | BOT | 71.78 | 0.84 | 8.69 | 0.79 | 898 | 55 | 6 |
| | ALL | 67.10 | 5.57 | 7.25 | 1.65 | 908 | 56 | 12 |
| IRI | TOP | 62.07 | 2.30 | 5.74 | 0.31 | 887 | 36 | 6 |
| | BOT | 61.73 | 3.18 | 7.83 | 1.10 | 832 | 29 | 6 |
| | ALL | 61.90 | 2.65 | 6.78 | 1.34 | 860 | 42 | 12 |
| VIO | TOP | 46.18 | 4.15 | 3.94 | 0.19 | 762 | 9 | 6 |
| | BOT | 56.08 | 3.31 | 5.11 | 0.33 | 724 | 52 | 6 |
| | ALL | 51.13 | 6.29 | 4.53 | 0.67 | 743 | 39 | 12 |
| VIV | TOP | 77.67 | 8.88 | 5.49 | 0.81 | 790 | 19 | 6 |
| | BOT | 81.19 | 6.70 | 7.10 | 0.44 | 751 | 22 | 6 |
| | ALL | 79.43 | 7.72 | 6.29 | 1.05 | 770 | 28 | 12 |

Mean value, standard deviation of diameter, thickness and density of the specimen used in compressive tests. (25,Luisa Molaria)




Compression test: examples of stress versus longitudinal and circumferential strain for BAM species. (25,Luisa Molaria)

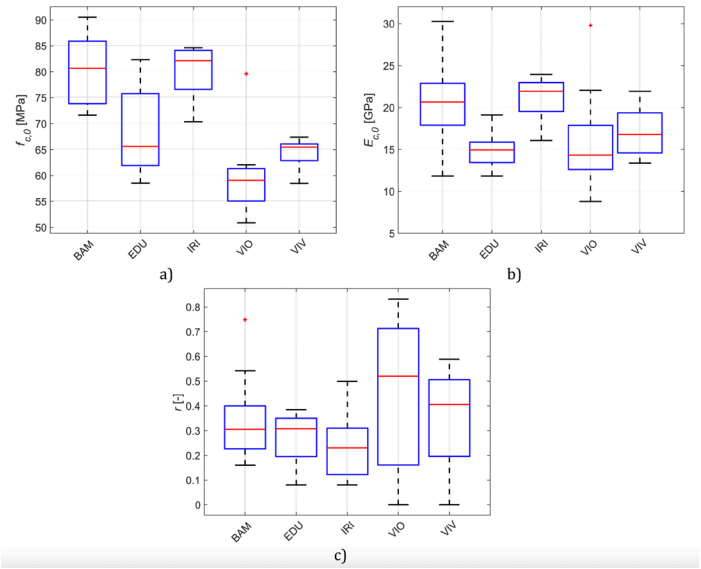
Loading has been provided by means of a hydraulic press universalmachine (METRO COM, 600 kN maximum static capacity), in displacement control, with an imposed displacement velocity of 0.3 mm/minute. A linear variable displacement transducer (LVDT) HBM 1-WA/50MM-T was used to measure vertical displacement. The upper plate of the press is provided by a spherical joint to mitigate a possible uneven load distribution on the sample cross-section. A layer of Teflon tissue of extremely low thickness was interposed between the specimen and the load plates, in order to limit friction. A picture of the **set up** is shown on top.[25,Luisa Molaria]

The mean value and the standard deviation of the external diameter D, of the thickness δ and the density ρ of the culms are reported on left. The mean **diameters** span from 51.13 mm, for VIO, to 79.43 mm, for VIV. The **thickness** goes from 4.53 mm of VIO to 7.25 mm of EDU (which shows a very thick culm at the bottom in respect to the upper part). The **density** is comparable for BAM, EDU and IRI, while lower values have been found for VIO and VIV. For all the species, the density of the **TOP** specimens is higher than the **BOT** ones, except BAM for which the two values are similar. [25,Luisa Molaria]

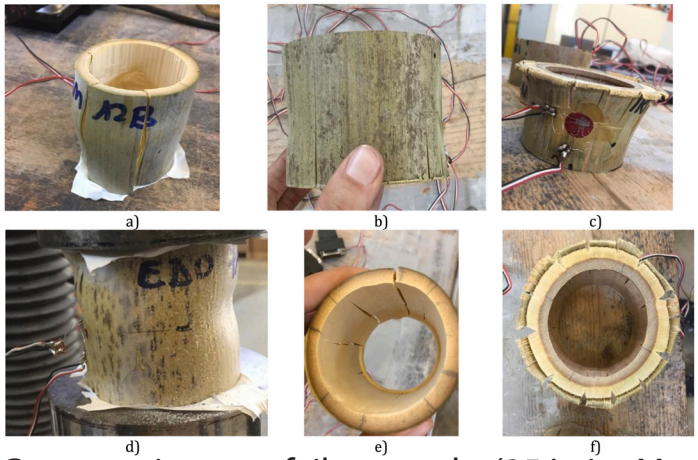
The tested specimens were equipped with two orthogonal bidirectional strain gauges as shown in left a to measure the deformation in the direction of the application of the load **(parallel to the fibers) called εz** and in the **circumferential direction named εt**. It shows longitudinal compression stress versus longitudinal strain (negative values) and versus circumferential strain (positive values) for all the specimens tested for **BAM**. All the other species show the same behaviour. [25,Luisa Molaria]

| Species | $f_{c,0}$ [MPa] | | $E_{c,0}$ [GPa] | | $r$ [-] | | $w$ [-] | |
|---|---|---|---|---|---|---|---|---|
| | *Mean* | *St.Dev* | *Mean* | *St.Dev* | *Mean* | *St.Dev* | *Mean* | *St.Dev* |
| BAM | 80.43 | 6.75 | 20.34 | 5.02 | 0.34 | 0.17 | 9.60 | 0.79 |
| EDU | 68.69 | 8.06 | 14.04 | 3.64 | 0.27 | 0.10 | 10.84 | 0.30 |
| IRI | 80.12 | 5.00 | 21.89 | 3.99 | 0.35 | 0.20 | 10.38 | 0.39 |
| VIO | 59.50 | 7.26 | 16.27 | 5.71 | 0.47 | 0.28 | 10.15 | 1.50 |
| VIV | 64.35 | 2.80 | 17.37 | 2.61 | 0.39 | 0.15 | 10.11 | 0.23 |

Compression test: mean values and standard deviation for each species considering all the tested specimens. (25,Luisa Molaria)




Compression test: (a) strength, (b) Young modulus, (c) Poisson ratio for each species considering all the specimens. (25,Luisa Molaria)




Compression test: failure mode. (25,Luisa Molaria)

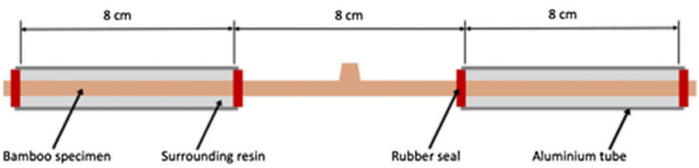
The graph reveals an initial linear stress–strain relationship followed by a non-linear behaviour. The mean values and standard **deviation** of the ultimate compressive stress, of the Young modulus, of the ratio between the transversal and longitudinal strains and of the water content are collected on left. [25,Luisa Molaria]

The left figure shows the box plot of compressive strength, Young modulus and Poisson ratio of the different species. The analysis of Variance conducted by using Matlab tool Anova shows that for **compressive strength BAM and IRI** are significative different from EDU, VIV and VIO.For Young modulus BAM, EDU and VIV do not behave in a significantive different way in respect to other species. IRI behaves differently from VIO.For Poisson ratio the species do not show significantly differences.[25,Luisa Molaria]

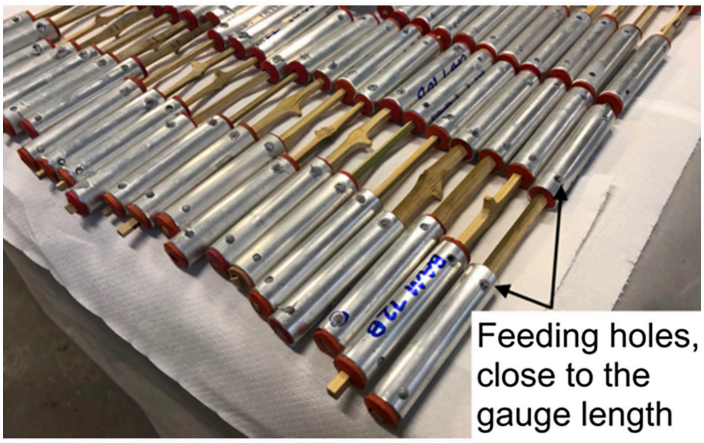
Four failure modes are encontered:

- expansion of the central part of the specimen (a),
- expansion of the bottom and upper part of the specimen (b),
- expansion of only one part (the upper or the bottom) (c),
- a local buckling (d).
- a local crush of the specimen in the part of the specimen in contact with the loading plates(e)
- a separation of the outer skin of the bamboo(f)[25,Luisa Molaria]

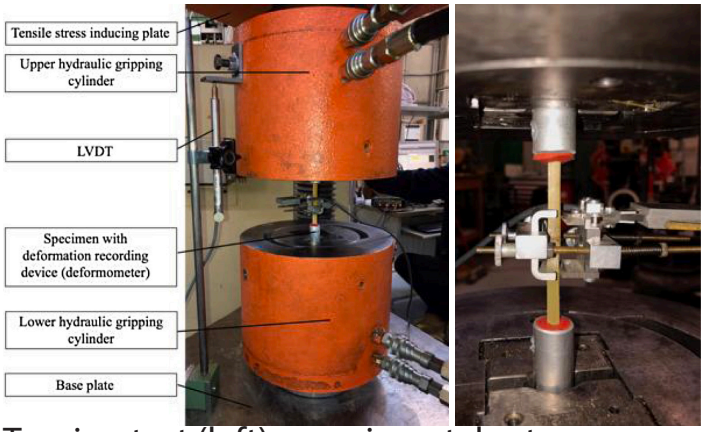
## 03-Tensile test



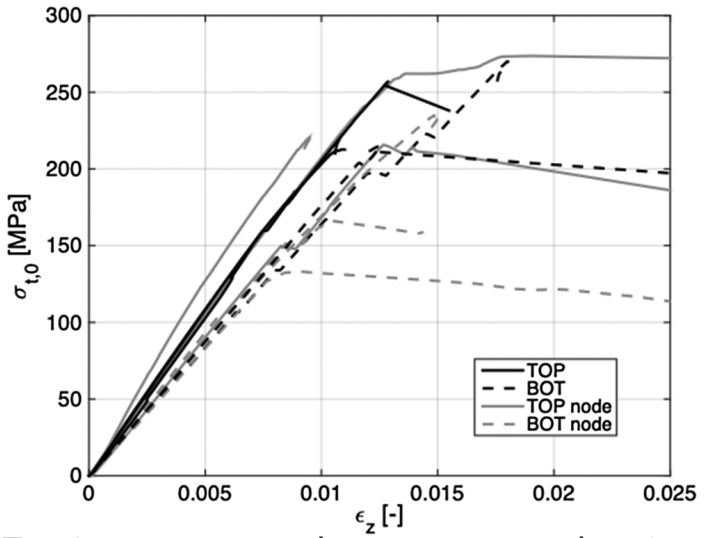

Sketch of the specimen(25,Luisa Molaria)




Tension specimens(25,Luisa Molaria)




Tension test:(left) experimental set-up, (right) zoom on the specimen with estensometer (25,Luisa Molaria)




Tension test: examples stress versus longitudinal strain for Bambusoides species (25,Luisa Molaria)

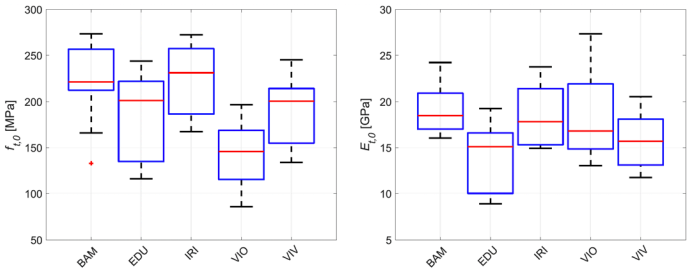
Each specimen is prepared splitting a bamboo stick of cross section with one dimension equal to the culm wall thickness of the culm δ and the width, b, equal to 5 mm. The stick is then buried at the extremities in an aluminium pipe filled by resin. For centring the stick and sealing the resin two hollow cylindrical shaped rubber seals are posed at the two ends of the piece of pipe as shown on left. An **epoxy resin** (SIKADUR-330) is filled from bottom to top, using a 100 ml syringe by two holes drilled in each aluminium tube. The specimen is then dried for 24-hour at room temperature. [25,Luisa Molaria]

The testing set-up is shown on left figure. The load is applied through universal testing machine GALDABINI, with maximum capacity of 100 kN. A DD1 HMB estensometer was installed directly on the specimen,holding on to the sides of it.To monitor the displacements between the jaws, an additional LVDTHBM 1-WA/50MM-T was installed. [25,Luisa Molaria]

The diagram depicted on left shows the longitudinal stress versus the longitudinal strains for **BAM species**.In some cases a linear elastic brittle behaviour is encountered, in some other cases there is a non linear behaviour after the maximum stress due to the successive failure of fibers as observed by Amada.The different behaviour is related to **different failure modes** reported in the following. [25,Luisa Molaria]

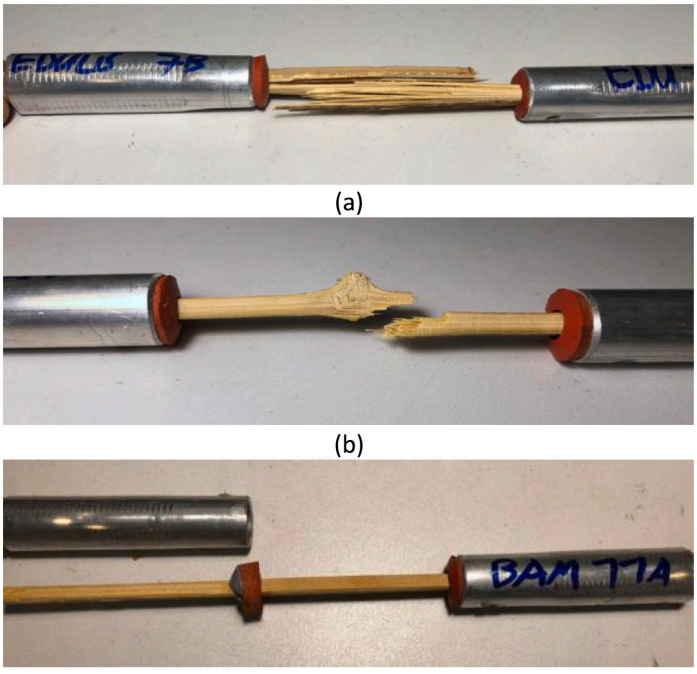
| Species | $f_{t,0}$[MPa] | | $E_{t,0}$[GPa] | | $w$ [-] | |
|---|---|---|---|---|---|---|
| | *Mean* | *St.Dev* | *Mean* | *St.Dev* | *Mean* | *St.Dev* |
| BAM | 220.28 | 41.91 | 21.80 | 2.60 | 9.59 | 0.78 |
| EDU | 193.51 | 42.73 | 15.19 | 2.92 | 9.09 | 0.30 |
| IRI | 229.38 | 34.92 | 18.22 | 3.12 | 9.11 | 0.39 |
| VIO | 148.91 | 31.40 | 18.17 | 4.63 | 9.04 | 0.23 |
| VIV | 188.84 | 37.62 | 14.90 | 4.75 | 8.94 | 1.50 |

Tension test: mean values for each species considering all the tested specimens. (25,Luisa Molaria)




Tension test box plots: (a) strength, (b) Young modulus. (25,Luisa Molaria)

In top table,the mean values and the standard deviation of strength,Young modulus and the relative water content are collected, on lower diagram the related box plot is depicted. A variance analysis shows that there are significative differences between **BAM and IRI** shows significative differences with VIO.Regarding the Young modulus, the variance analysis shows that all the species behave similarly. [25,Luisa Molaria]



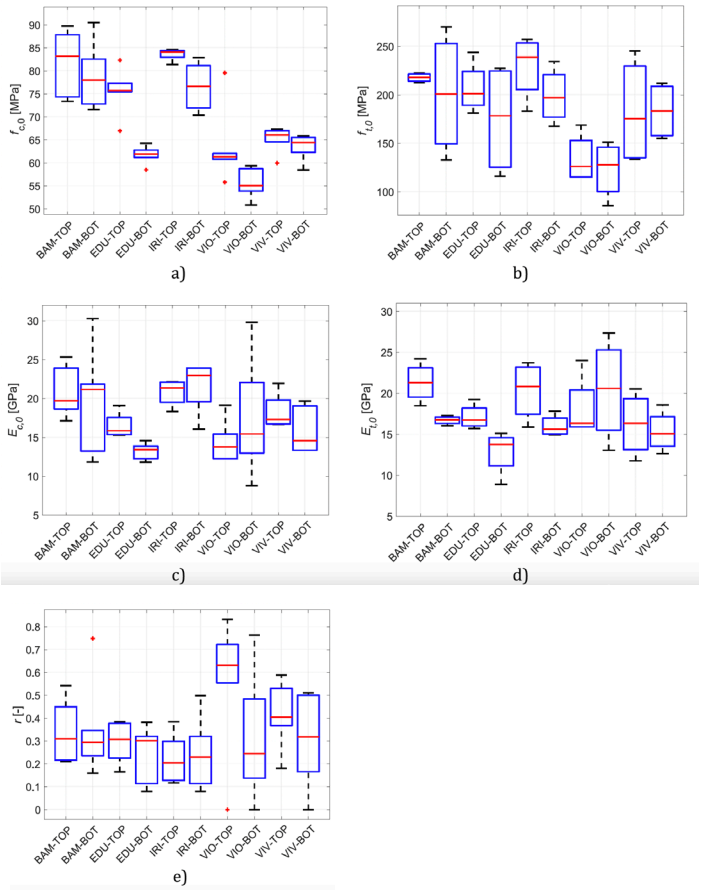

Tension test:(left) experimental set-up, (right) zoom on the specimen with estensometer (25,Luisa Molaria)

The failure of specimens in tension test can be divided into two groups.

The first group experiences a sort of **delamination**(20 times)(a);

The second group experiences a **localized fracture** (32 times) (b);

In some cases a **failure of the bond** between resin and metal pipe occurs (8 times) (c). The data of the tests in which this latter failure is encountered, are not considered. [25,Luisa Molaria]




Influence of the position of the culm:
(a) compression strength,
(b) tension strength,
(c) Young modulus,
(d) Young tensile modulus,
(e) Poisson ratio for all the specimens of each species. (25,Luisa Molaria)

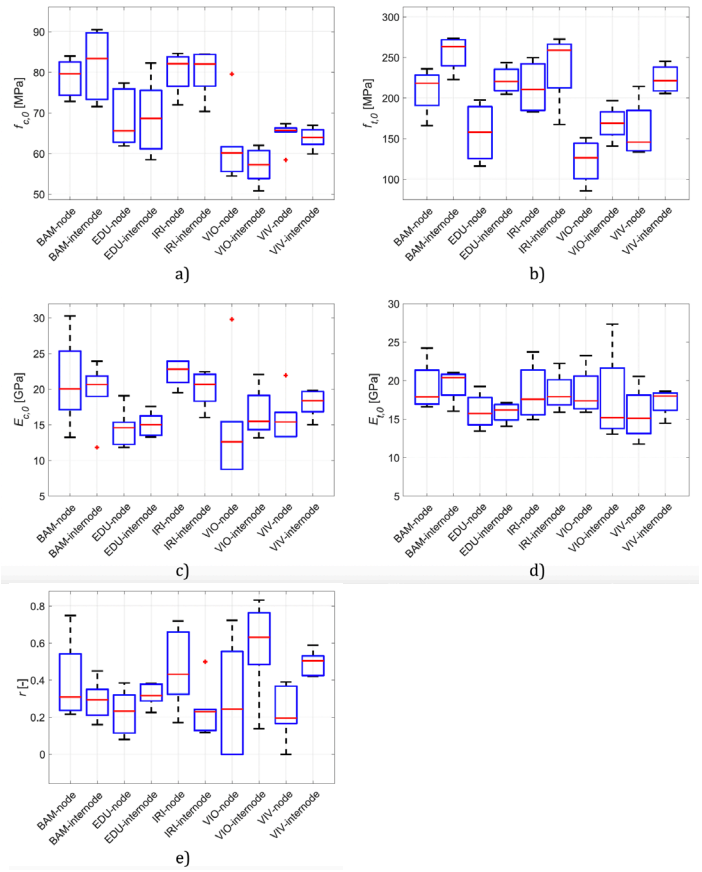
## Influence of the position of the sample in the culm

The values of compression and tension strength separated for specimens in different positions of the culm, are reported in (a) and (b). It can be noted that **in the upper specimens the tensile and compressive strength are higher** in terms of mean values in respect to the specimens extracted from the bottom part of the culm. On the contrary using a variance analysis the differences are not significative except for **EDU** for compressive strength.(c), (d) and (e) show respectively, **the values of Young modulus** in compression and tension and the values of the **Poisson ratio** in compression.Using a variance analysis also in this cases the differences are not significative except for **EDU and BAM** for Young modulus in tension. [25,Luisa Molaria]

| Species | $f_{c,0,TOP}/f_{c,0,BOT}$ | $f_{t,0,TOP}/f_{t,0,BOT}$ |
|---|---|---|
| BAM | 1.12 | 1.11 |
| EDU | 1.43 | 1.17 |
| IRI | 1.14 | 1.09 |
| VIV | 1.36 | 1.10 |
| VIO | 1.32 | 1.07 |

Ratio between mean strength in case of specimen from the bottom part of the culm and from the top part of the culm. (25,Luisa Molaria)

The ratio between the mean value of strength in tension and compression test for specimen from top and bottom part of culm is reported. The compressive strength decades deeper in respect to **the tension strength from the top to the bottom**. The species with the higher gap in the tension and compression strength between the top and bottom part of the culm is **EDU**, which has an evident difference also in geometry between the two parts with a particularly thicker bottom part of the culm in respect to the upper part of culm.




Influence of the node:
(a) compression strength,
(b) tension strength,
(c) Young modulus,
(d) Young tensile modulus,
(e) Poisson ratio and for all the specimens of each species. (25,Luisa Molaria)

## Influence of the presence of the nodes

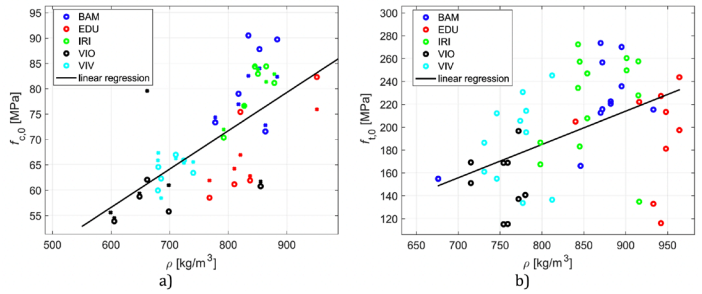
The **presence of node lowers** the tension strength in terms of mean values (b) while it seems to not significantly influence the other values (a, c and d).Significative differences highlighted by variance analysis van be noted only for tension strength for **EDU,VIO and VIV**.In The ratio between the strength in tension and compression test for specimen with and without node is reported. [25,Luisa Molaria]

| Species | $f_{c,0,Internode}/f_{c,0,Node}$ | $f_{t,0,Internode}/f_{t,0,Node}$ |
|---|---|---|
| BAM | 0.96 | 1.12 |
| EDU | 0.98 | 1.47 |
| IRI | 1.00 | 1.14 |
| VIV | 1.01 | 1.36 |
| VIO | 1.09 | 1.32 |

Ratio between mean strength in case of specimen with and without node for compression and tension tests. (25,Luisa Molaria)

## Mechanical characteristics versus density

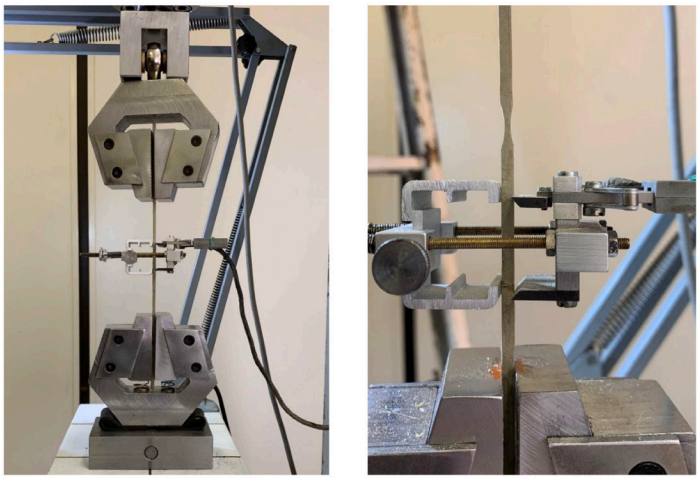
Correlation coefficients between density and the mechanical characteristics as strength, Young modulus and Poisson ratio are reported on the right. It can be noted that compression and tension strength show a good correlation with **density**, while Young modulus and Poisson ratio are not correlated. The regression line between strength and density is shown on the left. [25,Luisa Molaria]




(a) Compression strength versus density and (b) tensile strength versus density. (25,Luisa Molaria)

| Tension test | | Compression test | | |
|---|---|---|---|---|
| $f_{t,0}$ | $E_{t,0}$ | $f_{c,0}$ | $E_{c,0}$ | $r$ |
| 0.42 | 0.07 | 0.73 | 0.06 | −0.17 |

Correlation coefficients between density and the mechanical characteristics as strength, Young modulus and Poisson ratio. (25,Luisa Molaria)

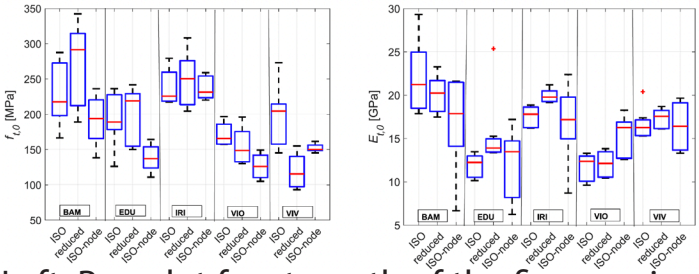


a) b)

(a) Experimental rig and (b) a specimen with reduced cross-section. (25,Luisa Molaria)

## Alternative set up for tension test

An experimental rig has been specifically designed to mitigate the effects of the crushing of the specimen at the jaws (leading almost invariably to a premature collapse). The designed grip system had been shown in (a). The width of the specimen is reduced by abrasion with a half-round file, following a template to guaranty a symmetric manufacturing (b). [25,Luisa Molaria]




Left: Box plot for strength of the five species. Right: Box plot for Young tensile modulus of the five species. (25,Luisa Molaria)

## Results, Comparison and evaluation of the new procedure

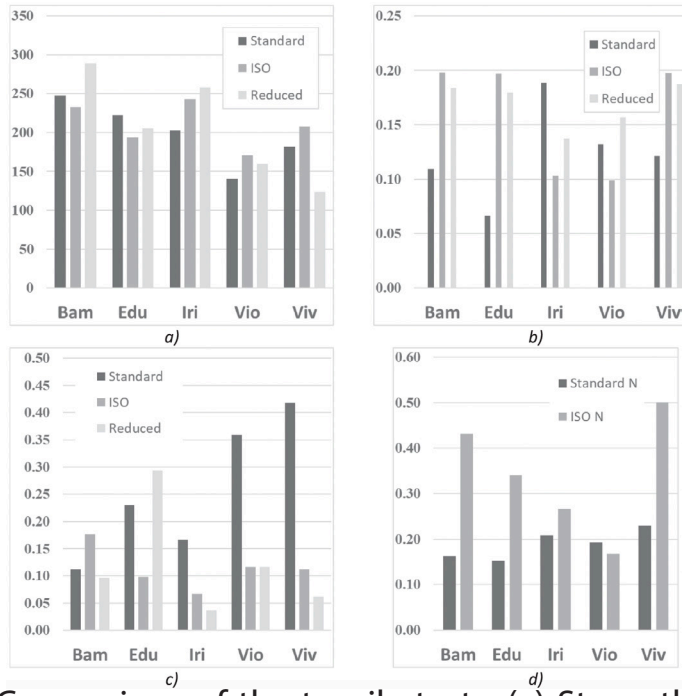
The experimental results obtained with the proposed setup with and without node (named respectively 'ISO' and 'ISO-node') and the results obtained for specimens with reduced cross section without nodes (named 'reduced') are presented on left four figures in terms respectively of strength and Young modulus for all the species.[25,Luisa Molaria]

| Species | $f_{t,0}$ [MPa] | | | | | |
|---|---|---|---|---|---|---|
| | ISO | | Reduced | | *ISO-node* | |
| | *Mean* | *St.Dev* | *Mean* | *St.Dev* | *Mean* | *St.Dev* |
| BAM | 232.31 | 46.01 | 288.73 | 53.10 | 191.61 | 35.64 |
| EDU | 193.50 | 38.13 | 205.45 | 36.95 | 138.75 | 19.06 |
| IRI | 243.29 | 25.11 | 257.79 | 35.39 | 237.83 | 16.38 |
| VIO | 173.61 | 16.53 | 159.44 | 24.97 | 127.49 | 16.20 |
| VIV | 207.65 | 40.99 | 123.73 | 23.23 | 152.01 | 5.79 |

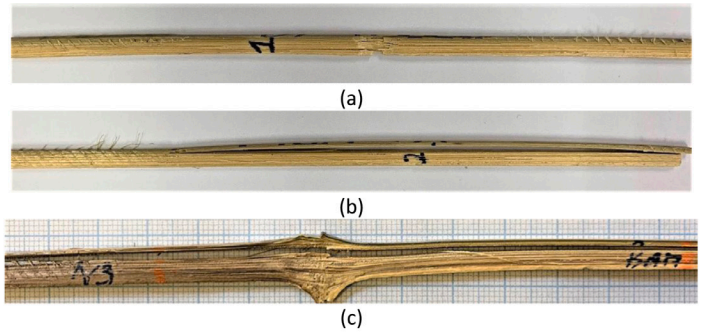
Tension test: mean values and standard deviation of the strength for each species considering all the tested specimens in the three different set ups. (25,Luisa Molaria)

| Species | $E_{t,0}$ [GPa] | | | | | |
|---|---|---|---|---|---|---|
| | ISO | | Reduced | | *ISO-node* | |
| | *Mean* | *St.Dev* | *Mean* | *St.Dev* | *Mean* | *St.Dev* |
| BAM | 23.03 | 4.07 | 20.61 | 1.99 | 18.64 | 8.05 |
| EDU | 12.20 | 1.19 | 15.93 | 4.67 | 12.22 | 4.16 |
| IRI | 17.74 | 1.17 | 20.11 | 0.75 | 16.60 | 4.43 |
| VIO | 12.05 | 1.36 | 12.29 | 1.43 | 15.06 | 2.64 |
| VIV | 16.87 | 1.89 | 17.45 | 1.08 | 20.42 | 10.22 |

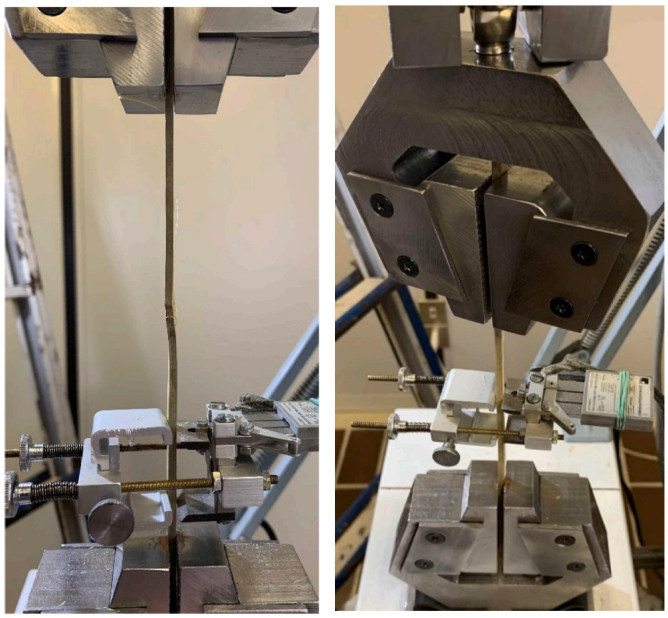
Tension test: mean values and standard deviation of the Young modulus for each species considering all the tested specimens in the three different set ups. (25,Luisa Molaria)




Comparison of the tensile tests: (a) Strength values [MPa]; (b) Strength: Coefficient of variation; (c)–(d) Young modulus: Coefficient of variation. (25,Luisa Molaria)




Two typical failure modes: defibring in the middle zone (a); delamination of the cortical layer in internode specimen (b) and in a specimen with node (c). (25,Luisa Molaria)




The examination of the results of the two groups of specimens, allows stating that the ISO specimens give results comparable in terms of ariance analysis with those obtained using the set up described in the first part of the paper (named 'standard'), even though, in the present study, different criteria are used to select the specimens. In particular,The left figure shows the mean and the coefficient of variation of the strength and of the Young modulus for all the species.For ISO specimen, the value of the strength and Young modulus is often less disperse as shown on the left by the relative standard-deviation(namely standard-deviation/mean). [25,Luisa Molaria]

It is very interesting to emphasize the failure modes encountered using this testing procedure:
-a distinct de-fibering in the middle zone (a);
-delamination of the cortical layer which propagates along the entire specimen (b and c). [25,Luisa Molaria]

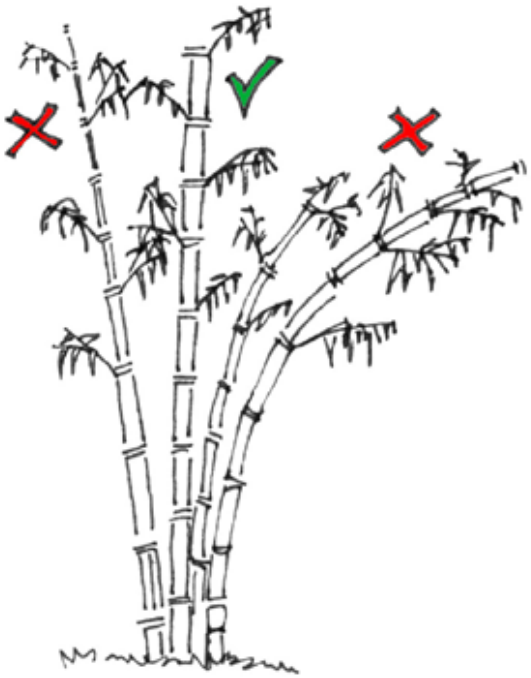
It is worthy of mention a brief comment about the response shown in (b), of an inter-node sample (BAM N5) affected by a natural knee (a), for the possible consequences in structural applications of the culms. In a first phase, the sample responds as two in-series beams, slightly misaligned under traction (smaller stiffness). The increasing tension changes the geometry towards the configuration of two aligned straight beam, whose stiffness (E) is therefore comparable with that of the other samples [25,Luisa Molaria]

(a) Specimen tested with natural "knee" which leads to (b) a natural twist to the anchorage of the press machine. (25,Luisa Molaria)

# 4.Bamboo Construction Detail

Bamboos grow so fast that farmer can harvest after 3 to 8 years, by picking straight and thick from top to bottom. During the moon phase between 6th and 8th day after full moon,12pm to 6 am is the best time to harvest mature bamboos. Generally, bamboos are planted as 5 x 5 meter spacing. After cutting and harvesting from ground, bamboos need to carefully treat and preferably protect against insects by using salt to fill all the cells. Boucherie method by using pump and borax/boric acid immersion are two main ways to treat raw bamboos.After 7 to 14 days treating, it can proceed to dry bamboos vertically and store away from sunlight, mud and rains. For the techniques of connection, tight rope connection is a typical technique to merge multiple bamboos together, as bamboo can use square lashing, diagonal lashing, and shear lashing. The other techniques are also feasible for connection by bamboo strips, rattan, purlin and braces with pre-drill holes. As well as bamboos can be jointed by plugin connection by inserting plug, bolts, steel clamps or steel tubes and wires. Also, there are many others for construction methods on foundations, floors, walls, roof, and windows. Building structure can be framed by straight rods, curved tension rods, and curved compression rods.

## 4.1 Harvesting and treatment process



(26,Komitu Architects)


(https://www.guaduabamboo.com/blog/when-and-how-to-harvest-bamboo)

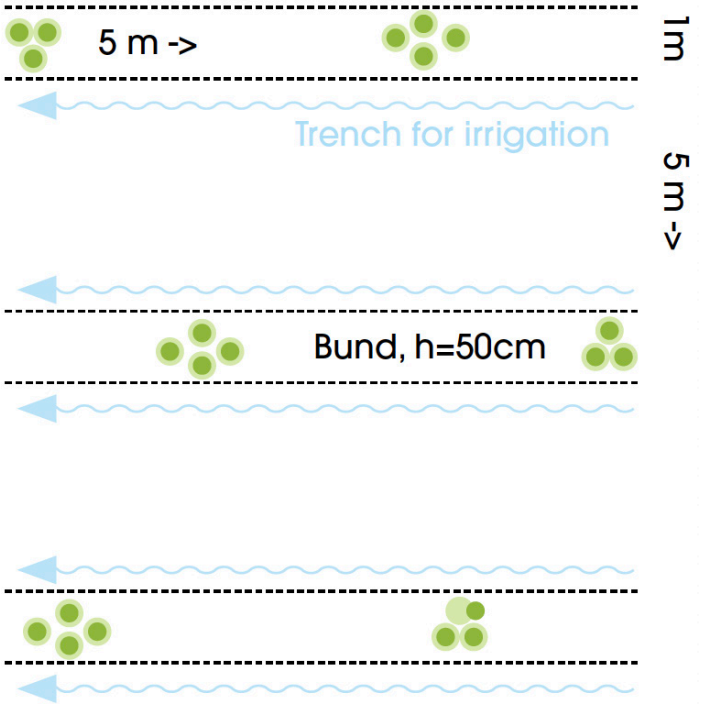
(https://www.guaduabamboo.com/blog/when-and-how-to-harvest-bamboo)

**Harvesting**

Besides choosing the correct species of bamboo, the bamboos should be harvested at the correct maturity and be given proper care.Fiber density, diameter, wall thickness and even sugar/starch content can vary in a species given even minor differences in temperature or soil nutrient. The individual quality of the bamboos will affect the final building design as well. The maturity of the bamboo can be recognized from the skin: young bamboo (0-2 years) have a smooth,shiny skin and culm sheaths, whereas old bamboo has fungi and mosses growing on the surface.The age of a bamboo culm should be at least 3 years old but not more than 8 years. Once bamboo is older than 8 years, it starts to dry and gradually loses it mechanical properties. The bamboos you harvest should be:

-**Straight**
-**Mature** (3 - 8 years old)
-As evenly **thick** as possible from top to bottom. [26,Komitu Architects]

The recommended time to harvest bamboo is at the end of rainy season beginning of the dry season, as that is when the sugar and moisture content in the bamboo plant is at its lowest. **The moon phase**: the starch content is lowest between **the 6th and 8th day after full moon** due to the higher gravitation of the moon.**Time of day**: best time to harvest bamboo, is before sunrise (between**12pm to 6am**), when most of the starch is still in the roots and photosynthesis has not yet started.Bamboo harvested in this manner has 3 advantages: they are less attractive to insects, are less heavy to transport and will dry faster. [26,Komitu Architects]

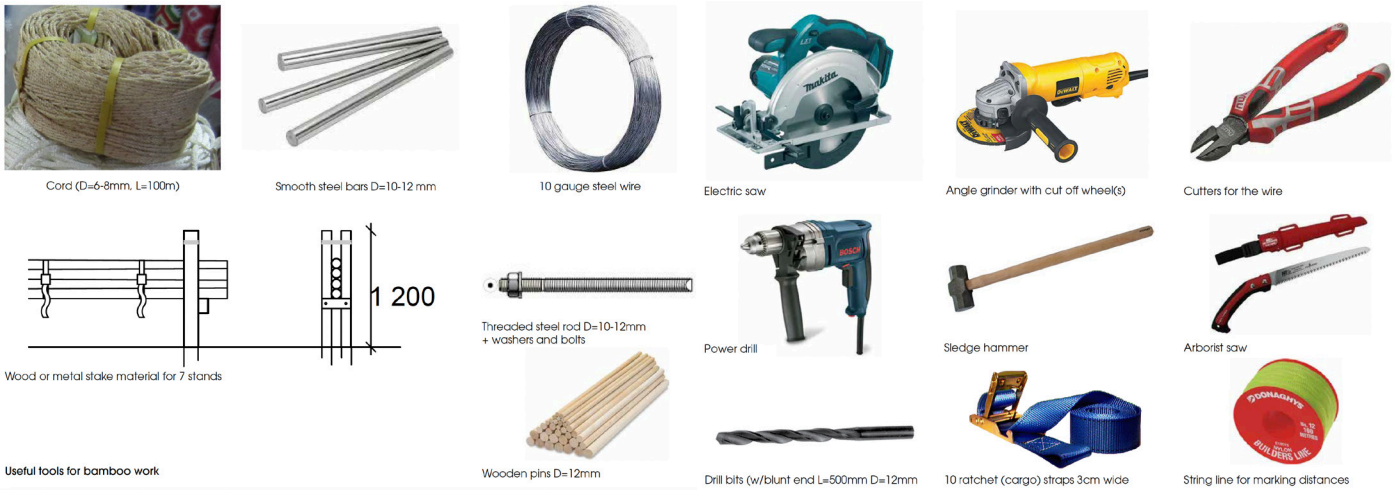



(26,Komitu Architects)

## Planting bamboo

To plant your own bamboo grove of medium-diameter, thick-walled species:**5 x 5 meters spacing** is optimal. This requires 400 clumps per hectare, or 160 clumps per acre.If the objective is to plant bamboo for erosion control along riverbanks or to protect an area from landslides and avalanches, the spacing can also be 3 x 3 meters or even 2.5 x 2.5 meters. In such cases, bamboo can be mixed together with appropriate, fast-growing timber species. [26,Komitu Architects]

## Useful tools for bamboo work




(26,Komitu Architects)


(26,Komitu Architects)

## Treatment process

Bamboos must be treated properly before building and preferably protected against UV. The goal of the treatment is to **fill the cells of the bamboo with salt to prevent insects** etc. from eating their way through it. Traditionally bamboos have been soaked in a local body of water,(preferably sea water) for some weeks,soaked for months in mud or smoked on a fire. [26,Komitu Architects]

(01)

(02)

(03)

(04)

(05)

(06)

(07)

(22,"Bamboo Construction Source Book.")

**Option 01-Boucherie method**

01-Hand Operated Pump

02-Fill up the Pump
Fill up the Pump Cylinder up to 3/4 with Borax / Boric Acid Solution using a funnel.

03-Prepare Bamboo
Make a fresh cut on the bamboo with the Hardwood back saw about 10 cm away from the node.

04-Place firstly the clamp and then the Hose Nozzle.

05-Tighten the clamp so that the Nozzle becomes air tight.

06-Pump until the presssure is between 20-25 psi.

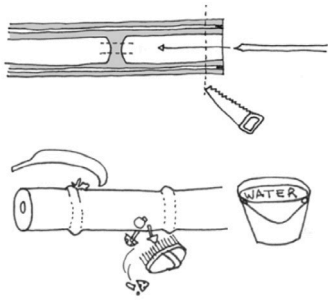
07-Repeat the process to all the avilable hoses.

**Chemical for Treatment**

For treatment of Bamboo total chemical should be used at 5% of total desolve chemical.Example: For 14 Litre capicity of pump chemcal to be used 700 Grams.
For **Structural Bamboo for pole, beam** etc Boric acid, Copper sulphate and sodiaum or potesium dicromate to be used in proporstion of 1.5:3:4
i.e. for 14 litre of tank
For **Non Structural member** like, wall lattice, Splits Boric acid and Borex to be used in 1:1.5: Proportion.
i.e. for 14 liter of tank
[22,"Bamboo Construction Source Book." ]


(01)


(02)



(02/03/04/05)


(04)


(06)


(07)


(08)
(26,Komitu Architects)


(26,Komitu Architects)

**Option 02-Borax/boric acid immersion**

01-Build a concrete pool big enough for the bamboos and cover the pool with a light roof to minimize evaporation.

02-Punch a hole through all node walls with an iron bar.

03-Clean fungus etc. away with a brush,water (and soap).

04-Clean traces of branches and leaves from the nodes.

05-Cut the ends of the bamboos to facilitate absorption .

06-Fill pools with clean water,leave enough space for chemical mixture.

07-Boil mixture of water,Borax and Boric acid in a barrel of 200L until chemicals hace dissolved and pour into the pool.

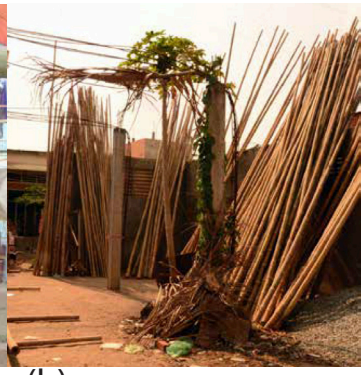
08-Soak bamboos for 10-14 days(minimum of 7 days) and add mixture when needed.

09-Clean the chemicals off bamboos with running water. [26,Komitu Architects]

Jar Test

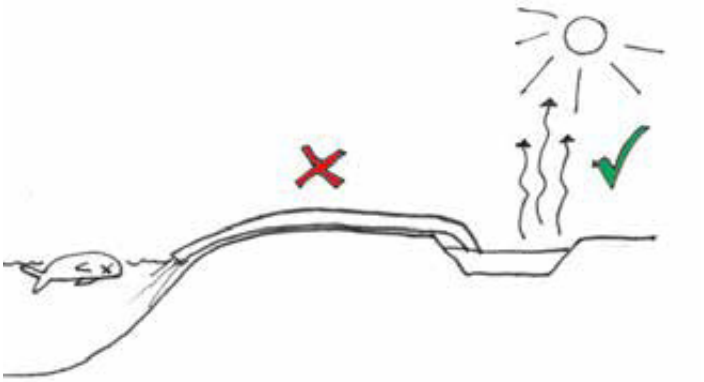
A simple jar test allows us to see **how much chemicals there are in the bamboos after a week of treatment**.Take a small piece of the wall of the bamboo from next to the second node.Remove the outermost and innermost layer of tissue and chop into small
pieces. Put clean tap water (test to be neutral) into a jar and put the bamboo pieces in. After a few hours test the water again and you can define the amount of borax in the tissue. Repeat the test if you don't first see any absorption. [26,Komitu Architects]

(a)



(b)

(c)



(d)


(e)

(26,Komitu Architects)

**After 7-14 days of treatment**, first **lift one end(a)** of the bamboos from the pool to let most of the water flow out of the other end. After most of the water has come out, lift the bamboos onto the cleaning racks and wash the excess salt away with water.

**Dry bamboos vertically(b)** for 2-3 days,protected from rain and direct sunlight to avoid cracking.

The same mixture can be used 3-4 times with some chemicals and water added when needed .

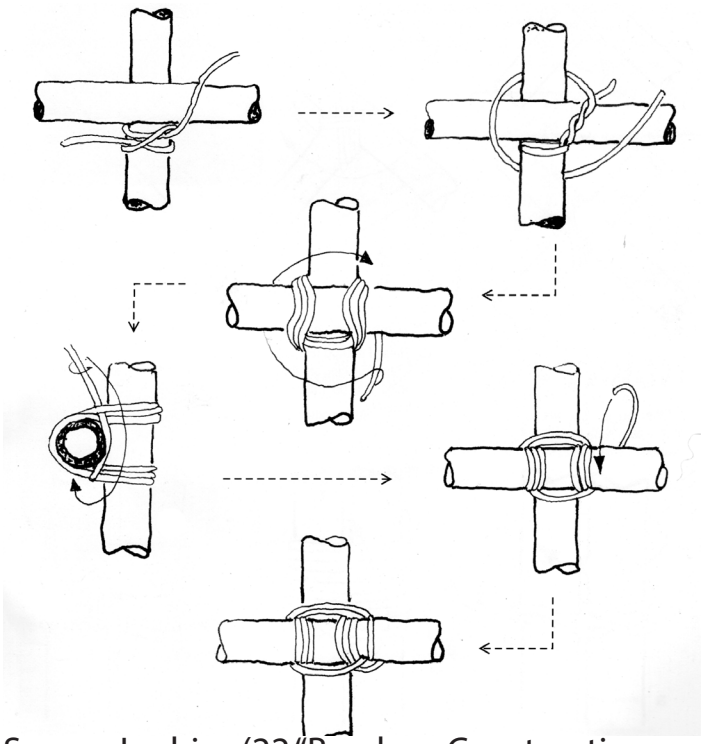
**Store the bamboos away from direct sunlight, mud and rains. (c)**

When treatment is finished, **remove the roof and let water evaporate**. Don't transfer the water to a lake or a river as animals and plants will suffer.

**Measure with moisture the fresh**, the treated and the dried bamboo and see when it has stabilized after the treatment and is therefore safe to build with. If you start building too soon after the treatment, the bamboos still have extra moisture in them and there is a risk of shrinkage and the joints failing when it stabilizes.[26,Komitu Architects]

## 4.2 Bamboo connections

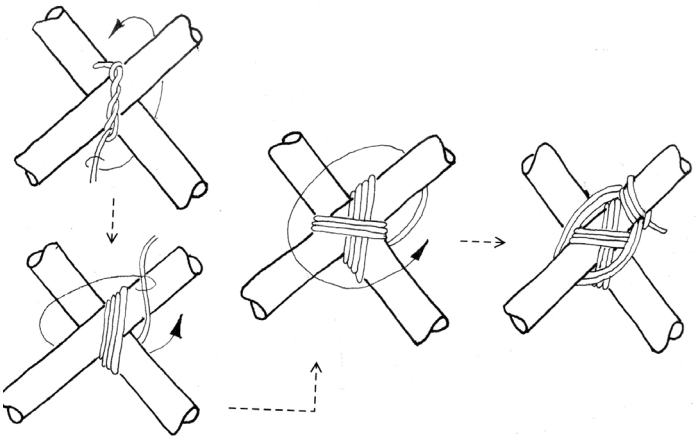
## 01-Friction-tight rope connections



Square Lashing(22,"Bamboo Construction Source Book.")

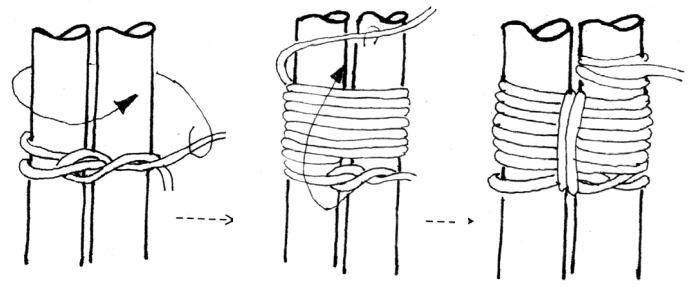
**Three types of lashing**

**Square Lashing**: Square lashing shall begin and end in a clove hitch. It shall be used in a condition where there is no tendency for poles to spring apart.



Diagonal Lashing(22,"Bamboo Construction Source Book.")

**Diagonal Lashing**: The square lashing shall begin and end in a clove hitch. It shall be used in condition where there is tendency for poles to spring apart.



Shear Lashing(22,"Bamboo Construction Source Book.")

**Shear Lashing:** A shear lashing shall begin and end with a clove hitch. Two ore more poles shall be first wrapped and then frapped to tighten the poles together. [22,"Bamboo Construction Source Book."]


(27,Bauen mit Bambus)

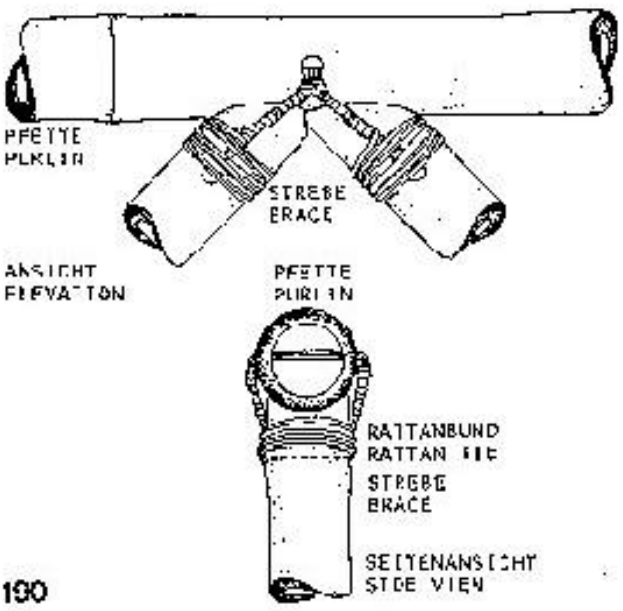
## Connection with bamboo strips

**Lashing ties**: The common type of connection at a joint is lashing. The ties are also of organic material and therefore provide optimal compatibility between the elements of the construction system.
**Cords and ropes** are made of bamboo bark,bast,coconut or sagopalmfibres. Nowadays also **plastic cords** are used.Bamboo ropes of twisted bamboo fibres are produced in lengths up to 350m. They are more wear-resistant than standard ropes. With a tensile strength of 720 kp/cmÑ a rope of an arm´s thickness can bear up to 14 tons.
**Binding wire** is (as plastic cords are) an industrial product.Zinc coated wire has the same lifetime as bamboo. [27,Bauen mit Bambus]


(27,Bauen mit Bambus)

## Fine handwork rattan connection

**Plait strips:** Usual plait materials are rind strips of bamboo, rattan or lianas. Soaked before use they are more pliable. When drying,the fibres shrink and the connection tightens. [27,Bauen mit Bambus]



(27,Bauen mit Bambus)

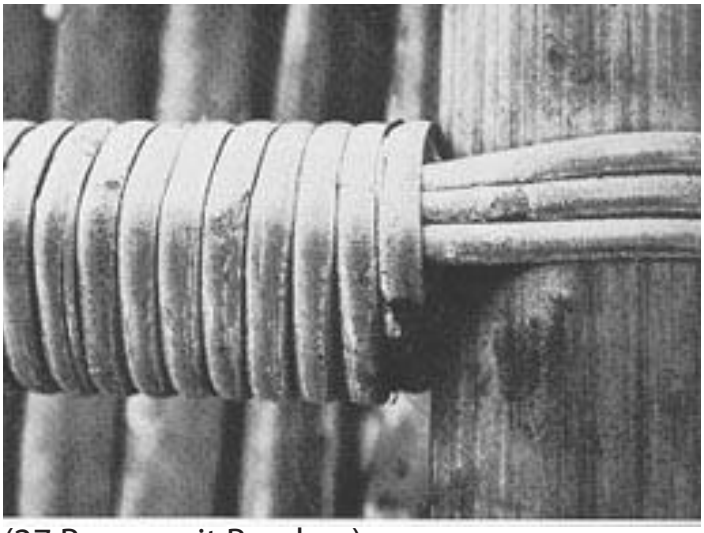
**Purlin and braces connection**

**Lashing ties:** connection of a purlin and two braces with three drill-holes. [27,Bauen mit Bambus]


(27,Bauen mit Bambus)

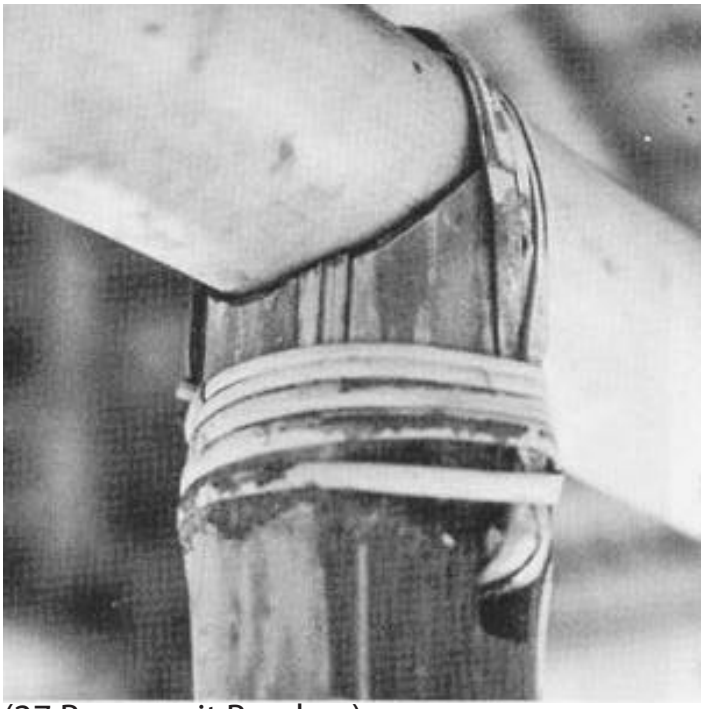
**Rattan connection through drill-holes**

Rattan tie to fix a plug connection[27,-Bauen mit Bambus]


(27,Bauen mit Bambus)

**Another rattan connection**

**Friction-tied rattan connection:The end of the beam** and the tie do the power transmission. If the connection is not tight enough, the beam may crack at the drill-hole.The additional bandage prevents the sling from slipping. If connected at a post nodium, the broader nodium in addition complicates slipping of the beam. [27,Bauen mit Bambus]



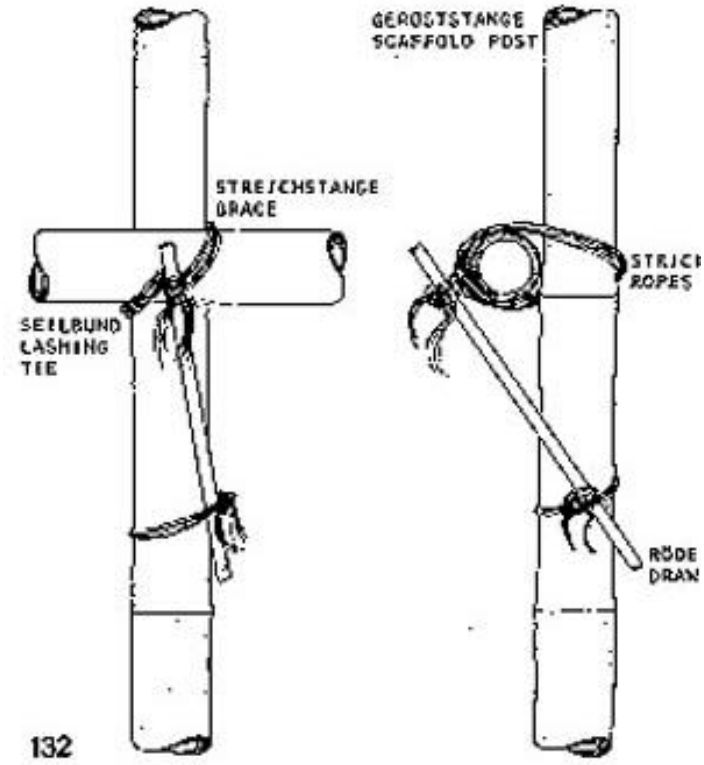
(27,Bauen mit Bambus)

**Variation of the connection above**

**Top of the post with drill-hole:** If post and cross-beam are of the same diameter, the lashing tie replaces a stop at the side. A croossing bandage shortens the sling and prevents the post from sliding. [27,Bauen mit Bambus]

**Traditional scaffolding -Lashing tie with drawing stick**

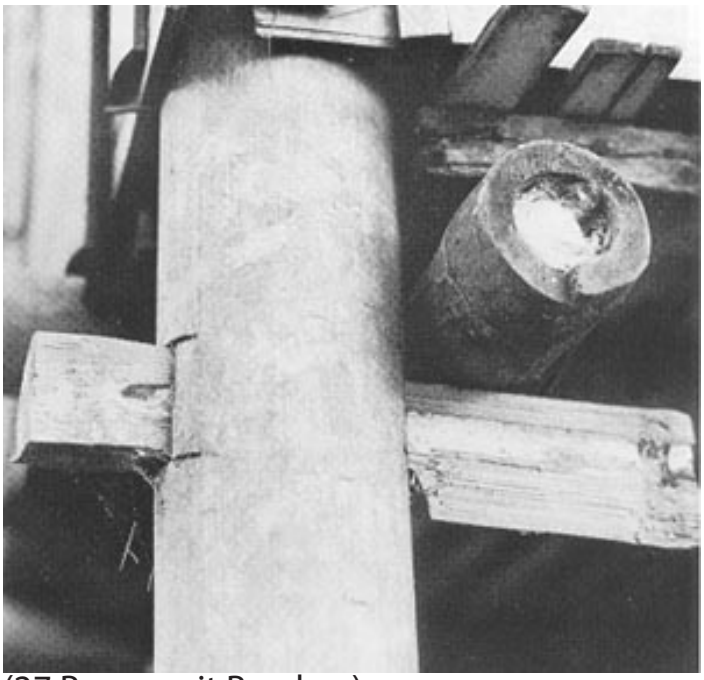
**Bamboo canes connection with lashing ties and a draw stick:** with the help of the draw stick the lashing tie is tightened. Then the stick is fixed to the post.
**Scaffold braces:** are bamboo canes which often are only fixed with the lashing ties.
[27,Bauen mit Bambus]




(27,Bauen mit Bambus)

(27,Bauen mit Bambus)

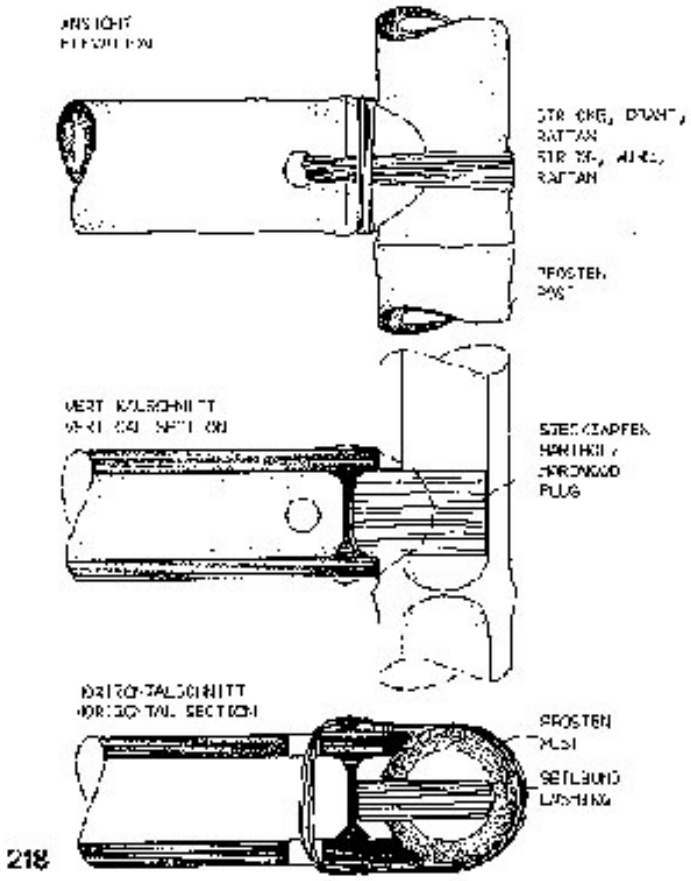
# 02-Plugin Connections and Bolt Structures



(27,Bauen mit Bambus)

**Plugin console**

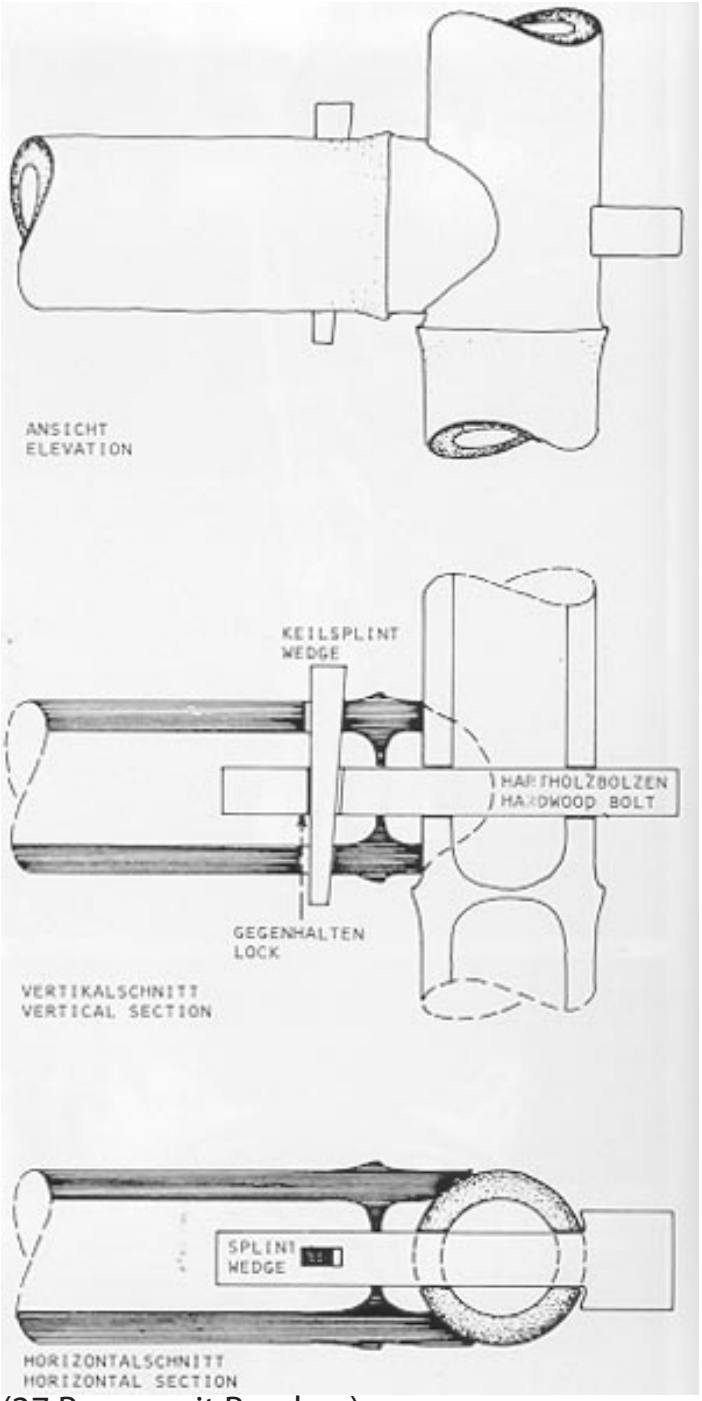
**Plugin connections:** Carpenterlike connections with mortise and tenon are seldom used in bamboo structures. On the other hand plugin elements like bolts or consoles you find very often. Additional lashing or wedging keeps things in place.
The use of **nails** may split the bamboo particular old and dry canes. Pre-drilling is a method to prevent splitting. There are two bamboo species which can be nailed: **Guadua angustifolia** and **Chusquea.** [27,Bauen mit Bambus]




(27,Bauen mit Bambus)

**Connection with inner plug**

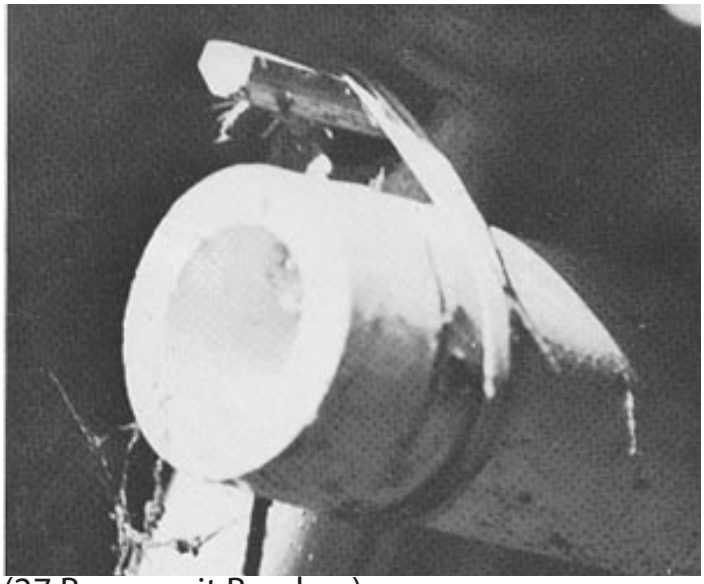
Connection with inner plug and a horizontal drill-hole to fix the connection with a lashing tie. If the lashing is tight and the plug fits quite good into the opening, both plug and lashing can do the power transition. But even if not,this connecting method can be very durable at less force. The inner plug prevents the beam from slipping down the post and the lashing is against unplugging. [27,Bauen mit Bambus]



(27,Bauen mit Bambus)

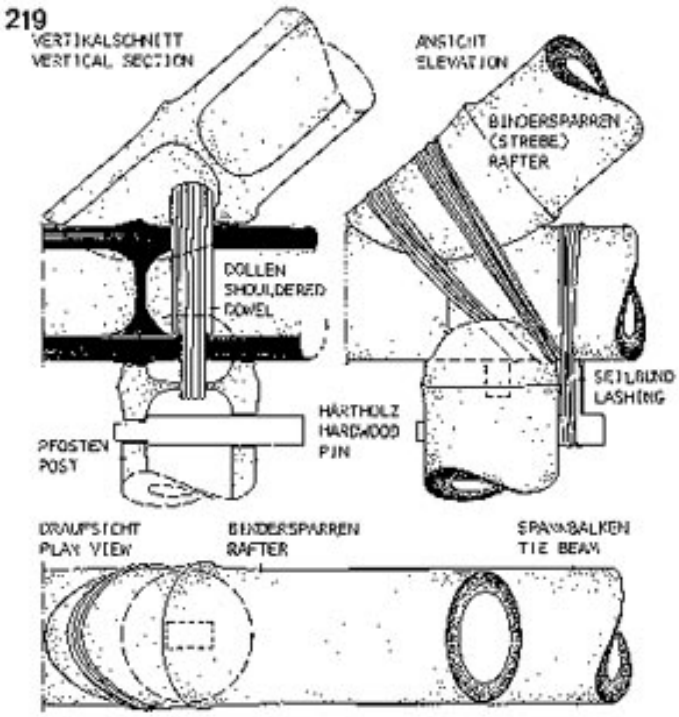
**Bolt structure**

**Plugin connection:** This is a type of connection for greater diameters with **a hardwood bolt and wedge**. Five holes, the bolt and the wegde - a more extravagant connection. If the bolt is conical, the connection is save in all directions. [27,Bauen mit Bambus]


(27,Bauen mit Bambus)

**Rope connection fixed with bolt**

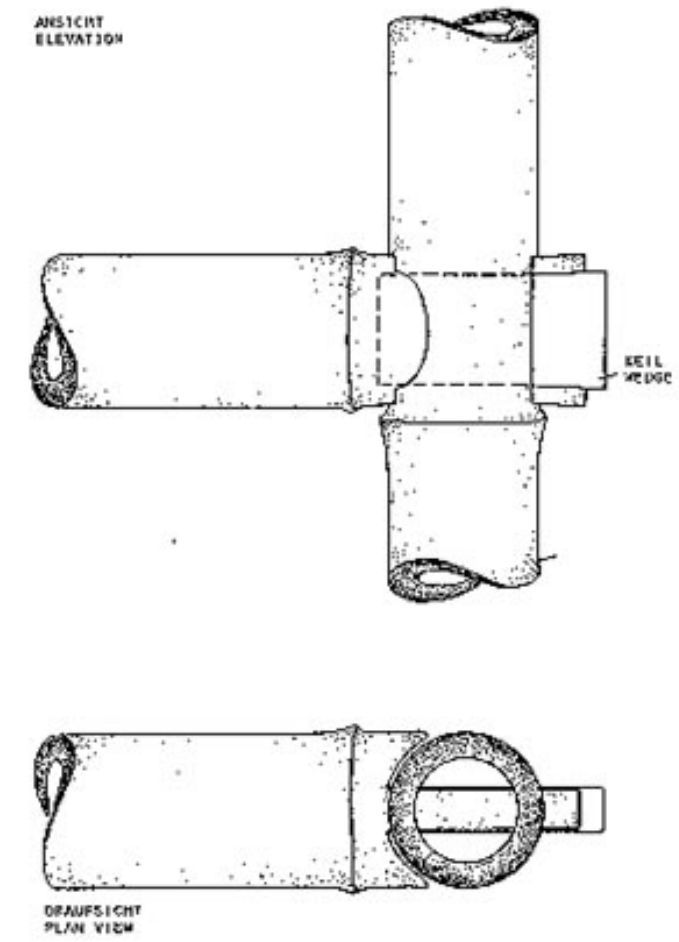
The **bolt** keeps the conncetion in place even if the rope or cord lenghtens. [27,Bauen mit Bambus]




(27,Bauen mit Bambus)

**Complicate joint with two connections**

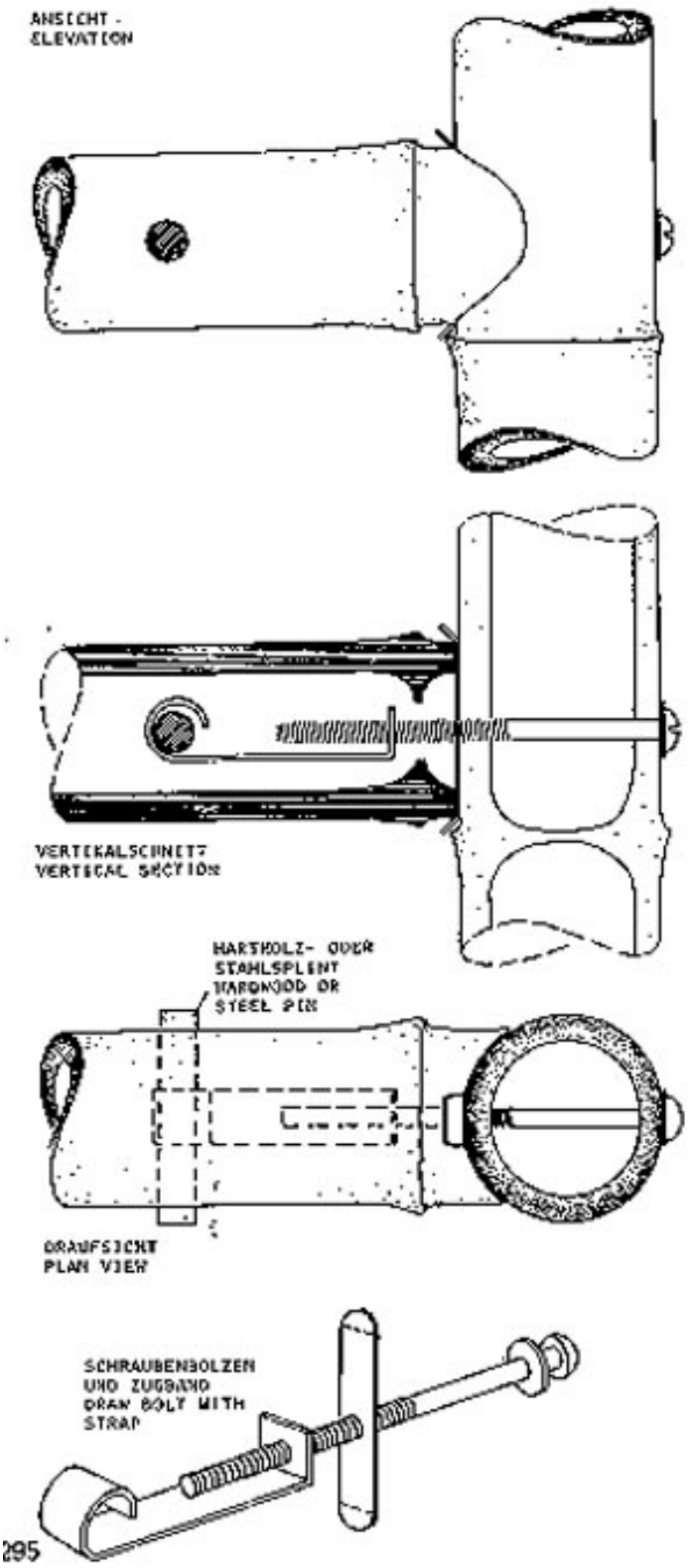
**Joint with two connections.** Again a combination of bolts and lashing to connect the canes. [27,Bauen mit Bambus]




(27,Bauen mit Bambus)

**Interlocking connection with wedge**

With the wedge driven into the opening, the strips of the **horizontal beam** are pressed into the hole and fix the beam. If the wegde shrinks,the beam can be easily pulled out of the opening. So additional arrangements like lashing or bolts are necessary for a save connection. [27,Bauen mit Bambus]



(27,Bauen mit Bambus)

**Connection with steel clamp**

Leaving the **low-tech sector**, with the use of steel elements a lot more connections become possible. Avoid connections which produce great forces vertical to the cane axis. They can destroy the bamboo cane. [27,Bauen mit Bambus]

(27,Bauen mit Bambus)

**Connection with steel tube and bolts**

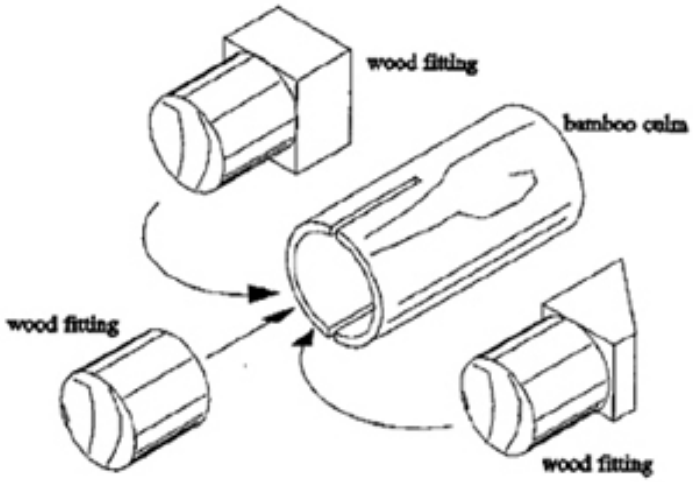
**Modern connection by Shoei Yoh in 1989**. For his bamboo roofs in Fukuoka, Shoei Yoh used a **steel tube** put into the bamboo and which is connected to the cane with bolts. The steel tube is strong enough to withstand the pressure of the tightened bolts. In addition there are two bolts in vertikal direction. For the connection to the knot a **steel bar** is welded into the tube and again it is screwed to the knot. Because of the numerous bolts the connection is also suitable for greater loads. The result is a very technical but strangely overstyled looking connection. [27,Bauen mit Bambus]

(27,Bauen mit Bambus)

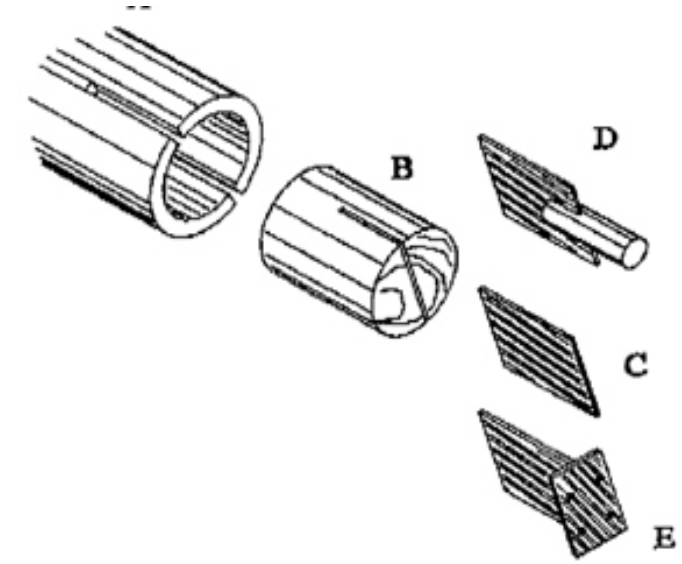
**Connection with steel wire**

**Modern connection by Renzo Piano Building Workshop in 1997.** The canes are connected to a **special designed steel element via binding wire**. Instead of a bolt driven through bar and cane, a wire is tied through the holes and tied around the bamboo. A fine artwork but because of the fine wire seemingly only for small forces. [27,Bauen mit Bambus]

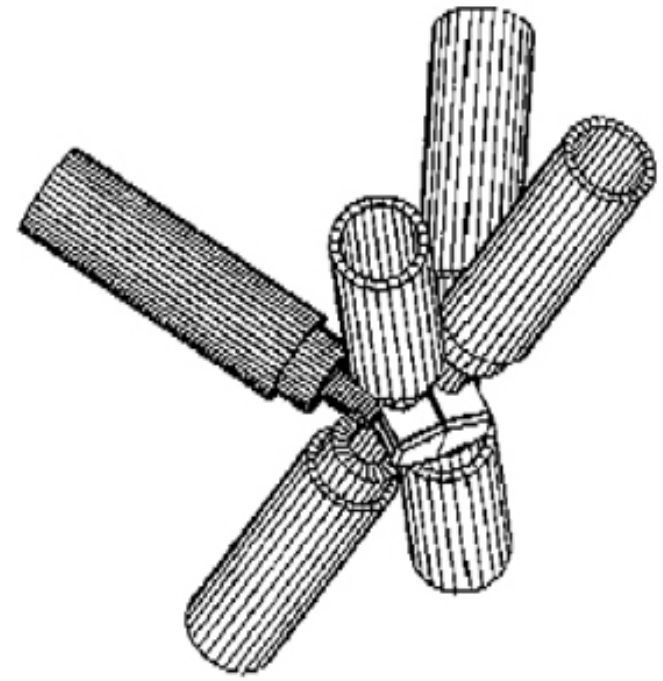
# 03-Interlocking Connections




Possible inner parts (27,Bauen mit Bambus)




Connecting system (27,Bauen mit Bambus)



Space truss, with centre steelbox element (27,Bauen mit Bambus)

**Woodcore Connection**

A piece of wood can be used and glue can be employed to stick it to the inner surface of the bamboo. Any normal glue provides a capaity far larger than that of bamboo in the tangential direction.

**Two slots** are needed in the bamboo cane to control cracking during the insertion of the wood cylinder.

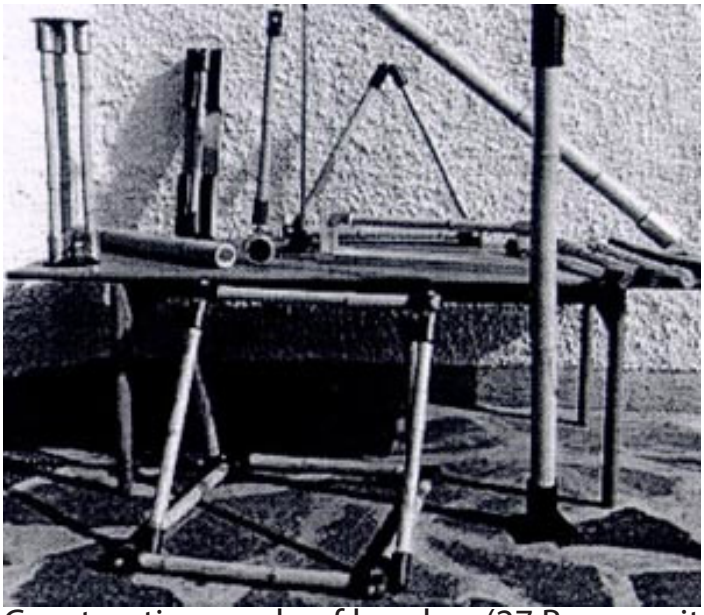
**The wood fitting** can be extended outside the culm to meet the outcoming piece of wood from other elements, then normal wood construction methods can be used for connection.

The steel plate C is introduced in the slot of the wood cylinder and glued to it with a mixture of epoxy resin and portland cement. The plate is projected, so that its outer extreme can be adapted for different applications, as indicated in the details D and E.

System advantages are its low price and the availibilty of the parts.

**In plane or space trusses**, the plates from two or more incoming elemets can be prewelded to eachother and then the rest of the connection can be assembled.

The figure shows a connection in which a small box is made of steel plates, so that the faces are perpendicular to the axis of the incoming elements. The steel tips are then welded directly to those surfaces. Welding is thought of here because it is cheaper than machining of the tips, but in some cases tis can be achieved as well. [27,Bauen mit Bambus]



Construction made of bamboo(27,Bauen mit Bambus)

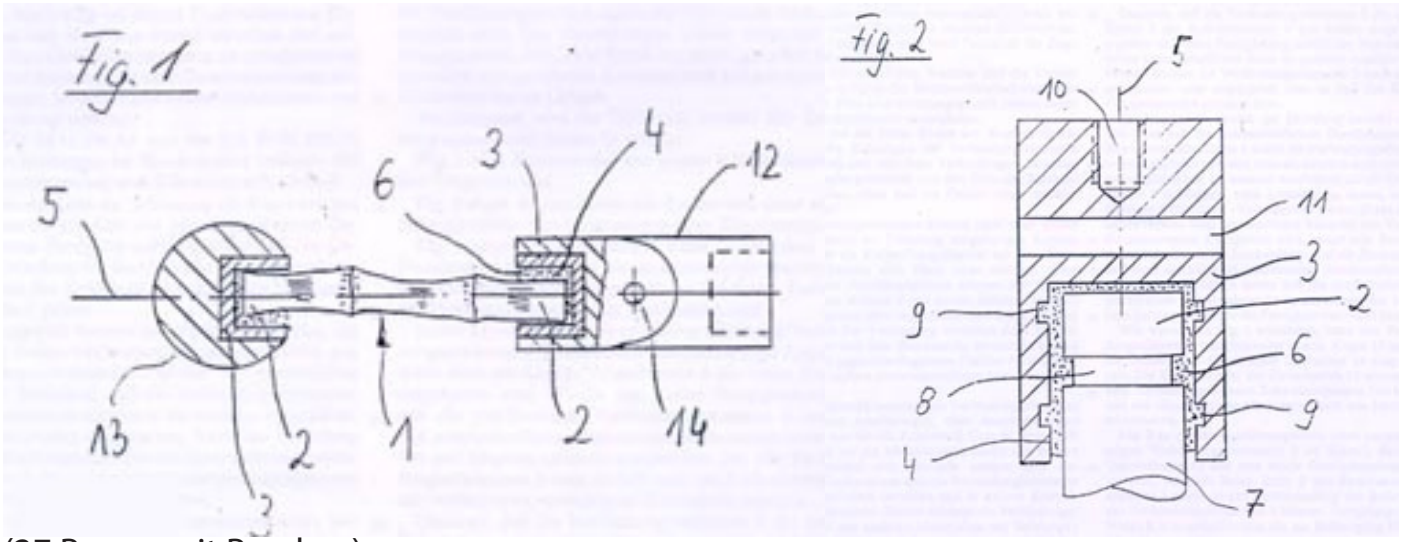

The inventor Bruno Huber (27,Bauen mit Bambus)

## Bambu-Tec Constructionelements

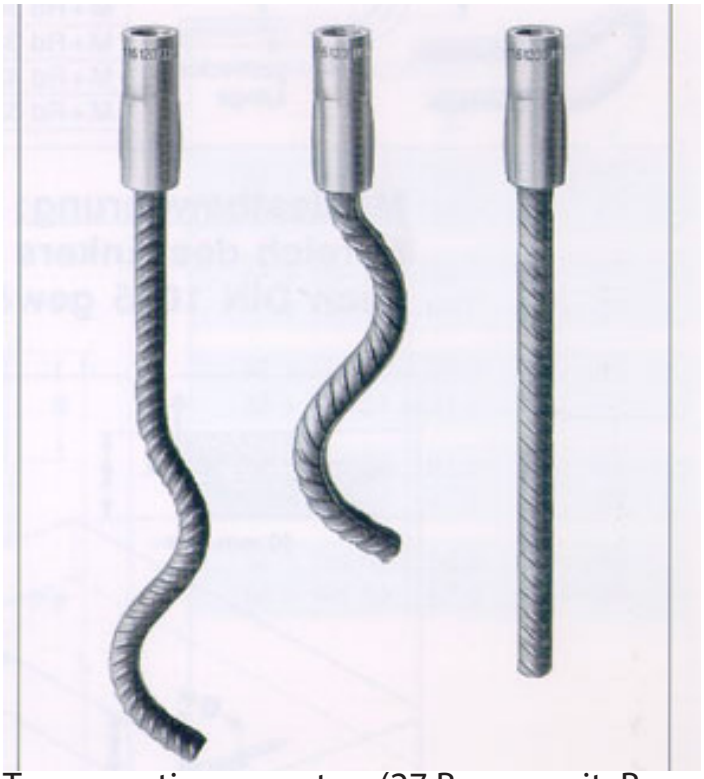
The bamboo canes are cut into the desired, unique length (e.g.0.5m,1m,2m). Both ends are covered with **caps** that are connected with artificial resin or another fillingmass. To give the connection cap/bamboo a high tensile strength the bambooends are given circular grooves and the inner cap is covered with circular notches, so the connecting mass acts like a claw between bamboo and cap.

The **capfastening** is done with a gauge, so the caps are aligned exactly parrallel and in a reproducable distance. The caps can be made of synthetic, aluminium or steel. It is even possible to produce them, by using the synthetic spray technique, directly on the bamboo. There can be bores, threads or flanges fixed to the caps. If you use steel or aluminiumcaps they can even be welded to other metalparts. [27,Bauen mit Bambus]

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




(27,Bauen mit Bambus)



Transporation armature(27,Bauen mit Bambus)

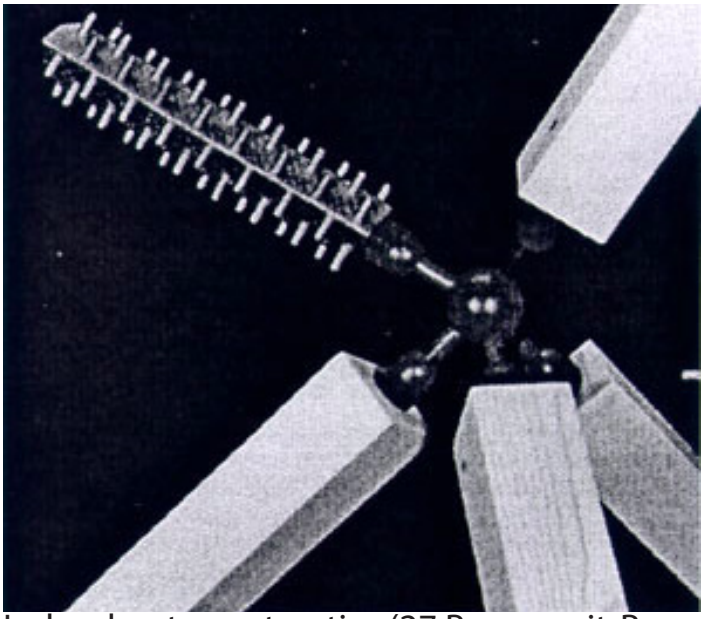
Armature connections(27,Bauen mit Bambus)


Armature connections via adapter(27,Bauen mit Bambus)

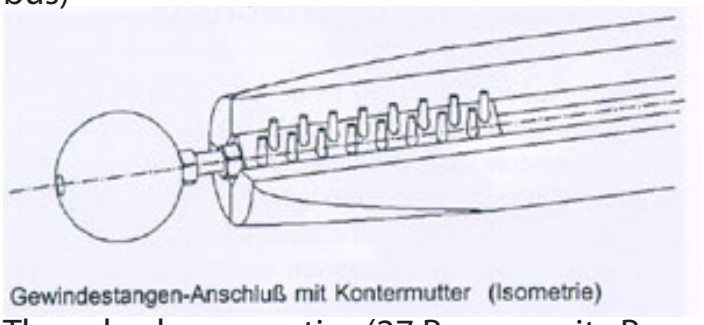
**Transportation armature/ Screw connections**

**Transportation armature with pressed concrete.** The sytemstrength depends on the **concrete/bamboo connection**, on the concretes(or fillingmass) compressive strength, on the thread diameter, the production series (long or short shaft, straight model) aswell as on the tractive direction (axial, slantwise , athwart)and the jointdesign.
System advantages are its price and its deliverability from stock. The installation can start immediately without long prefabrication of the dowels. [27,Bauen mit Bambus]

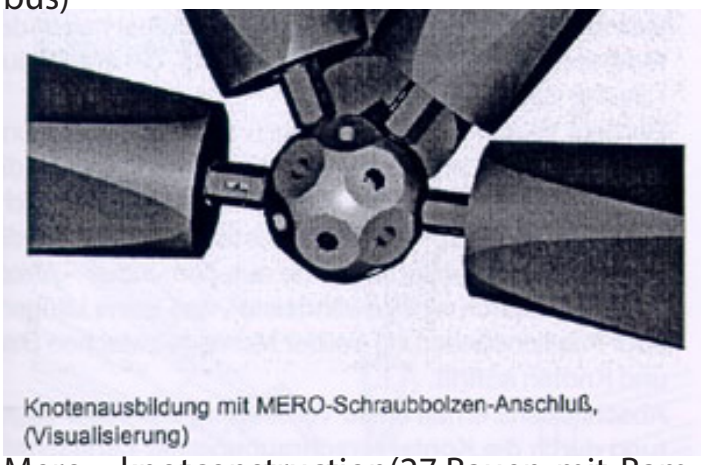
**Reinforcement Continuity Screw Connection System**. The optimal sollution for all static component connections. Static,-constructive and economically. The sleevestick
(with sleeve and connectionflange) - and the connectionstick (with furled metric thread) are sheded with the bamboo and therefore reach an interlocking connection. The connection is carryed out via an adapter with right/left outerthread for the doublesided sleeveconnection.
System advantages are [like transportation armature] its price and its deliverability from stock. The installation can start immediately without long prefabrication of the dowels. [27,Bauen mit Bambus]



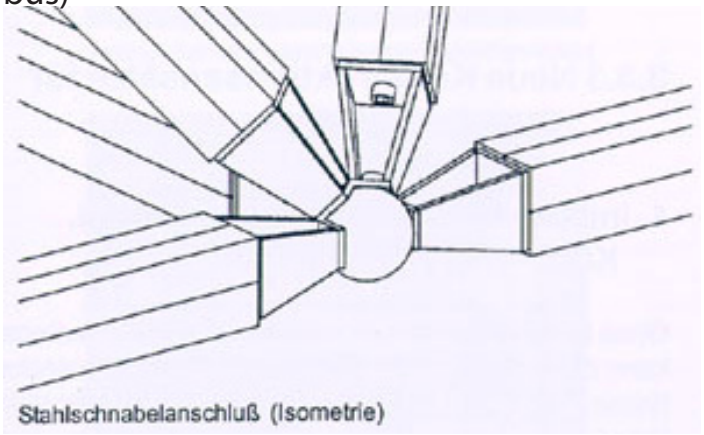
Induo-knot construction(27,Bauen mit Bambus)




Threadrod connection(27,Bauen mit Bambus)




Mero - knotconstruction(27,Bauen mit Bambus)




(27,Bauen mit Bambus)

## Induo-anchor technique

**Induo-anchor**. For big bamboodiameters the Induo-anchor can transfer nearly 100% of the maximum load of the cane cross section.

The Induo-anchor consists of a **cast iron core** with connectionteeth on its sides. It can easily be sheded with a **bamboo cane**. Concrete or artificial resin can be used for that.

Advantage of Induo is that any available knot connection-system can be used with it (e.g.Mero, Pan).

A simple connection can be manufactured with a threaded bar and two counter nuts. Steelballs with threadbores are used as jointpoints.

Disadvantage of Induo-anchor is its high price.

If used with the Induo-anchor the cast iron core is drilled in the perpendicular axis with fitting diameter to connect the screwbolt. [27,Bauen mit Bambus]

## Steel-neb-connection

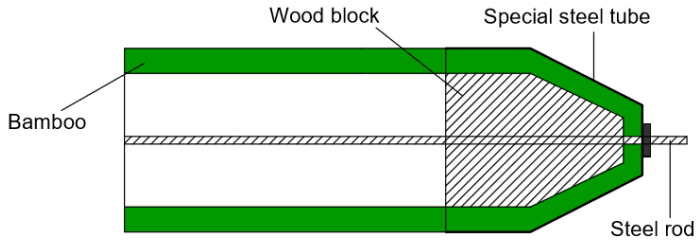
This connection method uses the Induo-anchor in its usual state with bores and threads. The base element of this connection is a conical steelconnecter which is centric screwed from the inside to the Induo-anchor bore on the one side and to the threadbore of the jointelement on the other. [27,Bauen mit Bambus]


Pan-knot(27,Bauen mit Bambus)


Various types(27,Bauen mit Bambus)

## Pan-knot spacetruss

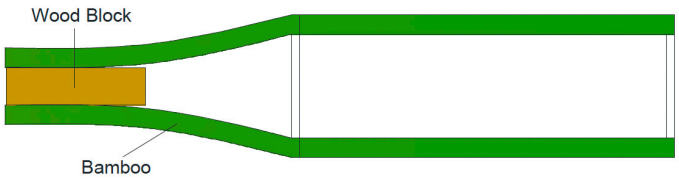
Small bamboo canes(diameter up to 80mm) can transfer ca.50% of the maximal tensile force if threaded bars are glued or sheded into the caneends. Forcompressive forces the maximum force is where the cane breaks if connected with a headplate. If overhead working is necessary tests by an officially recognized material testing institution and special permission of the building departement are required. (germany)
Pan-spacetruss consist only of two elements -**the Pan-ballknot and the cane with sheded threadrod**. That means more economic statics,drawings and production. Furthermore they can be dismantled and reused. [27,Bauen mit Bambus]




(28,Hong, C)

## Bacthiar jointing method

The joint is composed of steel tubes, wood blocks and steel rods. Its axial bearing capacity depends on the shear strength of the adhesive layer between the wood blocks and the bamboo enclosed by the tube. The bamboo components are connected with each other by the steel bar at the end, so that the complex assembly can be easily realized. [28,Hong, C]




(28,Hong, C)

## Ohta jointing method

The production of joint firstly removes some parts of the end of the bamboo and the inner skin of bamboo, then uses adhesive to bond the bamboo with the wood block, and finally presses into a regular whole under heat treatment. [28,Hong, C]

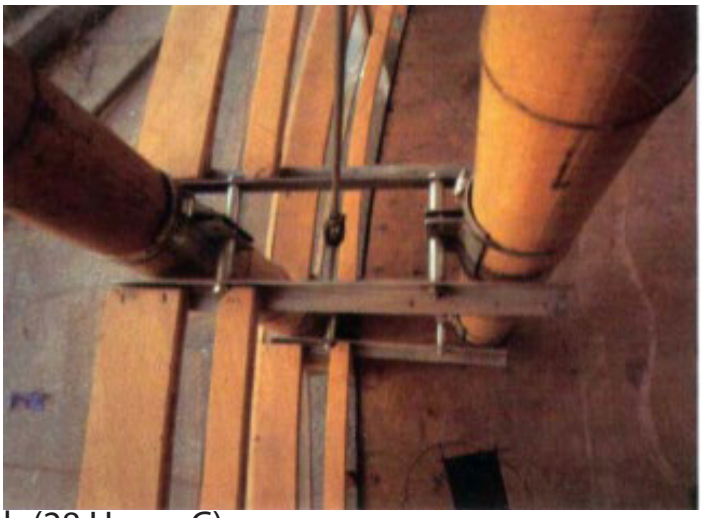
a (28,Hong, C)

**Steel-bamboo connection**

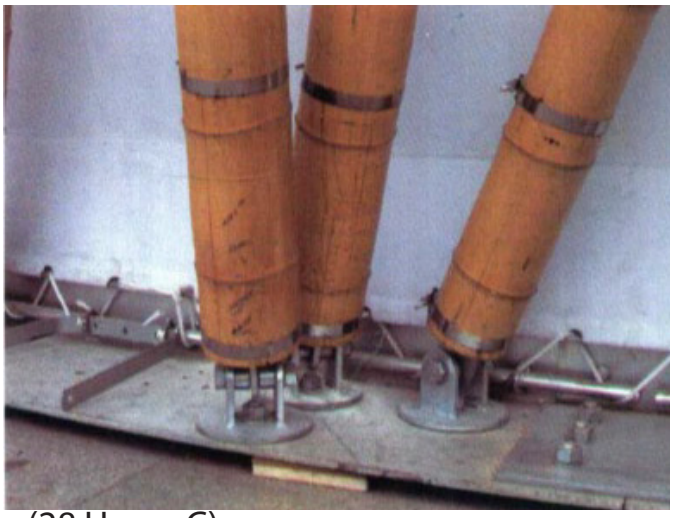
**a-Connection between raw bamboo and concrete.**

**b-Connection between main structure and enclosure structure.**

**c-Connection between raw bamboo.**
[28,Hong, C]

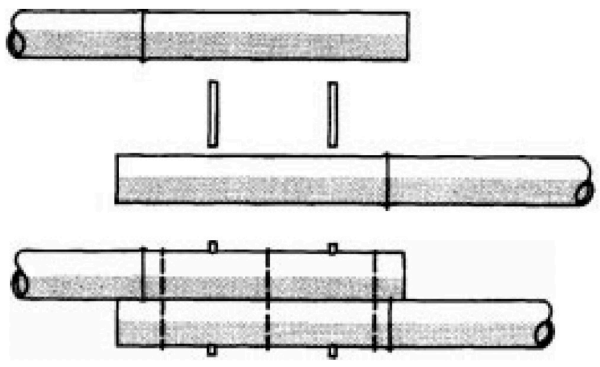


b (28,Hong, C)



c (28,Hong, C)

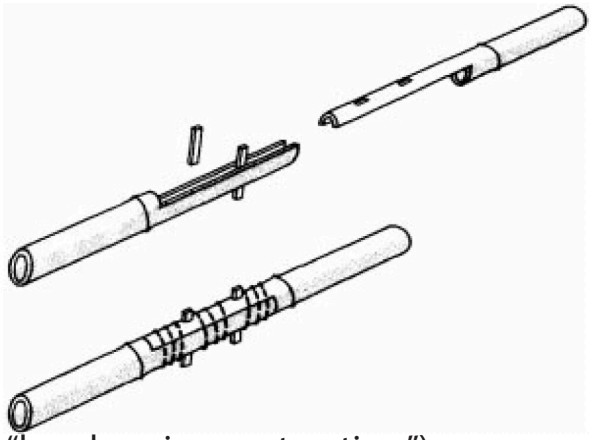
## 04-Spliced joints



(29, "bamboo-in-construction.")

**Full lapped splice joint**

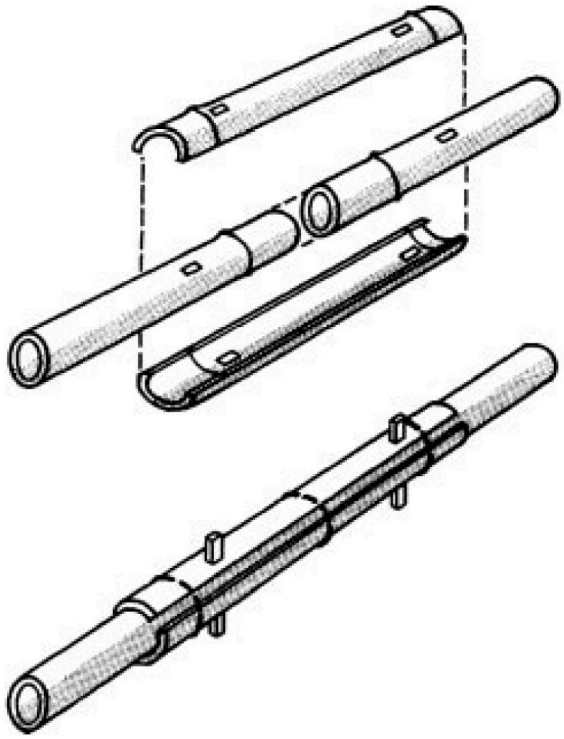
Full section culms are overlapped by at least one internode and tied together in two or three places. For greater strength, bamboo or hardwood dowels can also be used. One disadvantage of this joint is that it quite bulky.[29, "bamboo-in-construction."]



(29, "bamboo-in-construction.")

**Half-lapped splice joint**

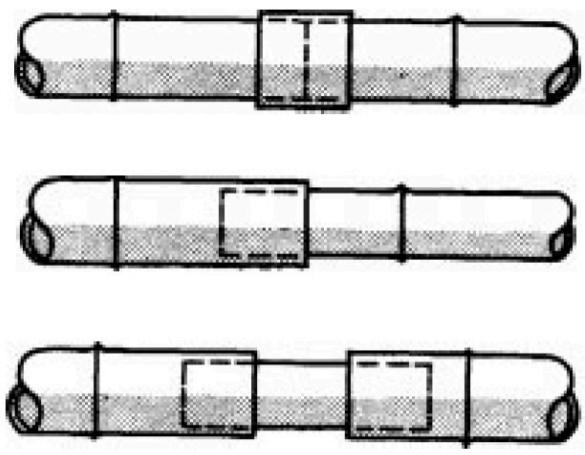
Culms to be joined should be of similar diameter and cut longitudinally to half depth over at least one internode length. The components are fixed as for the full lap joint.[29, "bamboo-in-construction."]



(29, "bamboo-in-construction.")

**Butt joint with side plates**

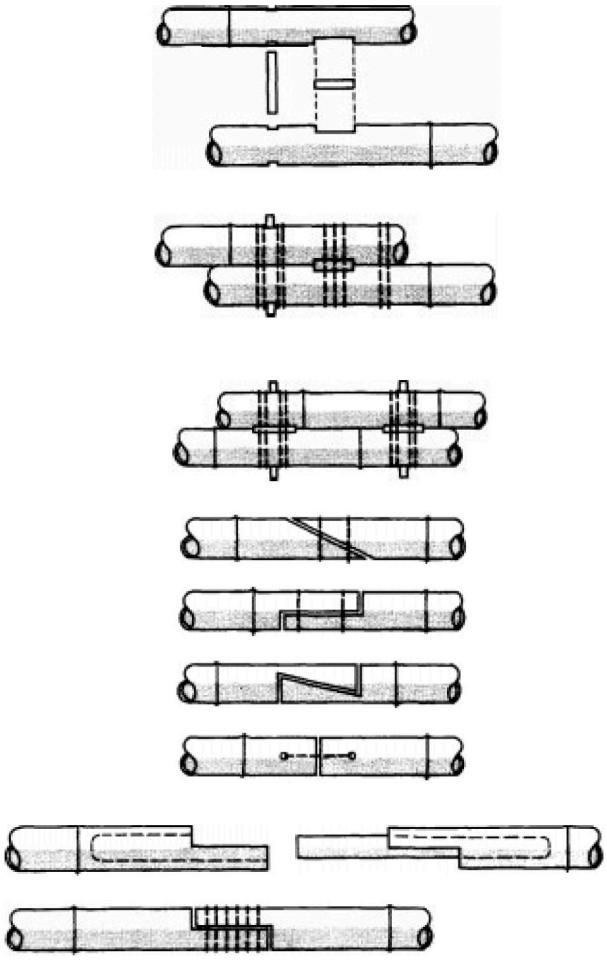
Butt joint with side plates: Culms of similar diameter are laid end to end. Side plates, made from quarter-round culms of slightly larger diameter and two or more internodes long, are fixed over the joint by tying and,usually,dowelling.[29, "bamboo-in-construction."]



(29, "bamboo-in-construction.")

**Sleeves and inserts**

Sleeves and inserts: short lengths of bamboo of appropriate diameter are used either externally or internally to join two culms together.[29, "bamboo-in-construction."]

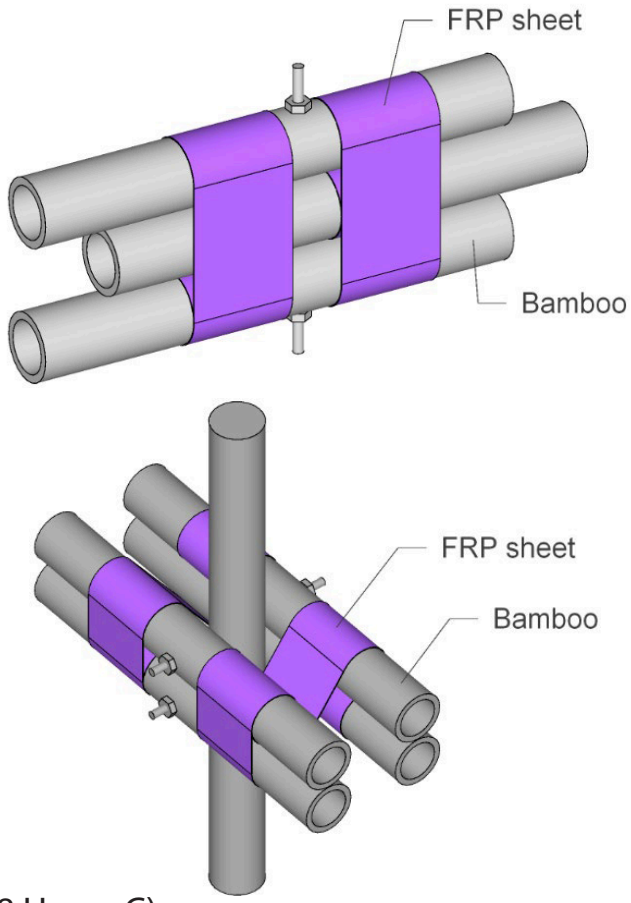


(29, "bamboo-in-construction.")

**Variations on splice joints**

Variations of the basic splice joints.[29, "bamboo-in-construction."]

## 05-Other specific joints




(28,Hong, C)

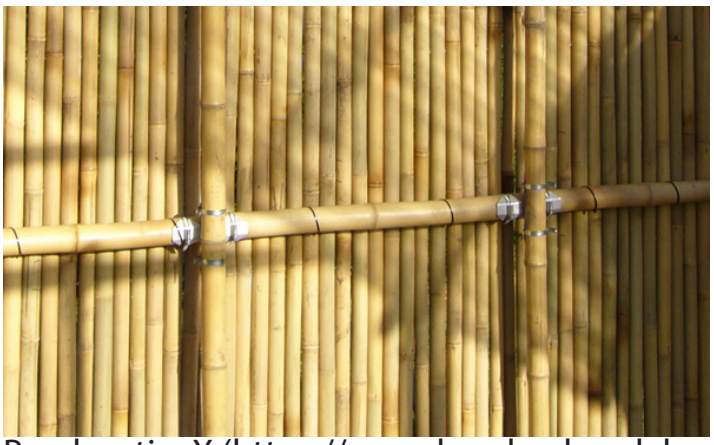
**Awaludin jointing method**

Awaludin et al. compared the mechanical properties of joints strengthened with natural fiber (Indonesian name, "ijuk") and fiber reinforced plastic. It was found that the slip modulus and bearing capacity of joints strengthened with FRP sheet had been greatly improved. The wrapping effect caused by FRP sheet effectively postpones the splitting of bamboo, while the effect caused by natural fiber is not significant. [28,Hong, C]

(https://www.bambushandel-conbam.de/)

## The BAMBOOTIX system

A more intelligent construction is the "BAM·BOOTIX" 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. [16,Gernot Minke]



Bambootix- X (https://www.bambushandel-conbam.de/)

Bambootix- T (https://www.bambushandel-conbam.de/)

Bambootix- I (https://www.bambushandel-conbam.de/)

(28,Hong, C)

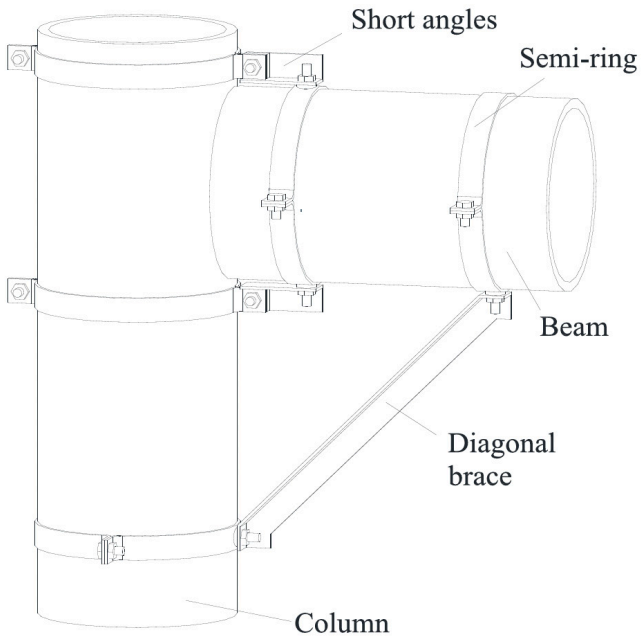
## Wang Shu jointing method

Chinese architect Wang Shu designed a bolted joint. He added U-shaped iron parts to the inner wall of raw bamboo. There are two metal sheets on the iron part, which is fixed by bolts to the inner wall of raw bamboo. The metal sheets contained in the joint alleviate the extrusion effect of nuts on the bamboo rod to some extent, but the raw bamboo is easy to rotate only under the fixing of the bolt, which may lead to instability. [28,Hong, C]

(28,Hong, C)

## Multi-layer metal cage

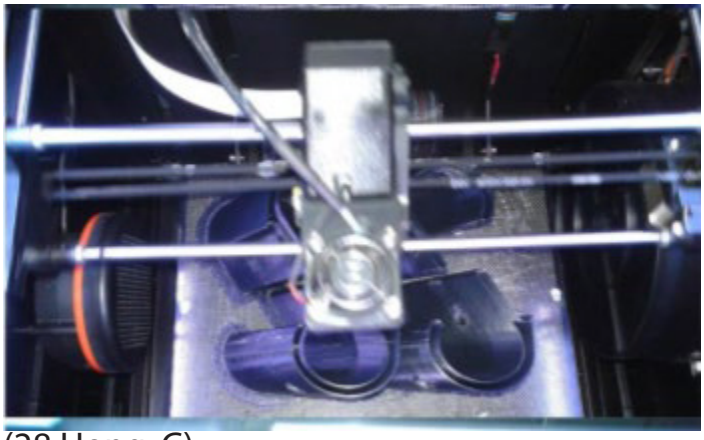
Studio Cardenas team [44] designed a multi-layer metal cage for connecting beams and columns when building the bamboo residence This joint has less damage to the material itself and avoids drilling holes on the bamboo as much as possible. In addition, there is an elastic cushion on the metal plate, which can not only alleviate the extrusion of steel members on the bamboo, but also increase friction to reduce the slip and rotation of the bamboo. [28,Hong, C]



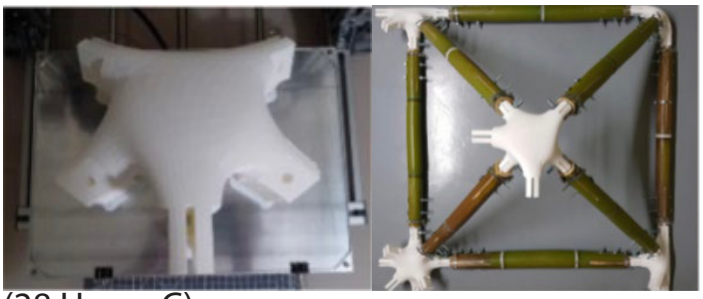

(28,Hong, C)

## Moran jointing method

Morán et al. proposed three kinds of bamboo joints which can transmit moment. The main body of the three joints consists of five pairs of light-weight steel clamps tightened around the culms, which are connected with steel angles and platens in different configurations. Through static monotonic and cyclic tests, it is found that the confinement of steel clamps on the bamboo members effectively avoids premature cracking at the joints. [28,Hong, C]



(28,Hong, C)



(28,Hong, C)

**Customised joint system fabricated by 3D printing**

Matson et al. created a customised joint system fabricated by three-dimensional printing. A parametric software is used to quickly adapts to the irregularity of the bamboo. The joints suitable for connecting bamboo of different dimension are fabricated separately based on the program, thus the secure connection of each unique joint at each intersection is guaranteed and the construction waste can be reduced. Di Paola et al. proposed the use of parametric modelling techniques as well. The joint allows to determine and control parametrically the adaptability to any spatial grid configuration of culms with heterogeneous dimensions. [28,Hong, C]

## 04-Combinations

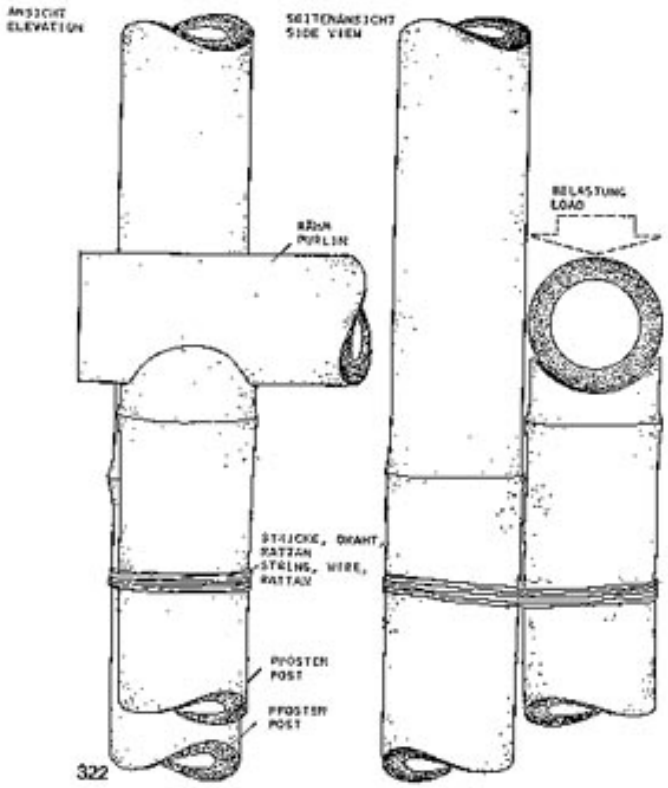
Doublejamb as support (27,Bauen mit Bambus)

**Double jamb connection**

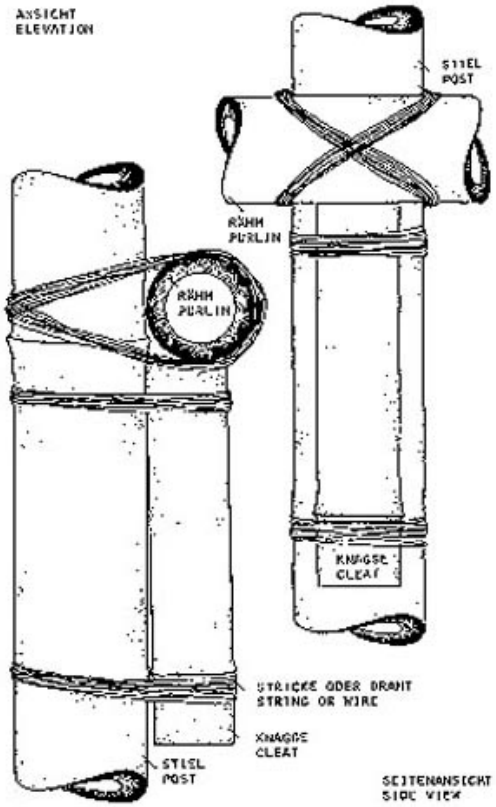
**Doublejambs**,tied knots, transitional cane,purlin with cleat. The second pole is replaced by a cleat. Advantage is that the wall of the cane is not weakened by bores. There is no reinforcement of the polebase. The roof and floor-loads are absorbed by different poles. Hereby damaged canes can be exchanged more easily. The rot endangered polezone is reinforced. [27,Bauen mit Bambus]

**Doublejamb with support**

Tied knots,transitional cane, purlin with cleat. The second pole is replaced by a cleat. [27,Bauen mit Bambus]



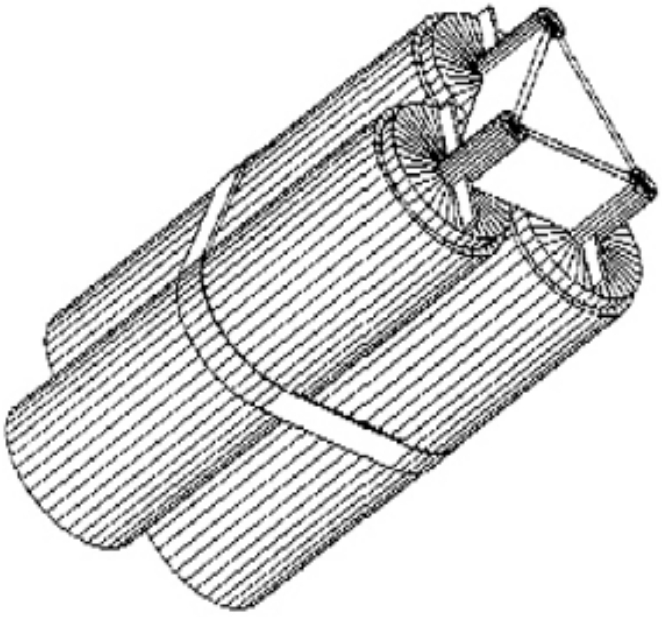

Doublejamb with support (27,Bauen mit Bambus)



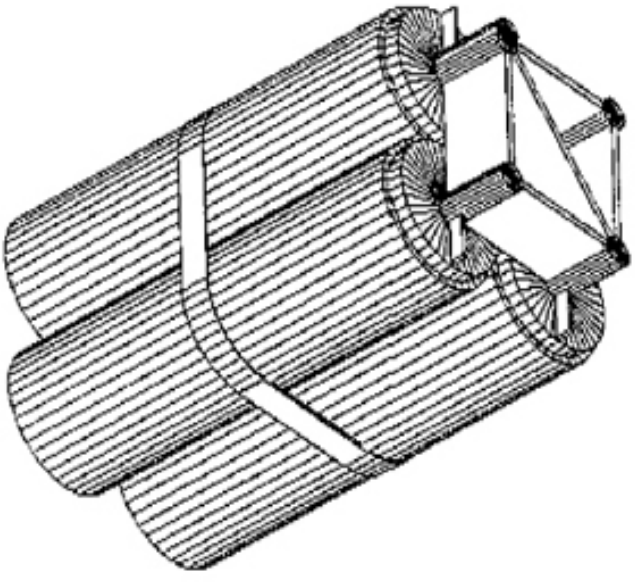

Doublejamb with support (27,Bauen mit Bambus)

**Cane bundles**

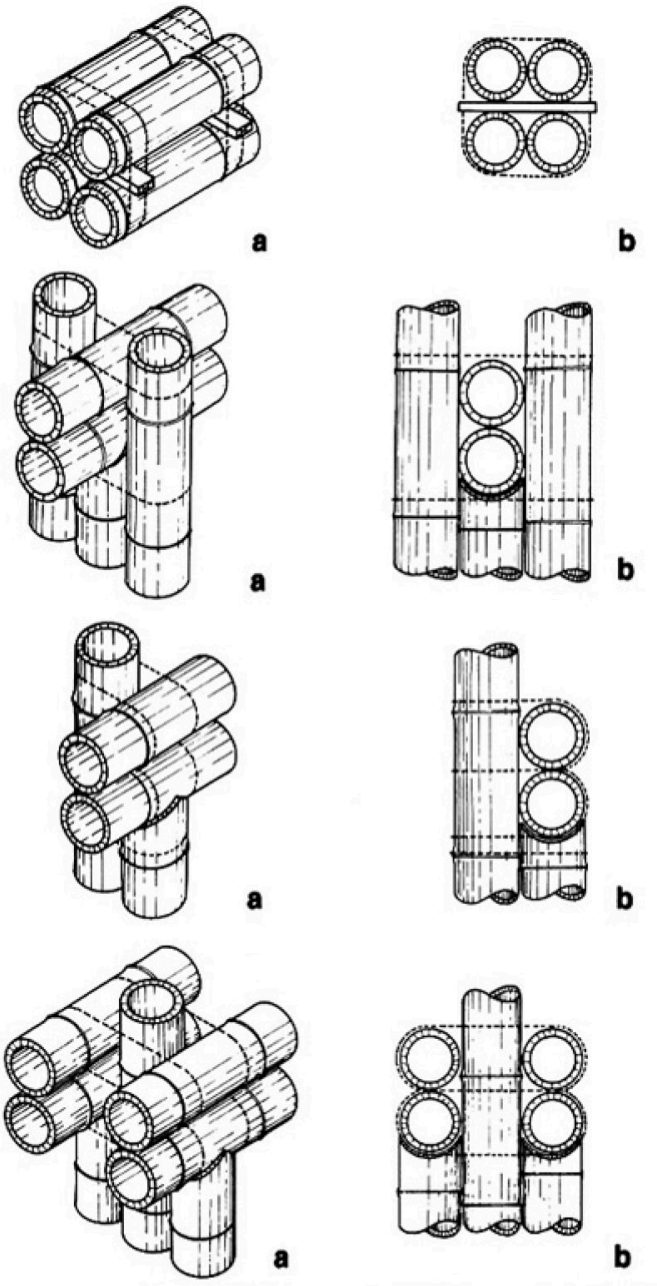
Cane bundles must be used for bigger loads.When using them for construction a possible connection can be achieved by projeting steel tips out of a wood cylinder (see interlocking connection), so that these tips can be welded to a plate or any other cetral component, to fix the relative position of the canes.
Probably it will be necessary to keep the canes together at midspan. A steel band can be used for that. [27,Bauen mit Bambus]



Structural element composed of three canes (27,Bauen mit Bambus)



Structural element composed of four canes (27,Bauen mit Bambus)




(30,Anastasia Maurina)

**Double post**

**1. Beams formed by 4 or 6 members.**

The top row is separated from the bottom with bamboo or wood slats so that the upper bamboos do not slide over the lower.

**2. Central double rafter.**

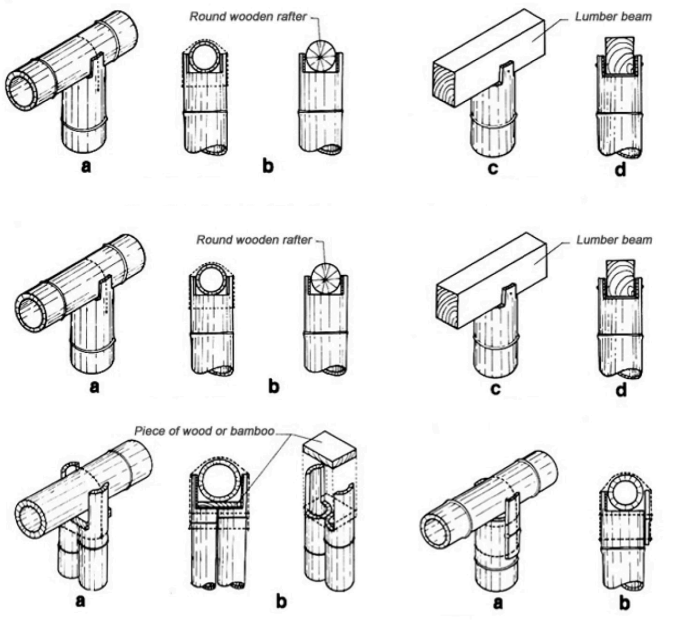
It has a wide range of applications in the construction of bridges and structures for rural facilities.

**3. Lateral double rafter.**

Each of the rafters is secured independently at the side support and each other. It is often used in the construction of bridges and structures for rural facilities.

**4. Lateral double rafters.**

used as a central support for bridge structures or sheds. [30,Anastasia Maurina]



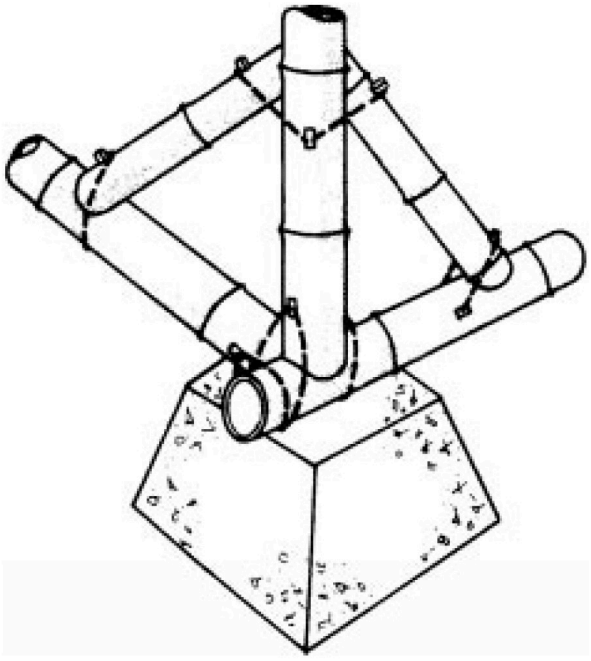

(30,Anastasia Maurina)

**Positive fitting connection**

These are the most common cuts to use when making bamboo joints:one ear / two ear / beveled / flute mouth / fish mouth. [30,Anastasia Maurina]

## 4.3 Construction methods

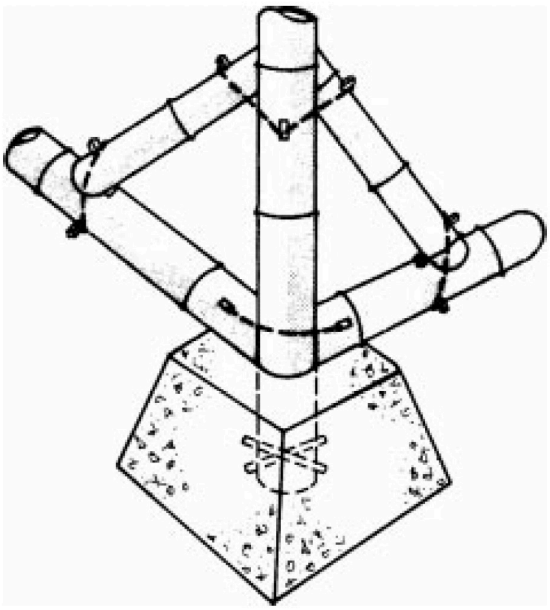
## 01-Foundations



Preformed concrete footings (29, "bamboo-in-construction.")

**Bamboo on rock or preformed concrete footings**

Ideally, where bamboo is being used for bearings it should be placed out of ground contact on footings of either rock or preformed concrete.[29,"bamboo-in-construction."]

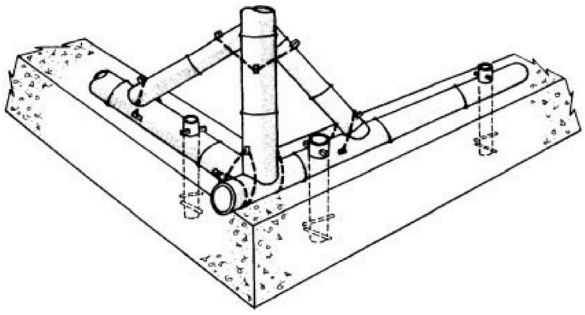


Single post footing (29, "bamboo-in-construction.")

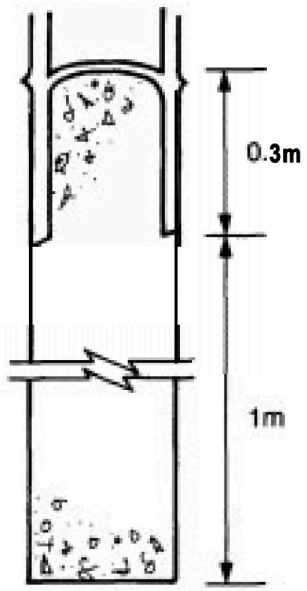
**Bamboo incorporated into concrete footings**

The approach is to incorporate the bamboo directly into the concrete footing. This can take the form of single posts or strip footings.[29,"bamboo-in-construction."]

(29



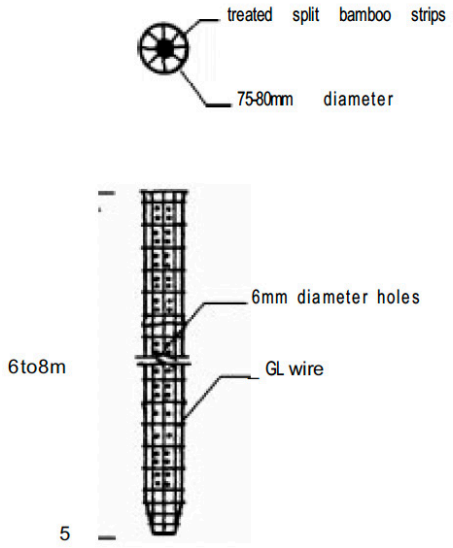
Strip footing (29, "bamboo-in-construction.")




(29, "bamboo-in-construction.")

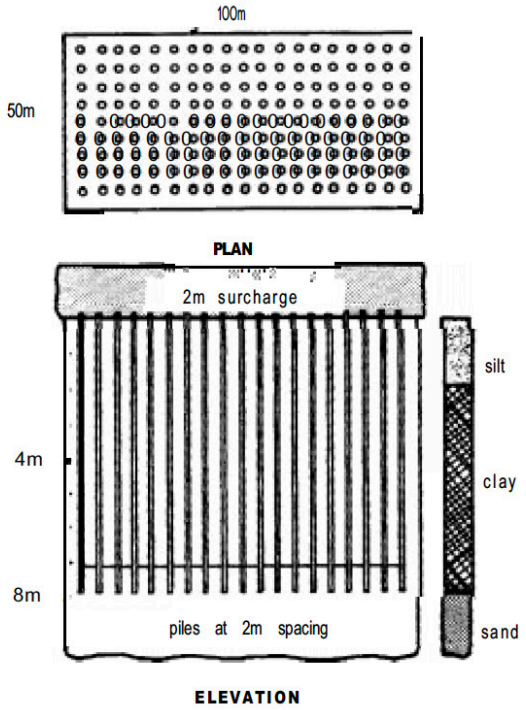
## Composite bamboo/concrete columns

An innovative development involves the casting of a concrete extension to a bamboo post using a plastic tube of the same diameter (Janssen, 1995). The result is a bamboo post with an integral, durable foundation [29,"bamboo-in-construction."]



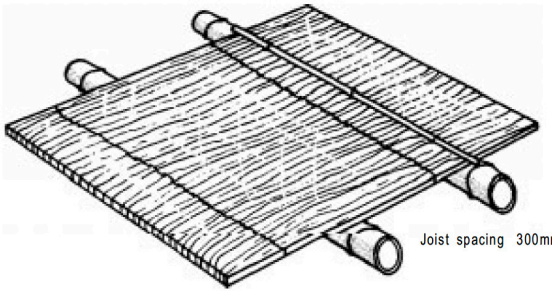

## Bamboo piles

Bamboo piles have been used successfully to stabilise soft soils and reduce building settlement. In the example cited (Stulz, 1983), treated split bamboo piles 8m long and 80 to 90mm in diameter were filled with coconut coir strands wrapped with jute. The sections were then tied with wire. After installation of the piles at 2m centres by drop hammer, the area was covered with a 2.5m surcharge of sandy material [29,"bamboo-in-construction."]

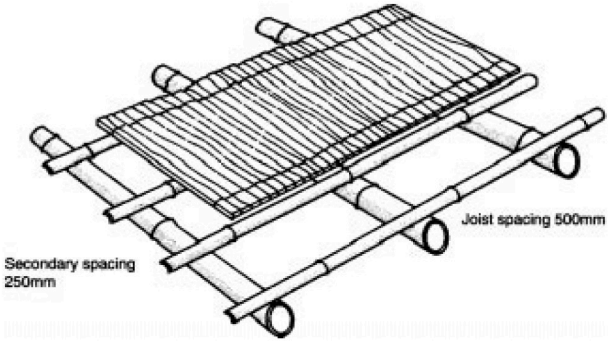



(29, "bamboo-in-construction.")

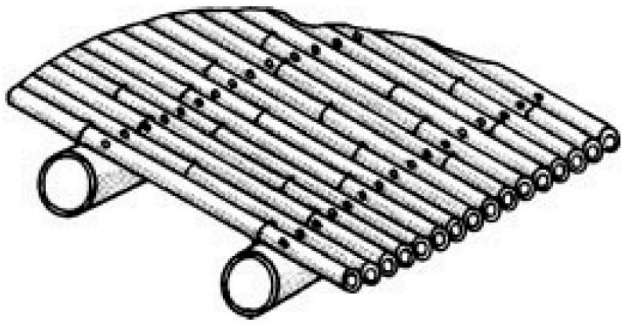
# 02-Floors structure



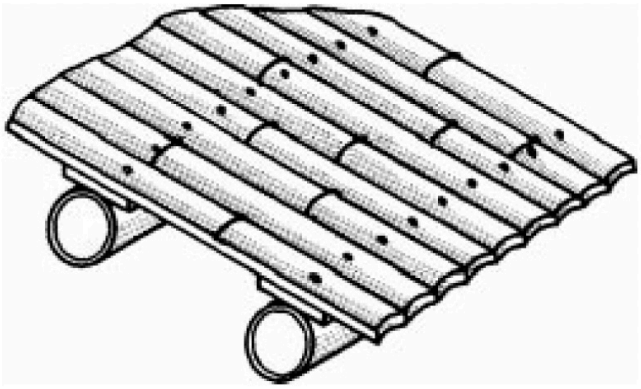

Joist arrangement - primaries only(29, "bamboo-in-construction.")




Joist arrangement - primaries and secondaries (29, "bamboo-in-construction.")



Bamboo cane floor decking (29, "bamboo-in-construction.")



Split bamboo floor decking(29, "bamboo-in-construction.")

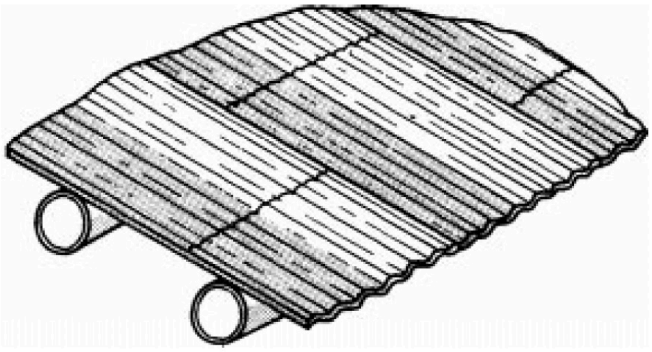
**Floor structure**

Bamboo joists then span in the shortest direction across the perimeter beams. The joists are often laid on the beams without fixing, but some form of mechanical connection is recommended. Depending on the form of floor decking, secondary joists, often taking the form of split culms, may be required. Joist diameters are in the order of 70mm. Joist centres are typically 300 to 400mm, or up to 500mm if secondary joists are used [29,"bamboo-in-construction."]

**Floor decking**

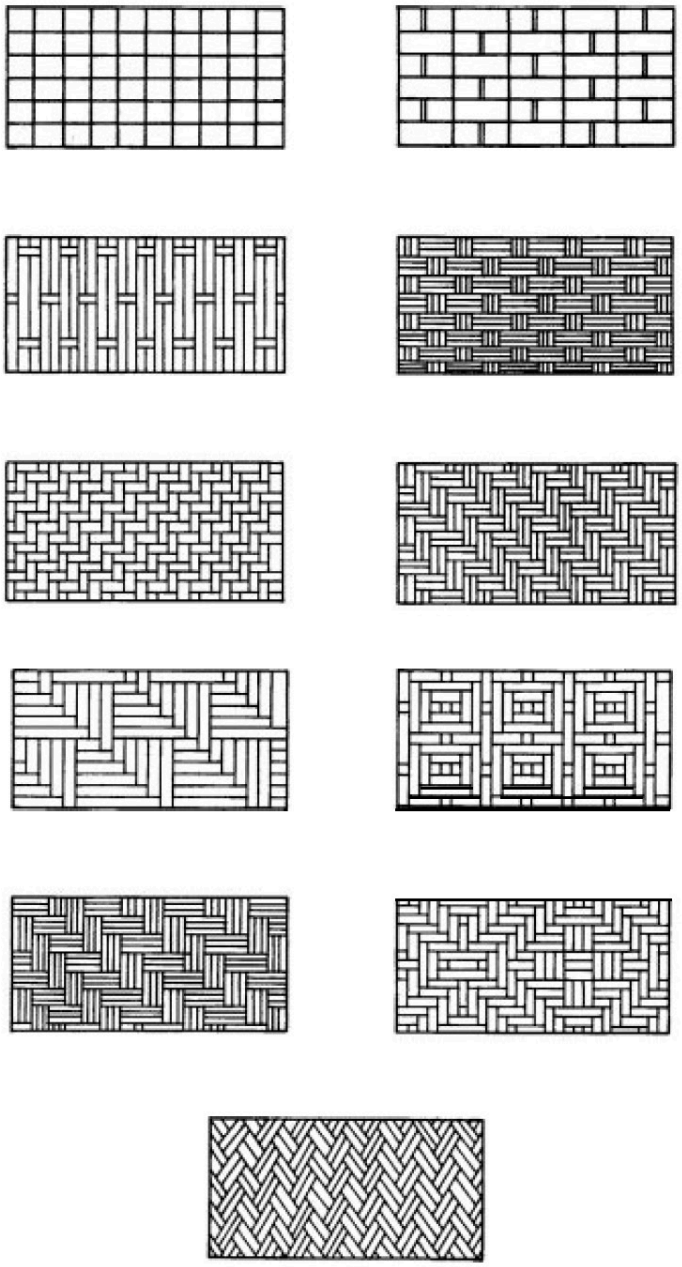
**Small bamboo culms:** small diameter culms are tied or nailed directly to the joists .[29,"bamboo-in-construction."]

**Split bamboo:** bamboo culms are split along their length into strips several centimetres wide. They can be fixed directly to the joists in the case of tying or nailing, or a timber batten can be fixed to the joist beforehand to facilitate nailing. [29,"bamboo-in-construction."]



Flattened bamboo floor decking (29, "bamboo-in-construction.")

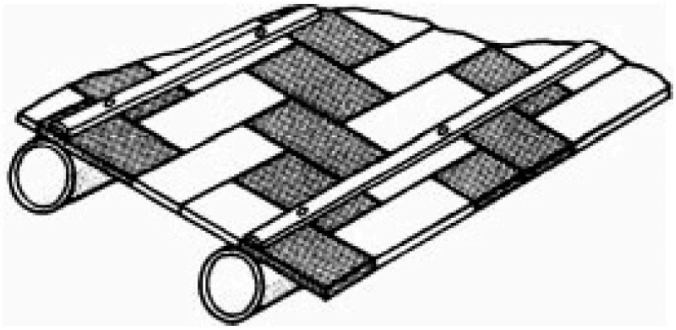
**Flattened bamboo (bamboo boards):** these are formed by splitting green bamboo culms, removing the diaphragms then unrolling and flattening them. The resulting board is laid across the joists and fixed by nailing or tying. [29,"bamboo-in-construction."]



Examples of woven bamboo mats (29, "bamboo-in-construction.")

**Bamboo mats**

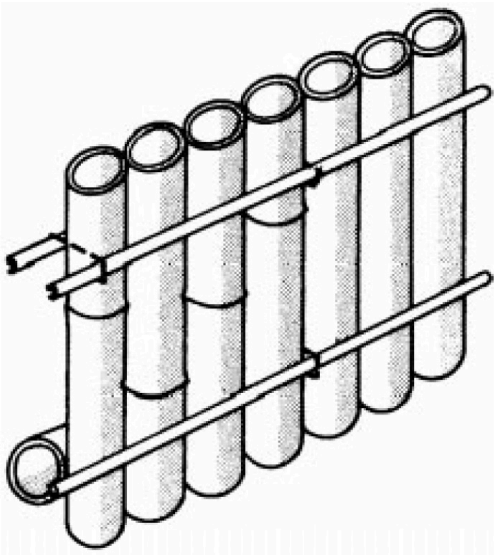
These are formed by weaving thin strips of bamboo. Strips vary in size from 20 x 2mm to 2 x1 mm, depending on the intricacy of the pattern. [29,"bamboo-in-construction."]



Woven bamboo mat floor decking (29, "bamboo-in-construction.")

Mats should not be fixed by direct nailing, but are held in place by bamboo strips or timber battens tied or nailed over the top. This is one of the easiest types of traditional floor to keep clean. [29,"bamboo-in-construction."]

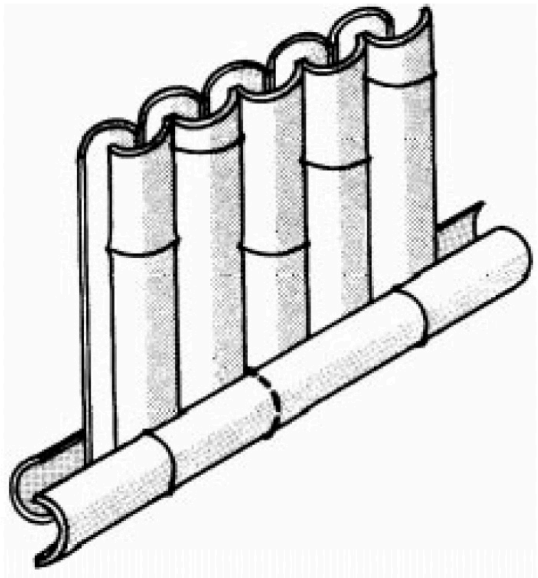
## 03-walls



Wall of whole bamboo culms (29, "bamboo-in-construction.")

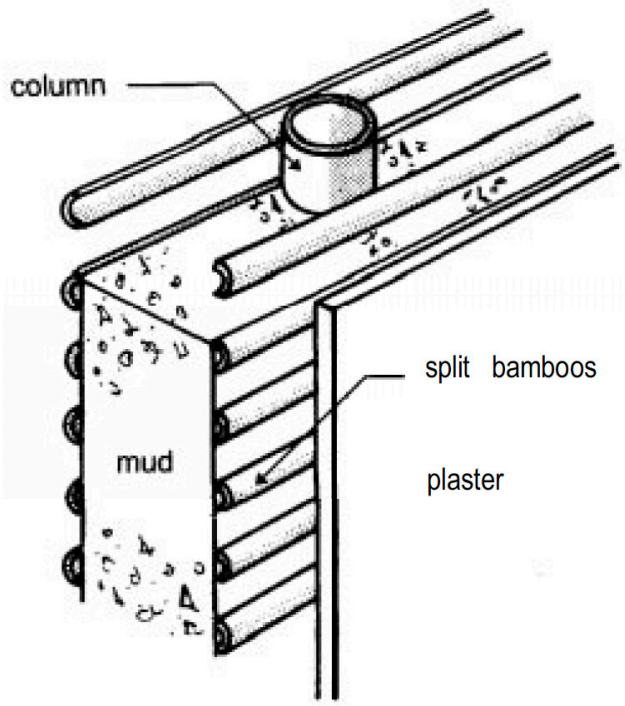
**Whole or halved bamboo culms**

The preferred orientation is vertical as this increases the shear resistance of the wall and is also better for drying after rain. Vertical members can be driven directly into the ground or fixed back to beams by tying with or without facing battens.[29,"bamboo-in-construction."]



Wall of vertical halved culms (29, "bamboo-in-construction.")

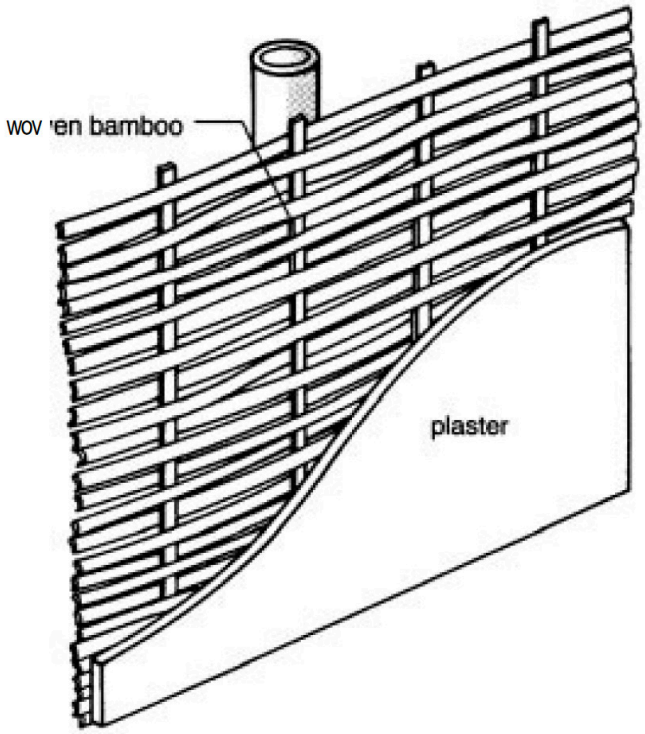
**Halved culms** can be fixed in the same way, either as a single or double ply construction, or anchored between horizontal halved culms (figure 18). Woven bamboo mats can be attached to one or both faces using tied or nailed bamboo battens. [29,"bamboo-in-construction."]




Bajareque wall construction (29, "bamboo-in-construction.")

## Bajareque

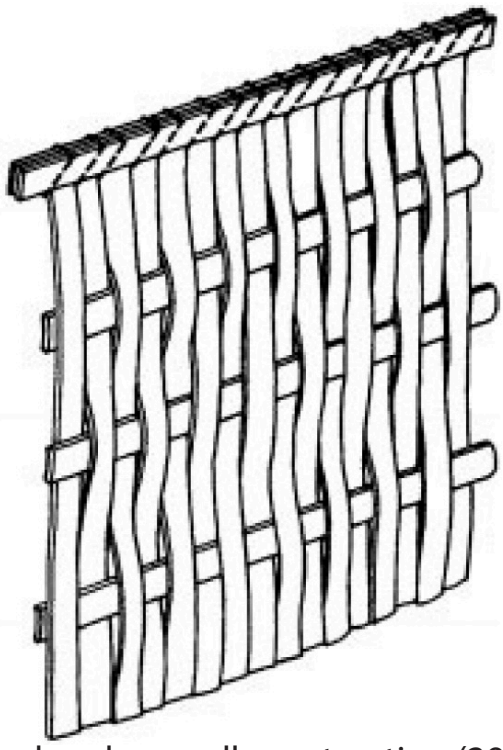
This is a type of construction commonly employed in Latin America. It consists of horizontal bamboo strips tied or nailed to both sides of the posts. The cavity is then filled with mud or mud and stones, producing a relatively massive form of construction [29,"bamboo-in-construction."]




Quincha wall construction (29, "bamboo-in-construction.")

## Wattle (wattle and daub, lath and plaster, quincha)

Common in parts of India, Peru and Chile, this com prises coarsely woven panels of bamboo strips (vertical weft and horizontal warp), plastered on both sides. [29,"bamboo-in-construction."]

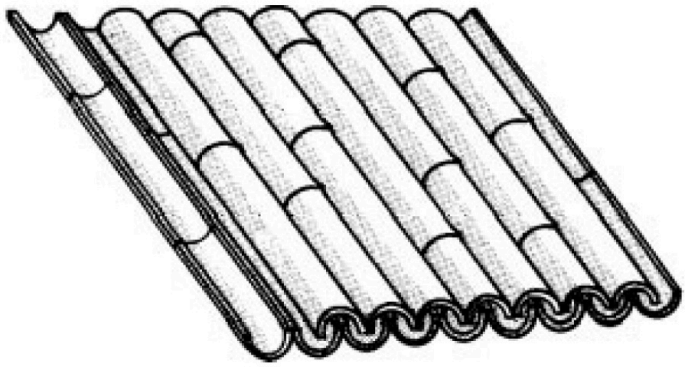


Woven bamboo wall construction (29, "bamboo-in-construction.")

**Woven bamboo**

Coarsely woven panels similar to those for wattle but with closer wefts can be used with or without plaster. [29,"bamboo-in-construction."]

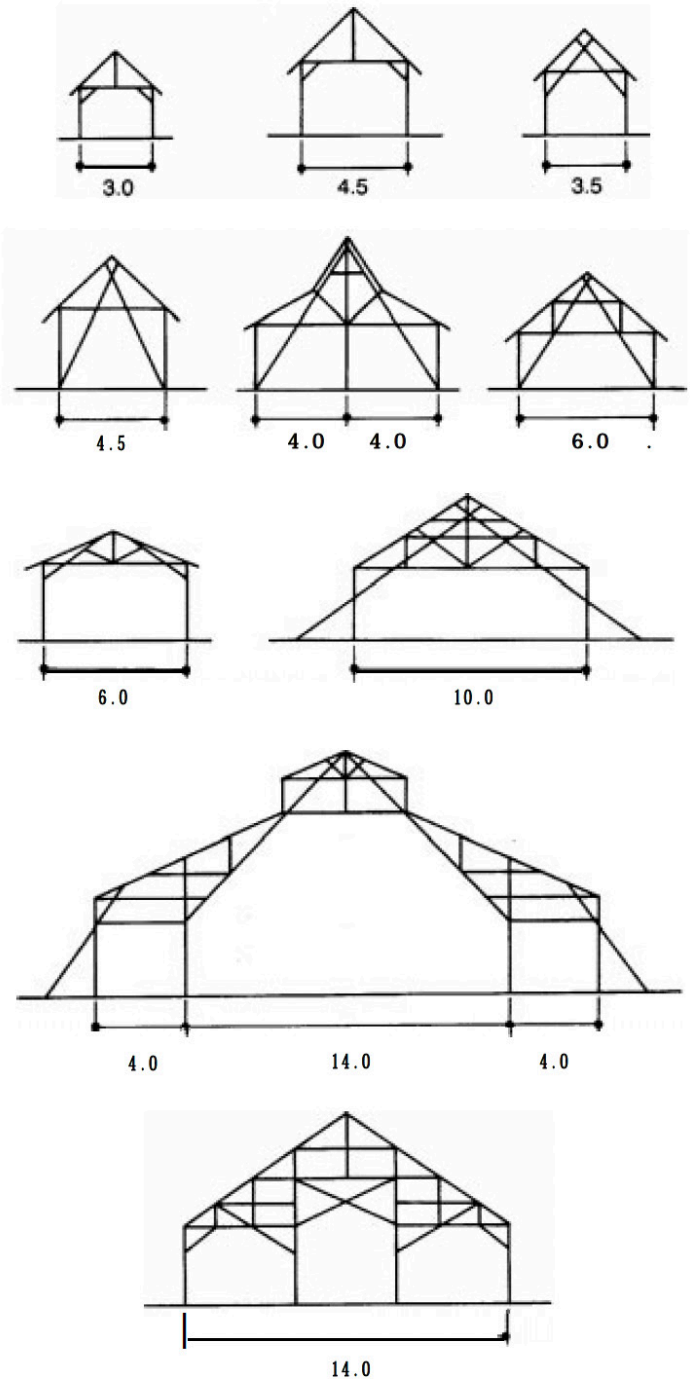
## 04-roofs



Roof of halved bamboo culms (29, "bamboo-in-construction.")

**Traditional roof construction**

The simplest form of roof comprises a bamboo ridge purlin and eaves beams,supported on the perimeter posts. Halved culms are then laid convex side down, edge to edge, spanning from the ridge to the eaves. A second layer, convex side up, is then laid to cover the joints. The maximum overall span using this method is about 3 metres. [29,"bamboo-in-construction."]

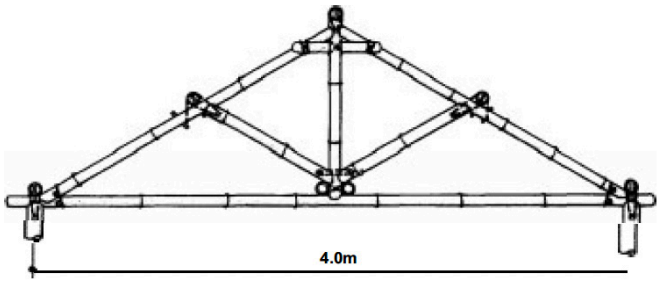



Possible roof framing configurations using traditional forms of construction - dimensions in metres (29, "bamboo-in-construction.")

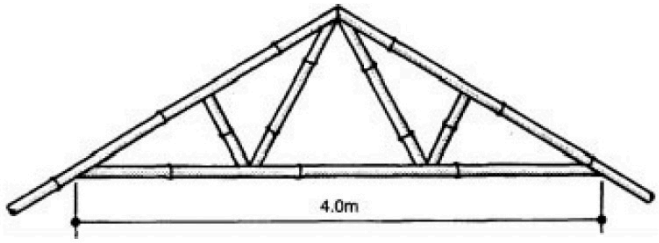
**Possible roof framing configurations**

A variation on this is the use of whole culms, suitably spaced to accept battens for tiles or thatch. To extend the span, a central post can be used. Beyond this, the options are almost infinite.

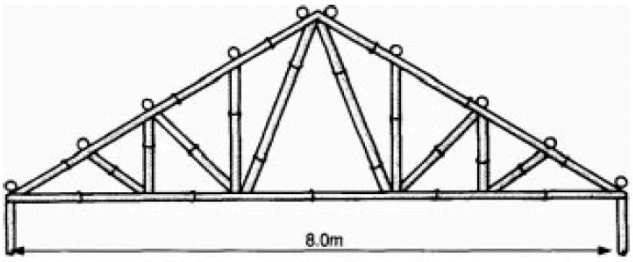
Trusses: Trusses offer a number of advantages over traditional forms of construction, including more economic and efficient use of materials, the ability to span larger distances, the use of shorter components(counteracting effects of bow, crook and taper) and the use of prefabrication. [29,"bamboo-in-construction."]



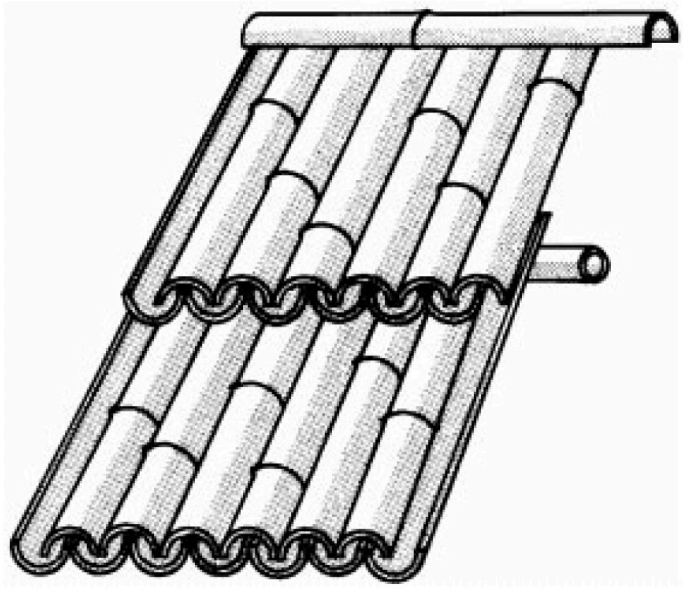

King-post truss (29, "bamboo-in-construction.")




Fink truss (29, "bamboo-in-construction.")




Janssen (1995) truss configuration (joints omitted for clarity) (29, "bamboo-in-construction.")

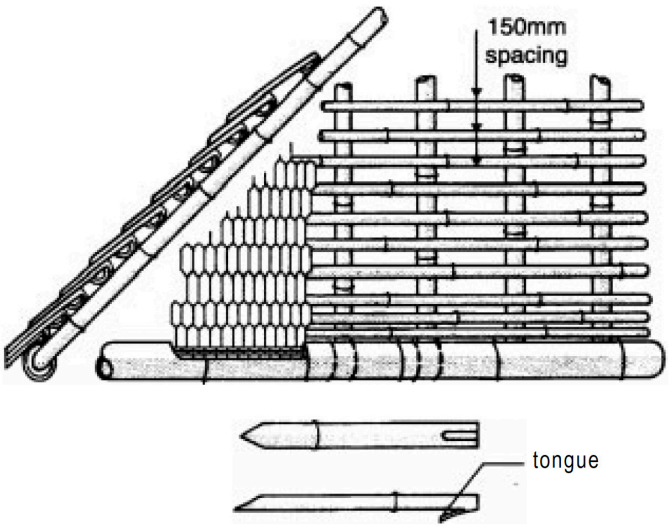


Bamboo tiles (29, "bamboo-in-construction.")

As with cut roofs, truss configurations are many and various. The King-post and Fink are the simplest,readily spanning 4m using traditional jointing. Culm diameters typically range from 40-100mm. Janssen (1995) has achieved an 8m span using improved jointing. [29,"bamboo-in-construction."]

**Bamboo tiles**

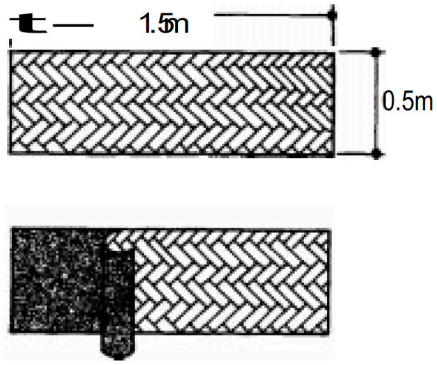
These can take the form of halved,internodal culm sections, fixed to battens and overlapped in a similar manner to the full length halved culms. Roofs covered in this manner are susceptible to leakage [29,"bamboo-in-construction."]




Bamboo shingles (29, "bamboo-in-construction.")

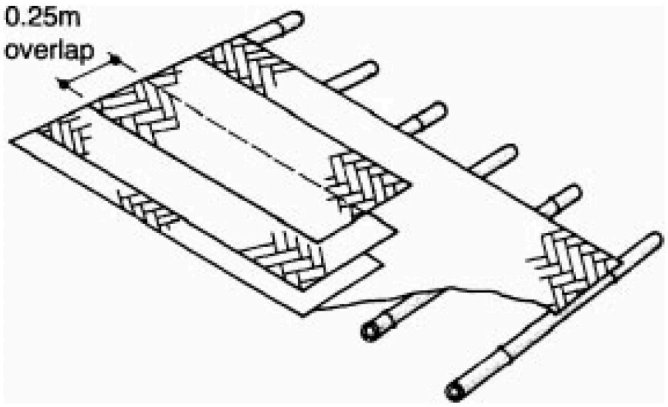
## Bamboo shingles

Shingles, measuring 30-40mm wide x internodal length (400-600mm) are cut from green culms, 70mm or more in diameter and then air dried.The shingles are hooked onto bamboo battens(maximum spacing 150mm - Narayanamurty et al. 1972) by means of a tongue cut into the underside. Three laps are required to make a roof watertight, requiring some 200 shingles per square metre. Nailing may need to be considered if high winds are likely. [29,"bamboo-in-construction."]



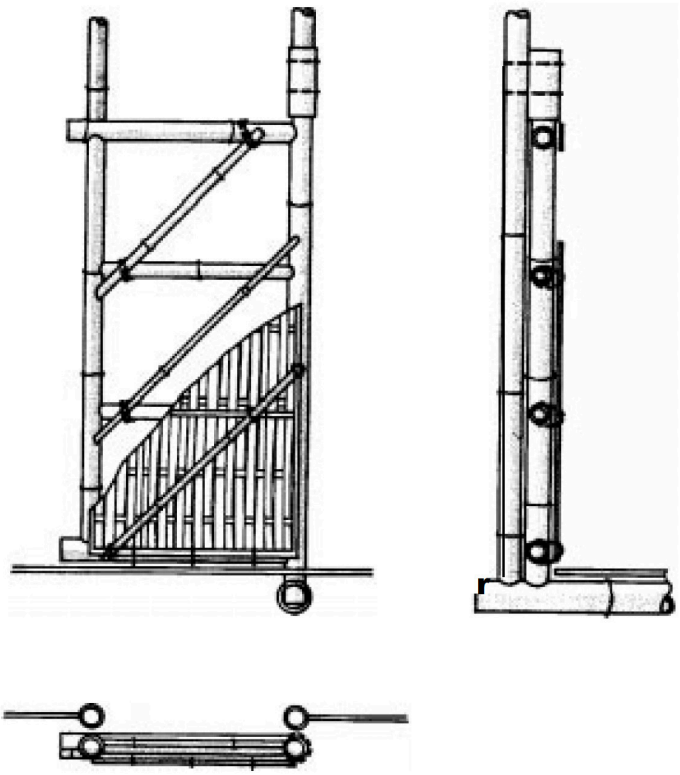

## Corrugated bamboo roofing sheets

PF resin is applied to a bamboo mats to form a five layer set which is then hot pressed between corrugated platens. UF resin bonded sheets overlaid with PF resin impregnated paper have also been produced. These products are strong and lightweight with good insulation properties. [29,"bamboo-in-construction."]



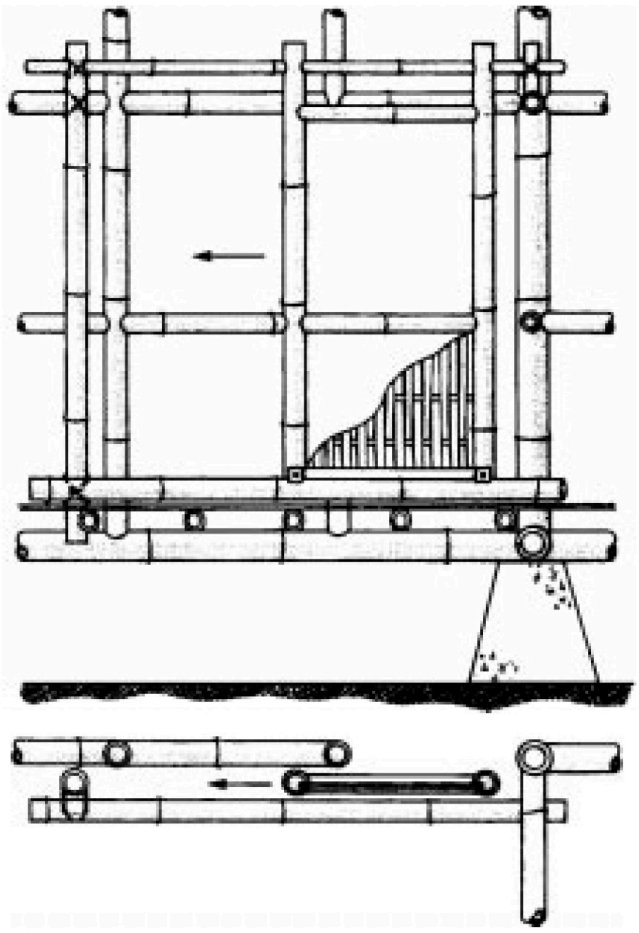

Bituminised bamboo mats (29, "bamboo-in-construction.")

## 05-doors and windows

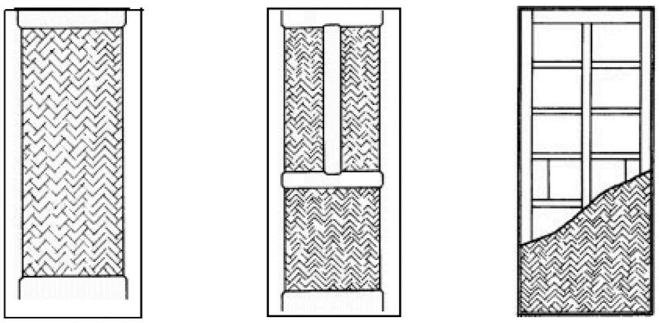


In traditional types of bamboo building, doors and windows are usually very simple in form and operation.Bamboo doors can be side hinged or sliding,comprising a bamboo frame with an infill of woven bamboo or small diameter culms.[29,"bamboo-in-construction."]

Arrangement of hinged door (29, "bamboo-in-construction.")

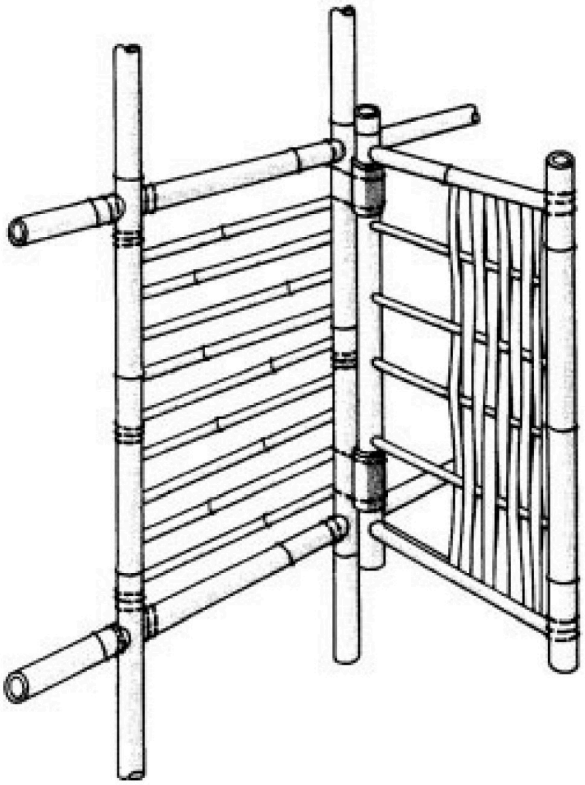


Arrangement of sliding door(29, "bamboo-in-construction.")



Bamboo mat board panelled and hollow core doors (29, "bamboo-in-construction.")

In higher grade buildings, wooden doors are common.Doors and shutters comprising bamboo mat board as panelling, or as flush skins for hollow core doors offer another solution (Ganapathy and Zoolagud,1993). [29,"bamboo-in-construction."]

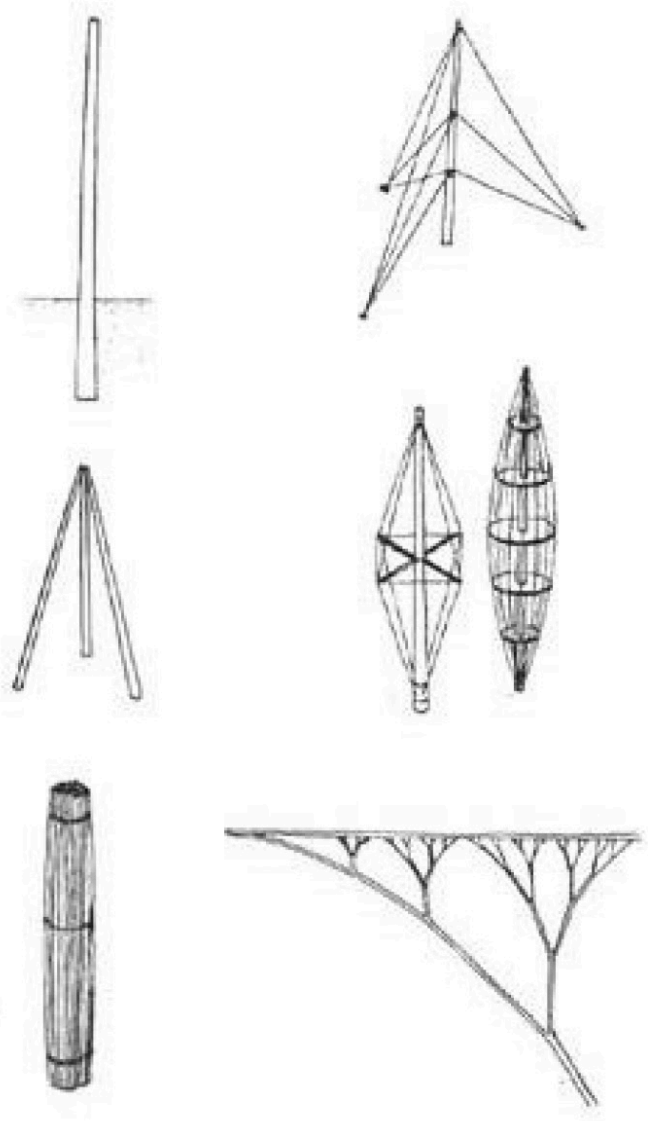


Hinged sash window (29, "bamboo-in-construction.")

Bamboo windows are generally left unglazed and can have bamboo bars, or a sash with woven bamboo infill.The sash can be side hinged or sliding, or,more commonly, top hinged to keep out direct sunlight and rain. At night, windows are closed to protect against insects and animals. Hinges are formed from simple bindings, or connecting bamboo elements. [29,"bamboo-in-construction."]

# 4.4 Rod shaped building structures

## 01-Straight Rods



Several Systems of Construction(27,Bauen mit Bambus)

**Structural systems with conical rods**

Straight rods can be arranged in a variety of ways. If it is fixed at the base, the characteristic bending curve for conical round poles results under a horizontal load acting on the side as in the case of a fishing rod. The pole can be mounted in an articulated manner, if its stability is assured by means of stays or other structural measures.Highly stable loadbearing systems are produced by joining poles to form tripods.When these are invented, they form a table-like structure which, with minimum contact with the ground, is stable.

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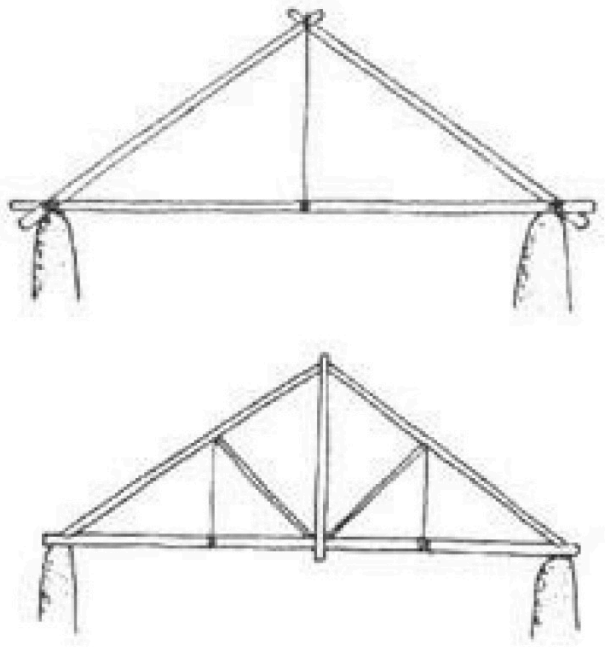
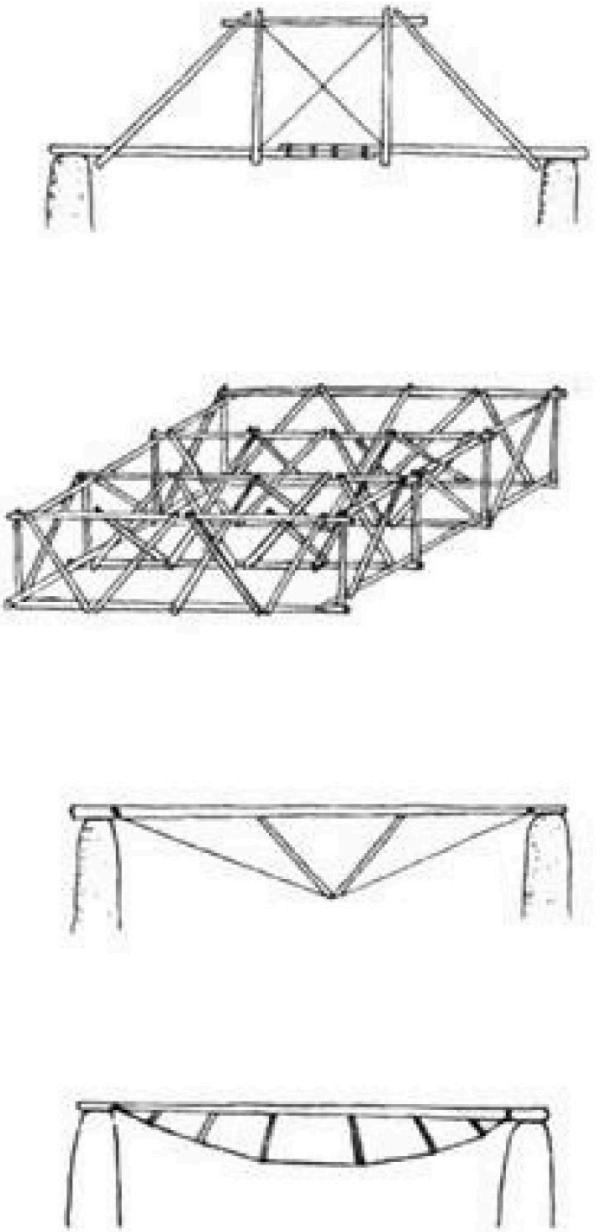


Half timbering etc. (27,Bauen mit Bambus)

## Half timbering

The combination of suspended and strutted frames is a relatively common feature of root strucutures and even bridge structures , the struts being passed on under the tie beam, thus forming further supports for the tie.Trusses can be described as a further development of suspended structures and,like these,have only vertical reactions from vertical loads.Parallel-boom girders are suitable for bridge and wide-spanned deck structures. [27,Bauen mit Bambus]

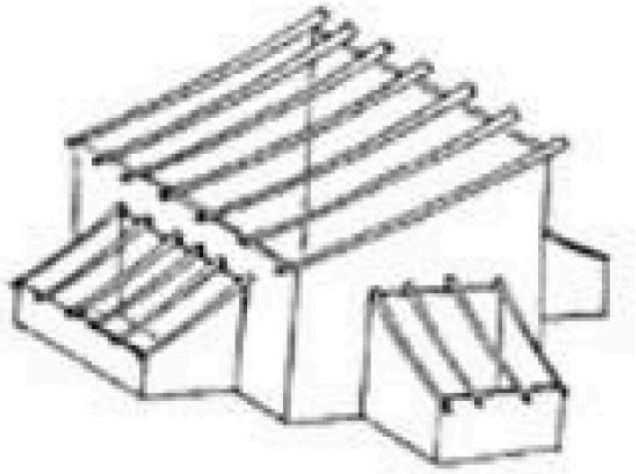


Framework gratings (27,Bauen mit Bambus)

## Framework gratings

Trusses arranged parallel to one another can be connected by means of spatial diagonals or crossing to form framework gratings. [27,Bauen mit Bambus]

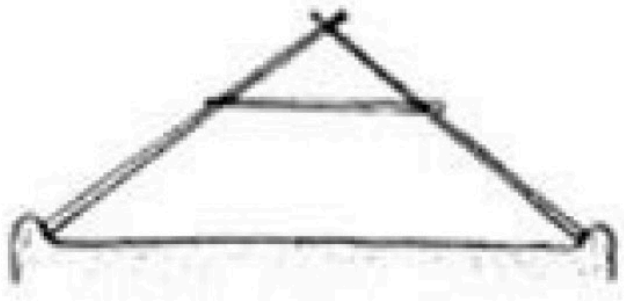
**Several roof forms**



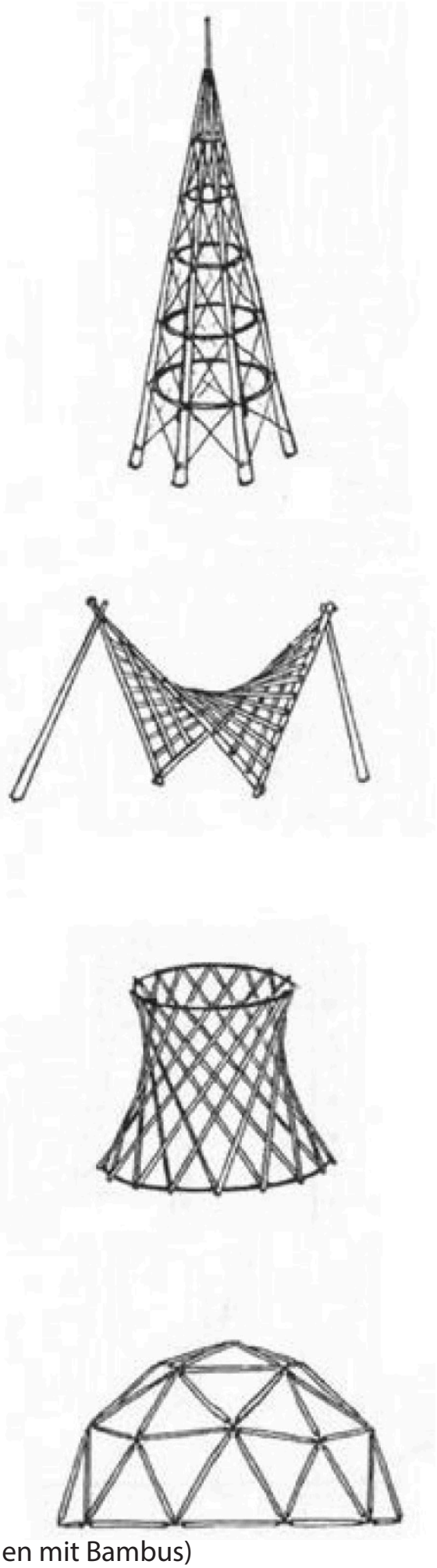
Pitched roofs are typival pole structures. Shed roofs are often placed in front of solid buildings as lightweight,hung-in structures;the front support can then be designed as a suspended column mounted in an articulated manner.

Poles joined to one another.

In case of larger spans,the loadbearing capacity of the poles can be increased by means of collar beams which reducse the spans of the rafters and, thus ,their sag. [27,Bauen mit Bambus]



Several roof forms (27,Bauen mit Bambus)

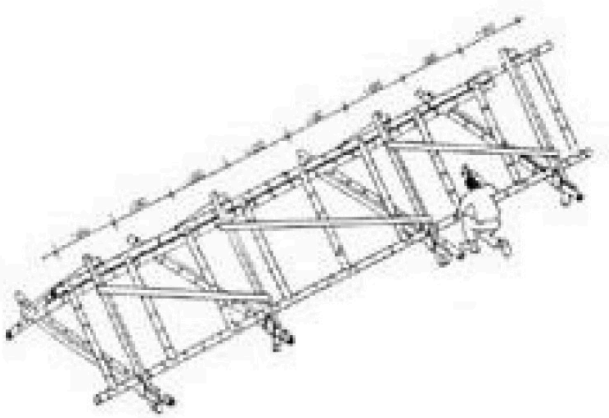


(27,Bauen mit Bambus)

**Curved surfaces with straight rods**

Spatial reinforcement by means of diagonal poles is required in order to transfer the often considerable horizontal loads which occur with towers.

Straight poles can be used to produce curved surfaces,so-called ruled surfaces. As far as building with poles is concerned, the anticlastically curved surfaces of the hyperbolic paraboloid and the hyperboloid of revolution are particularly interesting. The geodesic dome forms an approximation to a synclastically curved surface.In the case of this structure,special importance is placed on the joint with the connections for the poles which are not situated in one plane. [27,Bauen mit Bambus]



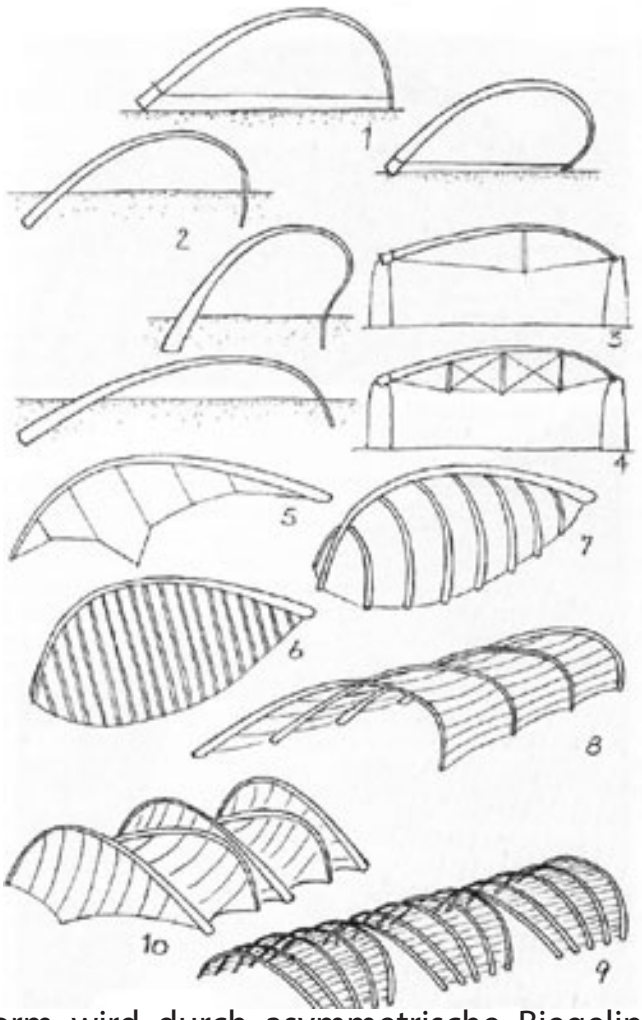
Dreigurt Fachwerkträger

(27,Bauen mit Bambus)

### Triple Boom Trussed Beam

Triple Boom Trussed Beam CIBAM has developped a new lightweight bamboo beam which can be easily produced.The prototype presented here has a width of 2m and is 8m long. Because of the stability and flexibility of bamboo it is highly resistant against earthquakes.The beams can be covered by various materials. [27,Bauen mit Bambus]

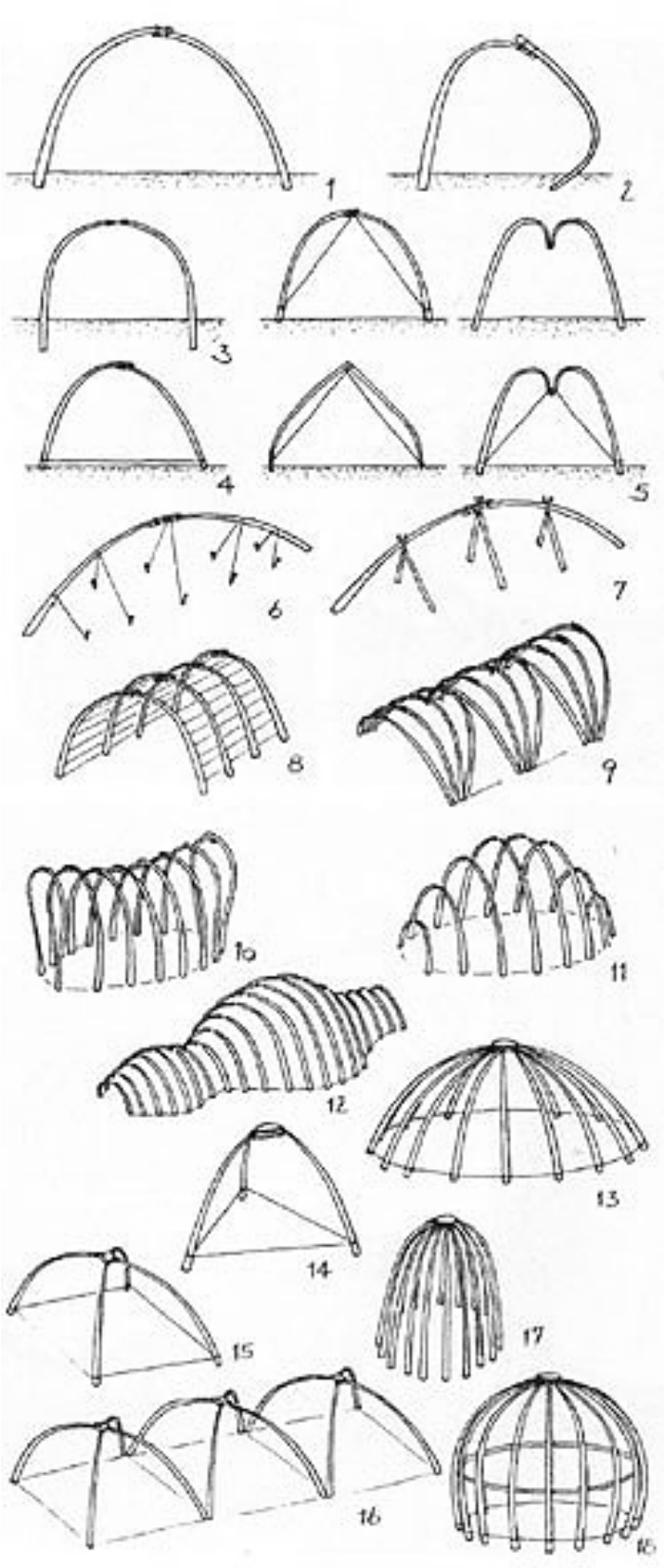
## 02-Curved Compression Rods




Form wird durch asymmetrische Biegelinie bestimmt (27,Bauen mit Bambus)

### Arches

The form of a simple arch of conical vegetal rods is determined by the nature of the not symmetric deflection curve. As part of a structural system, the arch must be prevented from tilting. This can be achieved by anchoring it with tension-proof ropes or membranes, straight and even curved poles,or by restraining it. This type stabilisation requires an additional mass since the rod must be suitably rigid in the transverse direction. [27,Bauen mit Bambus]



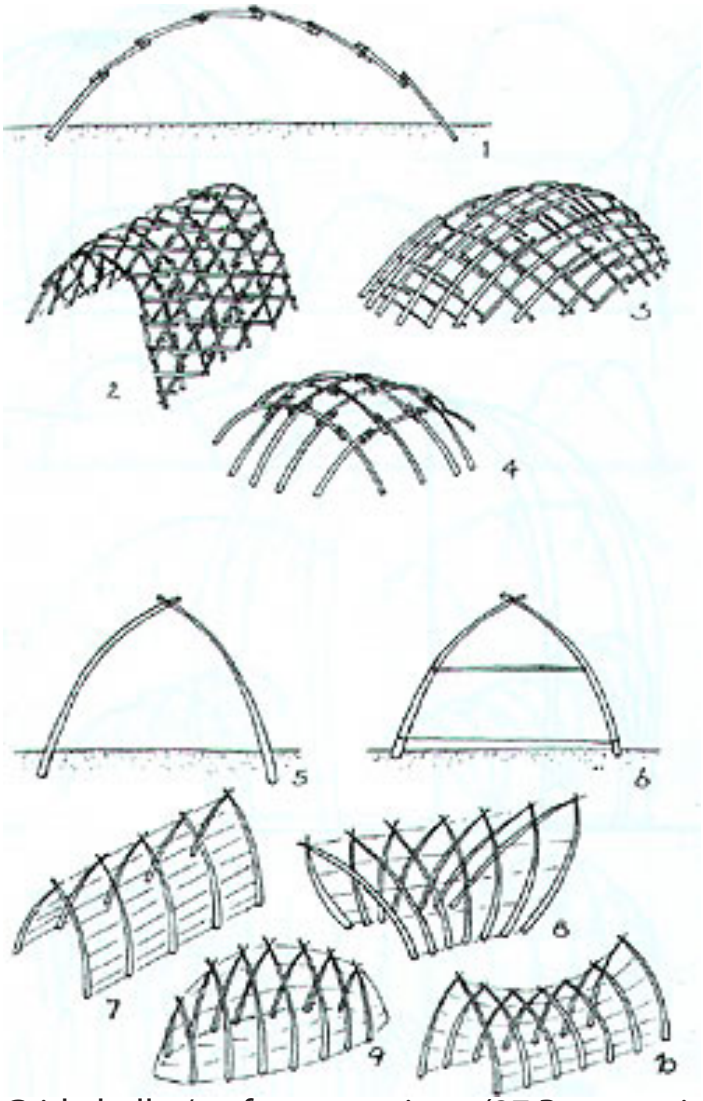

Symmetrie by addition of rods (27,Bauen mit Bambus)

## Composed Curves

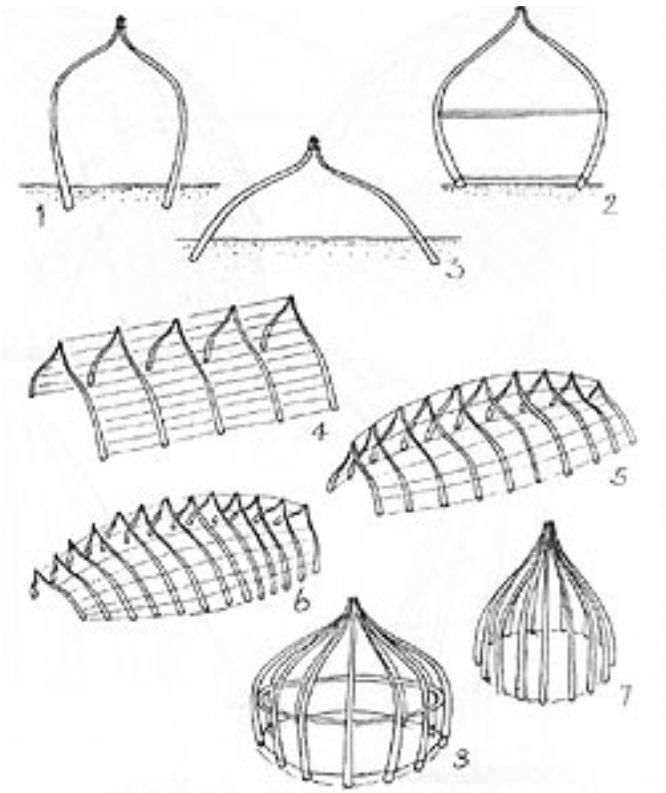
By adding several rods, you can achieve symmetric forms. The form depends depends on the way it's fixed to the ground.Longer curves can be stabilised, which also reduces their structural length.By adding several rods several room building constellations arise. By changing the length over elliptical floor plans, you can get domes.Another possibility of shaping is the use of grid shells by croosing the rods. [27,Bauen mit Bambus]

## Different Connections -Grid shells / soft connections

The way of connection of the singles rods builds up special kinds of shapes.For example you can use soft connections, which causes pointed arches. If you connect the rods parrallel, you get onion like geometries. [27,Bauen mit Bambus]



Grid shells / soft connections (27,Bauen mit Bambus)



Parallel, stiff connections (27,Bauen mit Bambus)

Bamboo Shed in South Ethiopia (27,Bauen mit Bambus)

**Modern structures made of split bamboo**

If split canes are used in the load-bearing structure, the curved shape is unavoidable. In this manner relatively large buildings can be erected from split bamboo canes.A traditional example are the huts of the Dorse tribe which lives on the Gamu high plateau in southern Ethiopia, Africa. The huts of this tribe have a very charasteristic shape: a circular plan with a projecting entrance lobby In collaboration with the School of Architecture (SA) of Ahmedabad, India, there has be the attempt to developnew contructional applications of bamboo by combining the great tradition of the bamboo craftsman with modern methods of lightweight construction. [27,Bauen mit Bambus]

Grid shell as transitions of the chain line (27,Bauen mit Bambus)

Finished grid shell (27,Bauen mit Bambus)

## Grid Shells

In grid shells, which are a method of construction developed at the IL, relatively thin bars form a spatially
curved load.bearing structure.The constructional principle is based on the idea of reserving the catenary
line of a chain and making it into the thrust line of an arch.These are some important questions:

1. Determining the effect of irregularities in the bamboo grid bars on the shape and the load-bearing behaviour of the grid shells.
2. Development and testing of constructional details suited to the material such as the joining of the grid
bars, the butt end joints of the grid bars, the design of the edge or boundary, the fixing of the grid to the
boundary, options for fixing the form, etc.
3. Adapting the assembly and shaping methods to the requirements of the tied grid.
4. Detremining the load-bearing capacity of such structures and their feasible spans.
5. Developing and testing of possible roofing material and interior fitting equipement. [27,Bauen mit Bambus]

Basket Shell under load (27,Bauen mit Bambus)

## Basket shell made from split bamboo

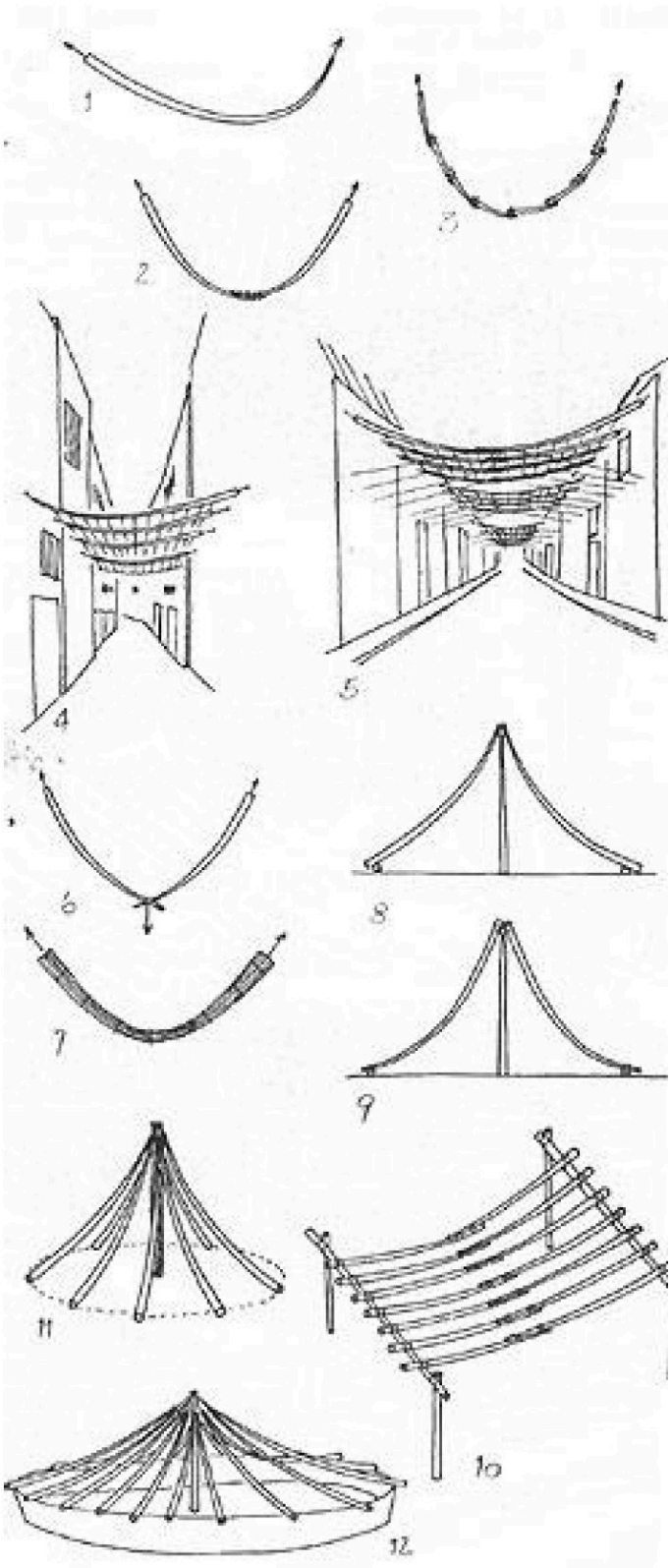
For this experiment an Indian craftsman was instructed to weave a small dome from very thin and narrow strips of bamboo using the conventional radial weaving technique. The shape of the model was largely identical to that of suspended form(-diameter:56cm, height:25cm,weight:865p).With two thirds of the edge resting on a surface, the model was loaded with suspended weights.Under an evenly distributed load of 1000 N/m2 of a base area,no measurable deformation of the surface was recorded. [27,Bauen mit Bambus]

Bamboo arched structures and barrel vaults(27,Bauen mit Bambus)

## Bamboo arched structures and barrel vaults

Within the research project "Building constructions using bamboo" the Research Laboratory for Experimental Constructions of the University of Kassel carried out studies in 1981 and 1982 on simple joining techniques for bamboo canes and the application of bamboo for the construction of dome or barrel-shaped roof structures. As a test material bamboo canes of 10-15 cm diameter and 6m length of the species Guaduaangustifolia were used. [27,Bauen mit Bambus]

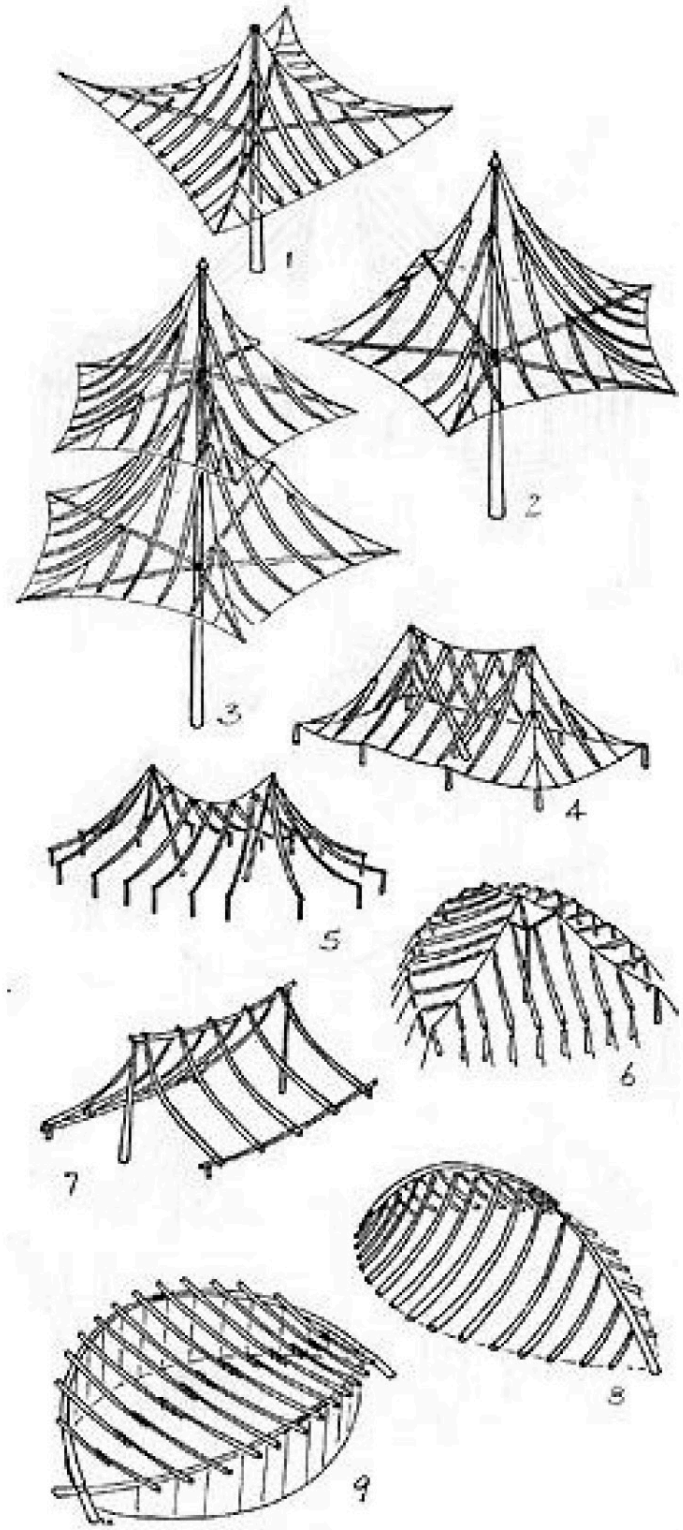
# 03-Curved Tension Rods




Hanging Curves (27,Bauen mit Bambus)

## Hanging Curves

Vegetal rods which, as a result of their low flexural rigidity but high tensile strengh, are suitable for structures subjected to tensile strebgh produce a caracteristic, asymmetric hangig / bending curve when hung between two bearings.This form becomes more obvious the greater the load is.
For larger spans and symmetrical roof forms, two or even several rods are combined. Normaly suspended roofs must be stablished by under spanning.A number of different arch forms are necessary depending on the load situation. Arches, which must bear for example an additional spot load in the centre,are built as suspended pointed arches.The addition of several hanging / bending curves forms characteristical structures in particular tent-like suspended roofs. [27,Bauen mit Bambus]




Tent-like structures (27,Bauen mit Bambus)

## Tent-like structures

DAs the traditional structure in Asia, the umbrella-like tent roof with groins and hoizontal compression struts has probably been developed to become the classic form. In addition to being able to form groins and edge supports as ropes, these elements can also be replaces by flexible rods.In order to cover large floor plans, it is posible to fan out into a two branch tent with suspended ridge. These structures are formed by combinations of compression and tension elements. [27,Bauen mit Bambus]

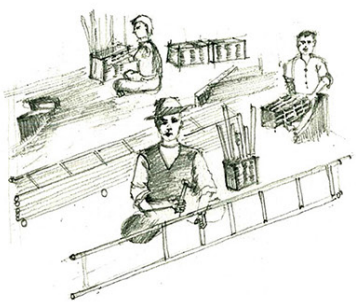
# 5.Bamboo Architectural Case Study

There are many bamboos building project from China and Vietnam, particularly from Atelier cnS and VTN Architects. Atelier cnS had worked so much on designing low-tech and affordable bamboo buildings spaces for rural areas, such as Changqi Stadium Bamboo Corridor, Huanglong Waterfront Bamboo Pavilion, Urban Park Micro Renovation. They used to design bamboo buildings or pavilion by integrating with steel skeletons and steel foundations. When discussing sustainable building for rural area, greenhouse is very meaningful for local community. Aquaponic systems, recycling of elements between fish feeding and planting vegetables, is a quite efficient methods for greenhouse. In China, there are some emergent techniques like bamboo winding composites and bamboo steel. After winding as bigger bamboo tubes, this kind of elements can be applied on pipe gallery, modular houses, and high-speed rail carriages. Bamboo steel is that after fabrication process, epoxy resin, densification and solidification, raw bamboos would enlarge the property of tension and become ligher.

# 5.1 Bamboo architecture

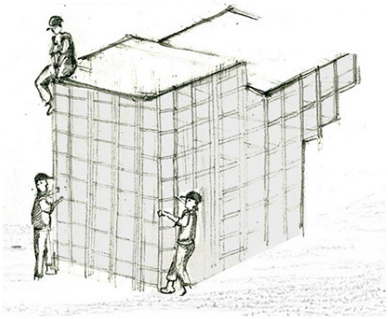
## 01-Green Ladder / VTN Architects

With green architecture in mind , the idea of “Green Ladder” is combination of bamboo ladders – a popular equipment made by bamboo – a traditional material in Vietnam. These bamboo units were assembled in Vietnam and transferred to Australia. The structural elements are linked together to form a **porous but robust grid-like frame**, supporting the planter pots inserted in-between. The pavilion acts as a physical link connecting visitors and nature. Ultimately becomes more than form, function and beauty, but a catalyst between human - nature. After three months exhibition at the main garden of the Library of Queensland, Australia, “Green Ladder” has been moved to the Sherman Contemporary Art Foundation (SCAF), Sydney ,displayed as a notable project for the upcoming exhibition. [https://www.archdaily.com/]



Making ladders in Vietnam.

Shipping units to Sydney.

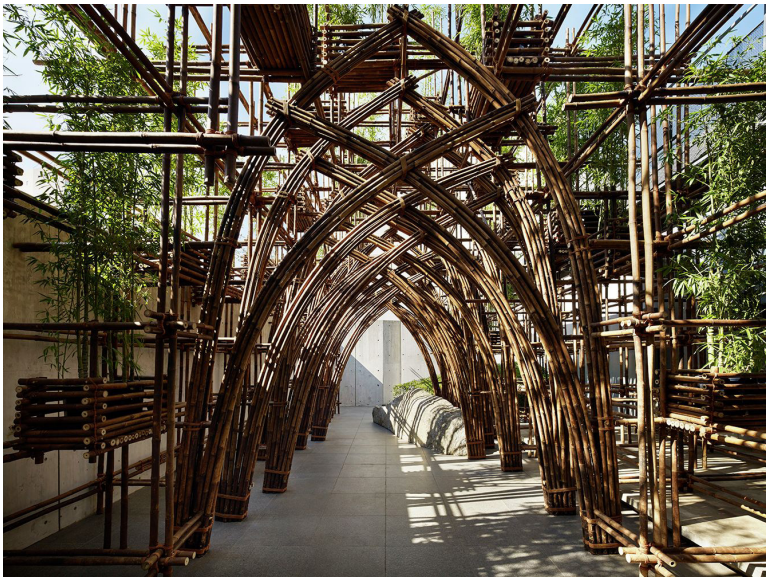


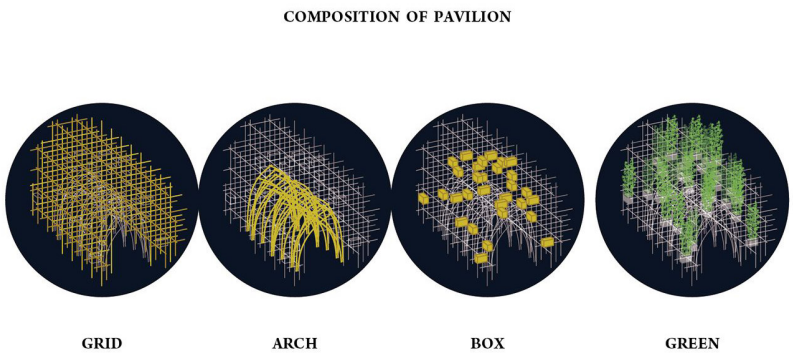
Assembling pieces in site.

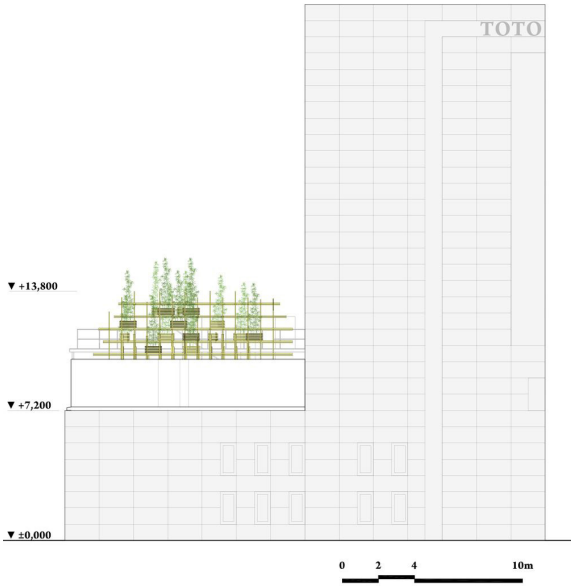
(Archdaily)

## 02-Bamboo Forest ,Vo Trong Nghia Architects (VTN Architects)

This Bamboo Forest pavilion is constructed for the 30th-anniversary exhibition "The Asian Everyday: Possibilities in the Shifting World" at TOTO GALLERY MA, one of the Japanese most influential galleries for architecture and design, located in Tokyo. The pavilion is a pure bamboo structure composed of three elements. Grid: intersecting two grids create the volume. Arch: eleven arches are inserted into the grids to create an open space to stroll through the pavilion. Box: thirty-one boxes are installed to solidify the whole structure. The pavilion embraces greenery with living bamboo planted into the boxes, expressing VTN's important pursuit of bringing greenery back to the city. All visitors are invited to consider the great potential of bamboo and envision what it may be like to have greenery in a city. [https://www.archdaily.com/]

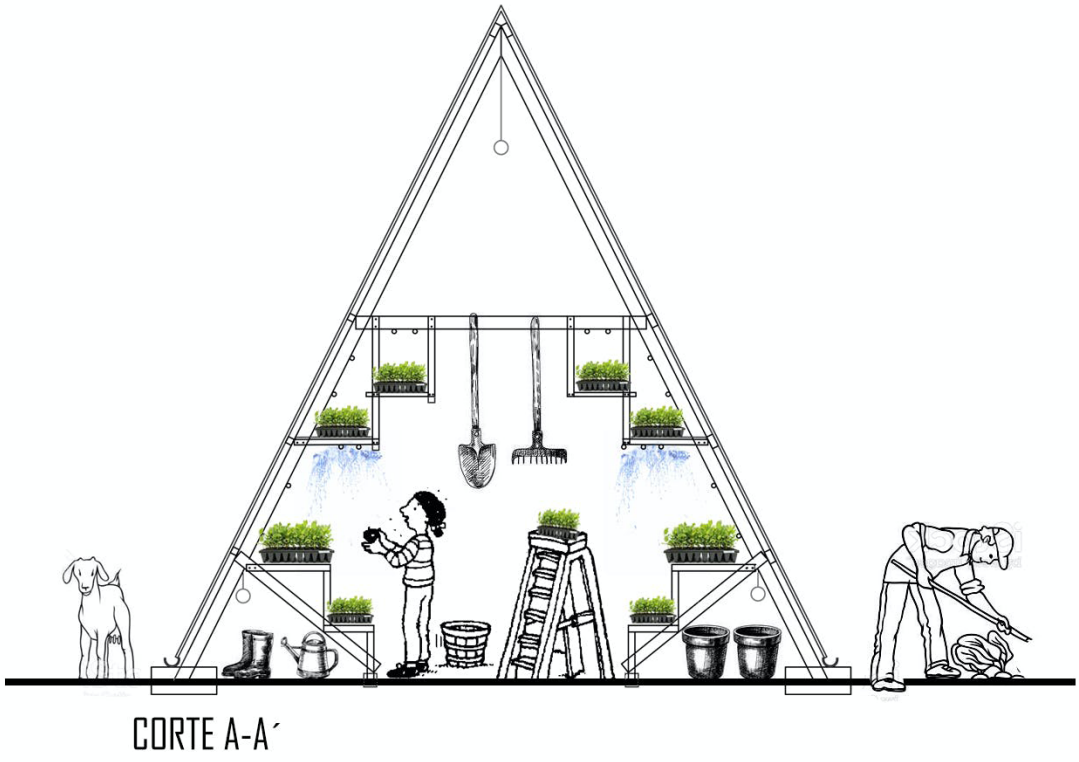





(Archdaily)

## 03-The Triangle of the Vegetables /Productive CommunityGreenhouse

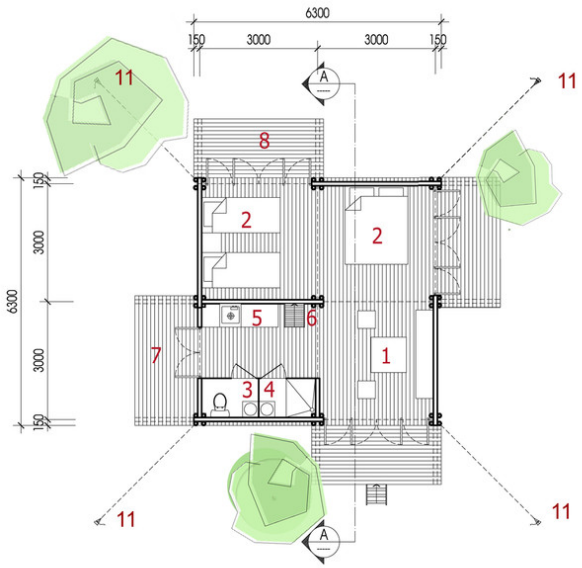



(https://archinect.com/naturafuturarq/project/the-triangle-of-the-vegetables-productive-community-greenhouse)

## 04-Bb Home / H&P Architects

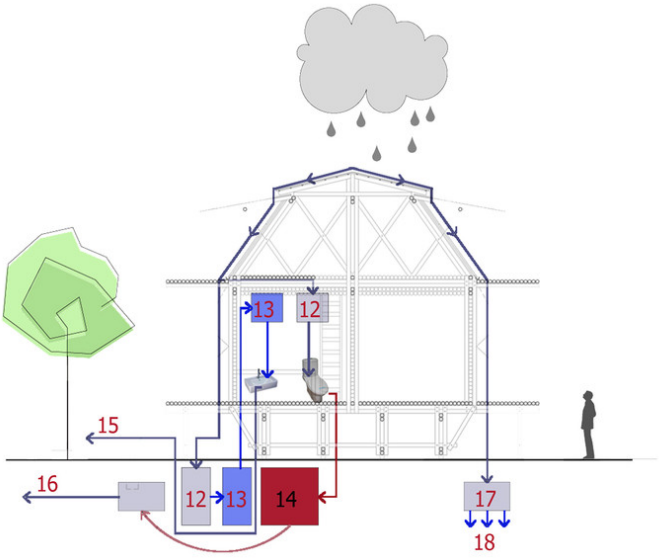
The users can build the house by themselves in 25 days. Besides, it can be mass produced with modules and the total cost of the house is only 2500$. Therefore, the house can warm people in the most severe conditions and help them control activities in the future, also remarkably contribute to ecological development as well as economic stabilization. This will give condions for self-control process and create connection between vernacular culture and architecture.[https://www.archdaily.com/]

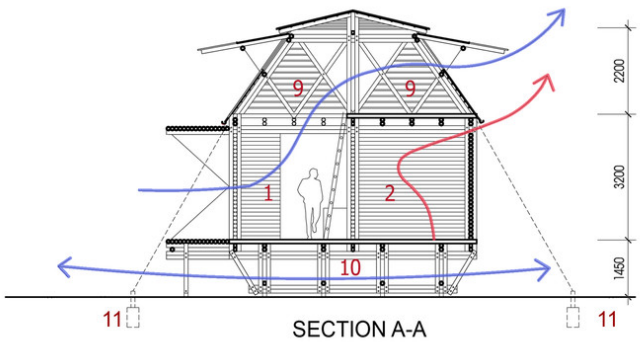
1st FLOORPLAN




1. Living room
2. Bedroom
3. WC
4. Bathroom
5. Kitchen
6. Stair
7. Laundry + Drying
8. Outdoor terrace
9. Indoor terrace (sleeping + learning + worship)
10. area breed animal / plant
11. Anchor steel
12. Rain water tank
13. Clean water tank (filtered)
14. Waste water tank
15. Water for gardening
16. Discharged to (after treated)
17. Filter tank for rain water
18. Rain water cleaned and returned to the environment (underground reloading)

0 3M



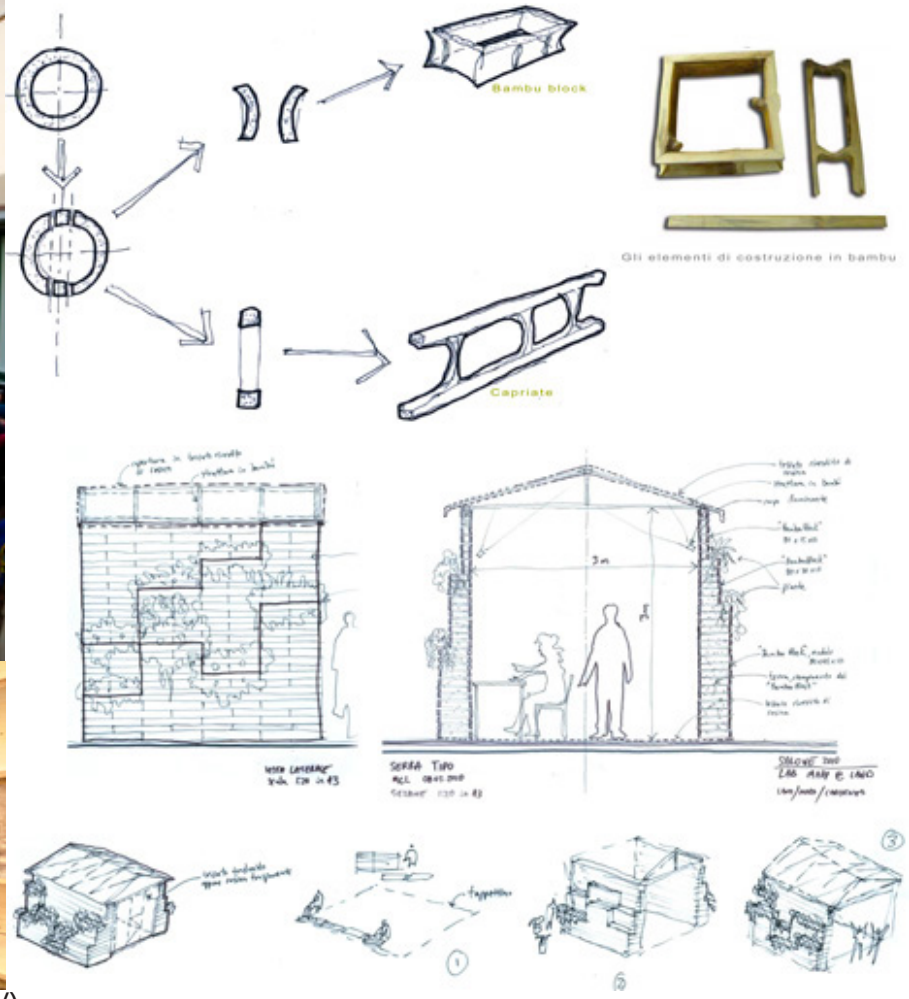




SECTION A-A

(Archdaily)

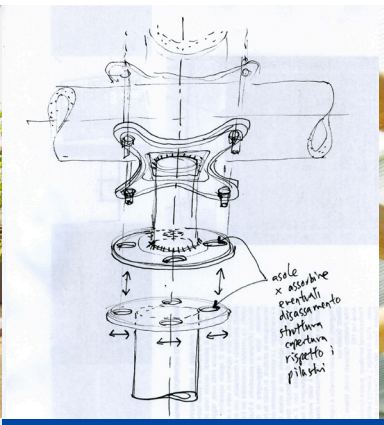
## 05-THINK GREEN AT FUORI SALONE, Studio Cardenas

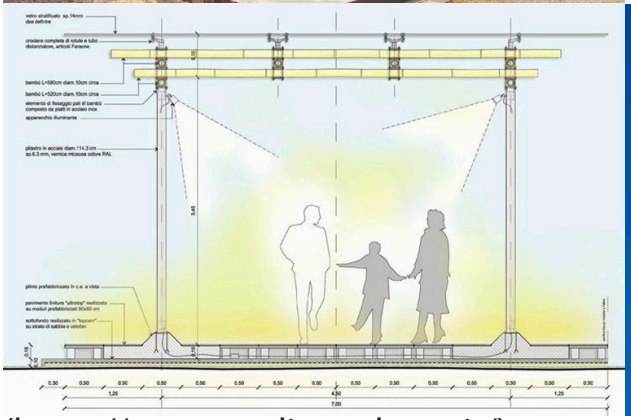


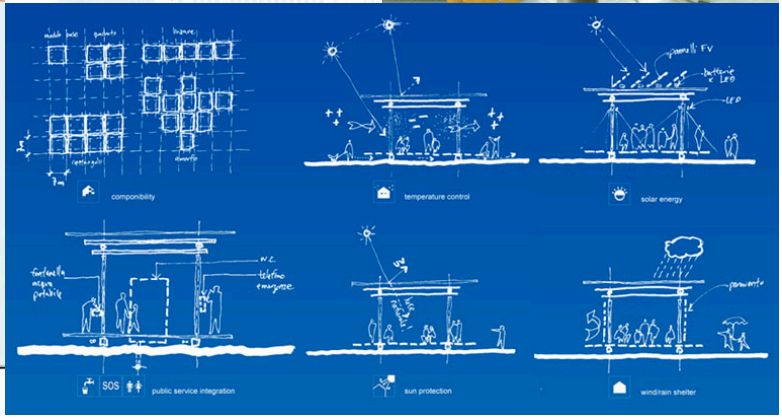



(https://www.studiocardenas.it/)

## 06-MICROCLIMATIC PAVILION, Studio Cardenas

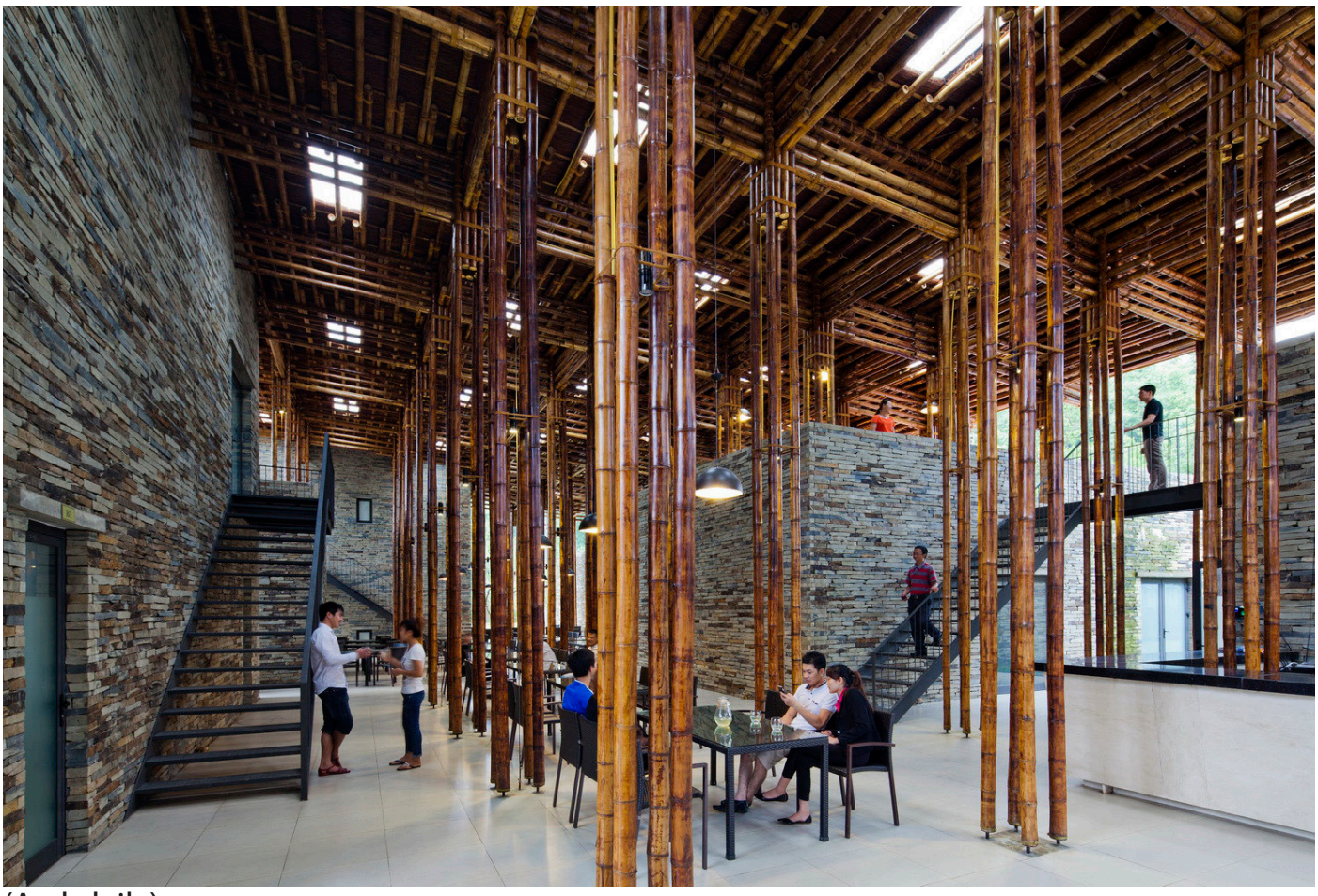







(https://www.studiocardenas.it/)

## 07-Son La Restaurant / VTN Architects



(Archdaily)

Due to difficult terrain, Son La is only accessible from Hanoi by a 7 hour car trip along precarious cliff roads. The accessibility makes transportation of building materials and work forces difficult. Thus, the project maximized use of local resources including workers and affordable local materials. With this situation, local bamboo and stonework was selected to be the main materials of the building.

The roof structure for the dining hall is made by local bamboo called “Luong” that grows to 8m in height. 96 bamboo column units composed of 4 bamboos together induce the vertical expression of the bamboo structure like bamboo forest. 80-100mm diameter bamboos are assembled by bamboo dowel nails and rope after they are treated by a traditional method in Vietnam, that involves soaking in mud and then smoked. [https://www.archdaily.com/]

(Archdaily)

## 08-Vo trong nghia constructs conference hall using two types of bamboo in vietnam

vo trong nghia constructed the main structural frame through the use of bamboo, spanning a distance of 13.5 m in the hall and 4 m in the corridor and finished with a roof height of 9.5m. the arch-like impression is created by the bent bamboo that is connected to the structure. meanwhile, the receded glass façade simultaneously serves as a foyer to welcome visitors and guests. the bamboo plant is constantly being explored and utilized within the construction industry due to its rigidity, sustainability and cost effectiveness. two types were used in the making of this building: for the straight columns the 'luong' bamboo type was chosen due to its strong and durable qualities, while reaching lengths up to eight meters and the "tam vong' bamboo chosen for its flexibility. [https://www.designboom.com/]

(Designboom)

## 09-Art Gallery Catuçaba,CRU! Architects

The clients' idea of an art gallery was that art and nature are intertwined and art should be presented in a natural environment. Throughout the hotel property various art installations can be found. By being in nature one should be more receptive to see and feel art, according to the hotel owner. The art gallery has to host changing exhibitions offering clients a variation of art. This art gallery was built by a community eco-building cooperative that was aided by CRU! Architects. The idea of this social building project was to provide training and job-development for a deprived community. After the community center, commissions were sought outside of the village of Camburi in order to have economic return for the cooperants, of which this art-gallery is an example. The entire bamboo-structure was executed by the local cooperative, whilst the brickwork, excavations and foundations were done by the local workers from the farm which the hotel is located on. [https://www.archdaily.com/]

(Archdaily)

## 10-CO-LAB Design Office creates bamboo yoga pavilion in Tulum

The pavilion at the Luum Zamá development in Tulum, Mexico, will host a variety of programs, such as yoga, meditations, workshops and other community gatherings.

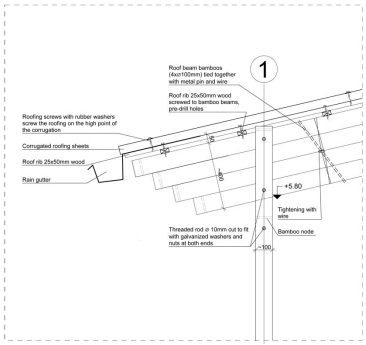
CO-LAB Design Office created the open-air structure in the beach town with bamboo that was farmed sustainably in the neighbouring Mexican state of Chiapa. Bamboo was chosen for its sustainability credentials as well as its ability to resist hurricane forces. Flat sections of bamboo beams were bent on-site, and then screwed and strapped together to create the pavilion.

CO-LAB Design Office created the structure with parametric software and also worked in close communication with local builders and an engineer who specialises in bamboo structures. Inside, the thatched design and bamboo rods are also visible.

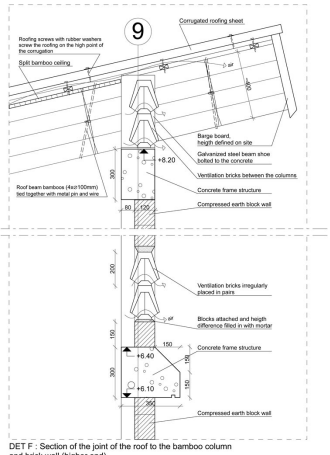
"Once the arches were raised, they were woven together by a structural triangular pattern and then further bound by two continuous layers of tightly woven bamboo lattice, interlaced in opposite directions for structural stability," said the studio.[https://www.dezeen.com/]

(Dezeen)

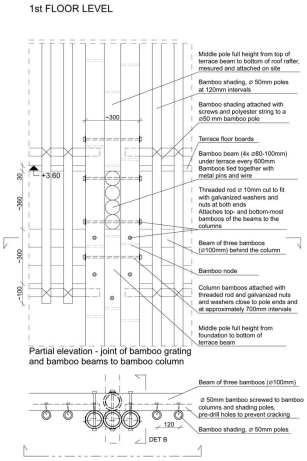
## 11-Kouk Khleang Youth Center

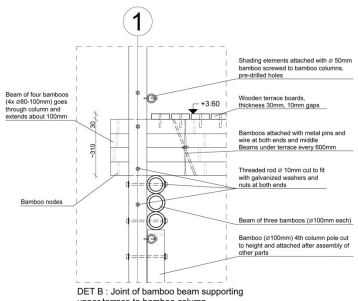



DET C : Joint of bamboo beam supporting the roof to bamboo column detail of the overhang (lower end)




DET F : Section of the joint of the roof to the bamboo column and brick wall (higher end)




DET B : Joint of bamboo beam supporting upper terrace to bamboo column

(https://urbannext.net/kouk-khleang-youth-center/)

The main aspirations of the material choices and construction techniques used in the building have been sustainability and cultural understanding. The main materials used in the building are bamboo, compressed earth brick and recycled plastic bottles. The main load-bearing structure of the building is a concrete frame, which is the most common building method in Phnom Penh. The frame is filled with locally produced earth blocks. The carbon footprint of earth blocks is ten times smaller than that of red bricks by mass. All bamboo parts are standardized and only hand tools have been used in their construction. Thus the building is easy to maintain and the techniques can be applied to local building projects in the future. During the project an illustrated, khmer-language bamboo construction guide was produced. Rainwater is harvested on site and the ground floor is raised to protect against flooding.[https://urbannext.net/kouk-khleang-youth-center/]

## 12-CONTEMPLATION BAMBOO PAVILION, SIMÓN VÉLEZ ARCHITECTS

(https://divisare.com/projects/390925-simon-velez-architects-xavier-de-jaure-guiberry-contemplation-bamboo-pavilion)

This monumental installation has been created as a "place of serenity", propitious to discovery and contemplation ; a corridor, a gateway between Art and Matthieu Ricard's commitments. Through CONTEMPLATION, photography and architecture enter in communion: the bamboo structure and natural materials used by Simón Vélez echo back the values of the photographer and the lights and shapes of the Pavilion underlines and sublimates the light-dark of the photographs.

This Pavilion is the first installation made in prefabrication by this duo of architects. It has created new architectural possibilities for them: it can be entirely disassembled, transported and reassembled wherever CONTEMPLATION will be settled. [https://arles2018.contemplation.art/en/simon-velezs-pavilion/]

## 13-Architecture students at bezalel academy created a reusable bamboo pavilion

In jerusalem, at the entrance to the bezalel academy of arts and design courtyard, a shadow-casting bamboo pavilion challenges visitors' perceptions of 'inside' and 'outside.' the pavilion is a result of a summer design-build studio course. Bamboo poles are uniquely sized and shaped; instead of forcing them into standardized shapes and treating them as such, 3d printed shuriken-shaped 'ninja joints' were designed to fit specific poles in specific places, each ninja joint printed with the exact dimensions of its corresponding pole in mind. the poles were then clumped together to create columns and the columns comprised much of the overall structure. the simple joint connectors mean that nearly 100% of the pavilion materials can be reused with ease. at the architecture department courtyard of bezalel, bamboo poles crescendo; they stand tall at different heights; centimeter differences are noticed by the touch, up close; the pavilion's pieces cast shadows together, and visitors wonder if they are inside or out. [Dezeen]

(Dezeen)

## 14-The bamboo carport

Just recently completed, the carport is our latest structure made from our own Maui-grown bamboo poles! It is a 20' x 20' plan and serves as a home to Georgia and Polu (the 2 cars on the farm). The structure uses a **stainless steel strap** as a fastener and is designed as a pre-fabricated kit that can be shipped and easily installed on site. The joinery technique was developed by our designer, Yuliya Bentcheva, as part of her graduate thesis work. It was inspired by the traditional 'passing joint' and lashing method, but modernized by the use of a metal strap to provide a stronger and longer lasting connection. We are currently working on a portfolio of auxiliary kit structures to be used for sport and farming equipment, outdoor space covers, storages etc. [https://whisperingwindsbamboo.wordpress.com/2012/07/22/the-bamboo-carport-7/]







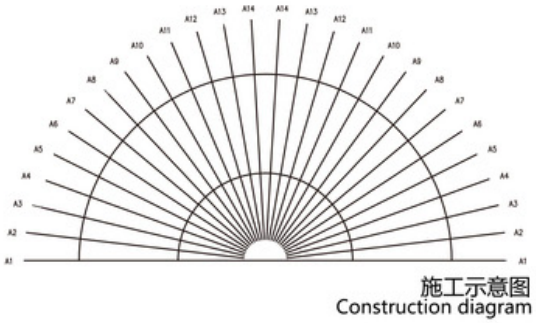
(https://whisperingwindsbamboo.wordpress.com/2012/07/22/the-bamboo-carport-7/)

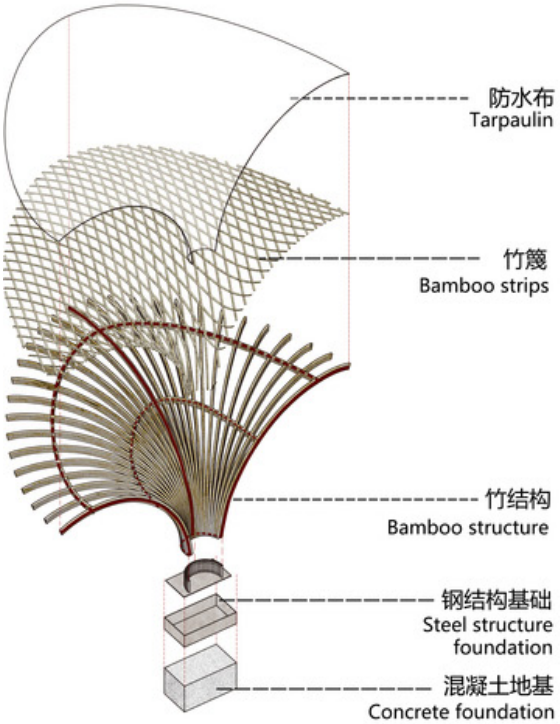
## 15-BAMBOO & ALUMINIUM STRUCTURES

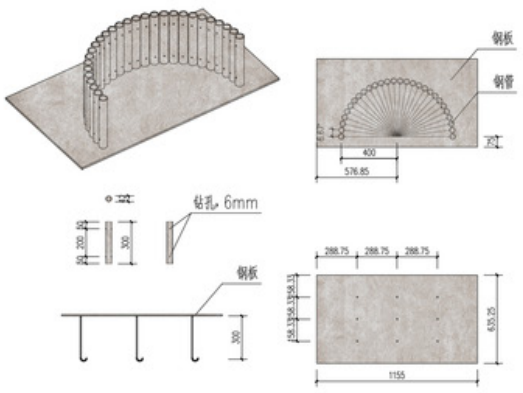
(http://www.alanwhitedesign.com/services/structural-design/bamboo-aluminium-structures)

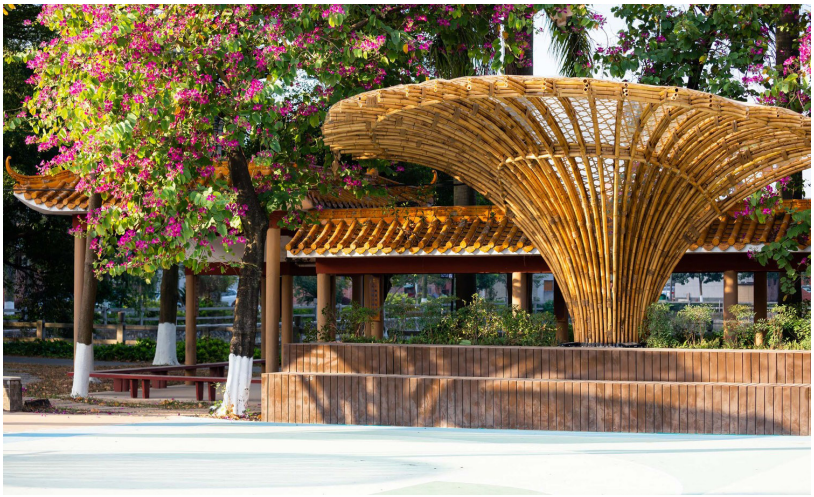
## 16-Changqi Stadium Bamboo Corridor / Atelier cnS

Changqi Village is one of the first batch of ancient villages identified in Guangdong Province. It has a large-scale well-preserved Lingnan gable building; the village has not been developed on a large scale. , Still maintains the original ancient village flavor. Lubao Town has a tradition of bamboo weaving. There are traditional old craftsmen weaving bamboo living utensils, and the bamboo village on the back of the ancient village is full of Moso bamboo. The new stadium bamboo gallery is in the place of the original stands, which provides villagers and tourists with a place to shelter from wind and rain. The design utilizes the toughness of traditional bamboo materials and combines the traditional bamboo weaving technique and beauty of Changqi Village. [Archidaily]



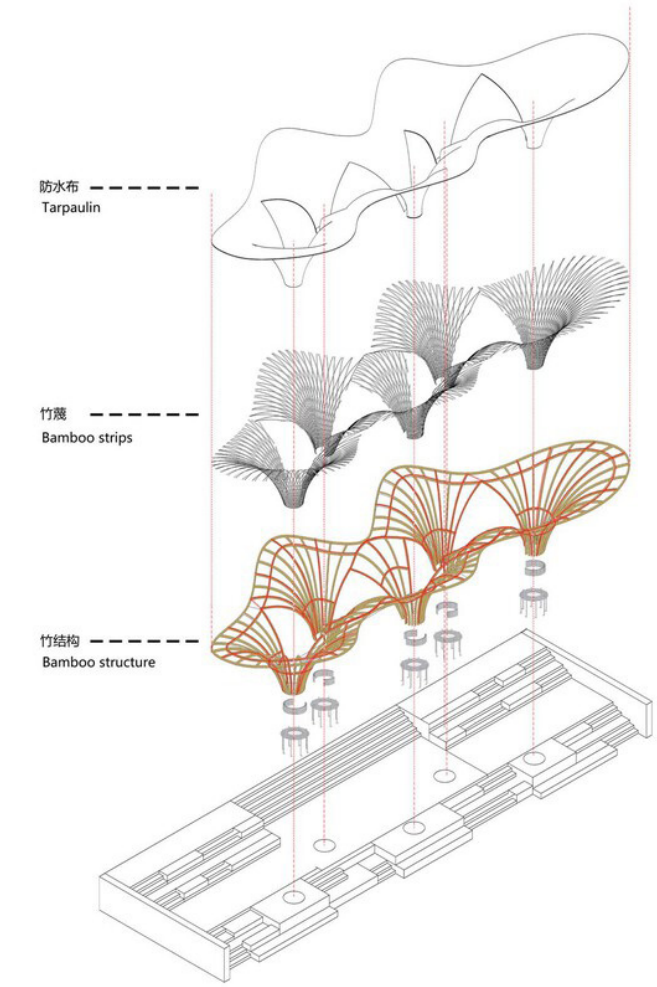



(Archidaily)

## 17-Huanglong Waterfront Bamboo Pavilion / Atelier cnS

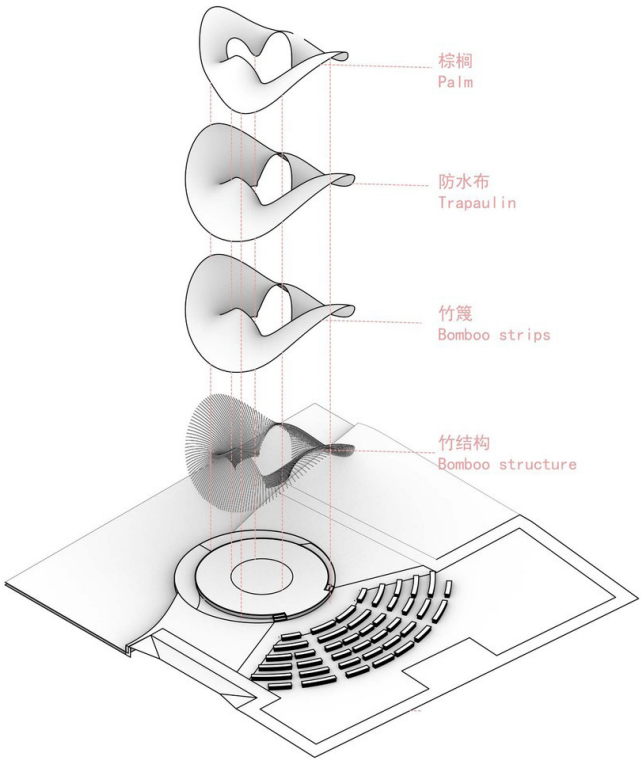



Utilizing beam-column, the original bamboo staggered joints are spliced to achieve a longer overhanging length, and the interior hidden **steel skeleton** cooperates with the stress to achieve the shape. On the one hand, the bamboo weaving on the surface provides interesting light and shadow changes and a sun-shading environment for the internal space. On the other hand, the skin effect increases the stability and integrity of the overall umbrella-shaped structure, and a transparent waterproof film is laid on the top to shield the structure from rain. The upgrade from unilateral cantilever to bilateral cantilever blurs the distinction between the front and back of the Bamboo Pavilion. With the optimization of the structure, the diameter of the bamboo column is reduced and the cantilever depth is maximized, and the diameter of the umbrella cover is up to 9.3 meters. [Archidaily]

(Archidaily)

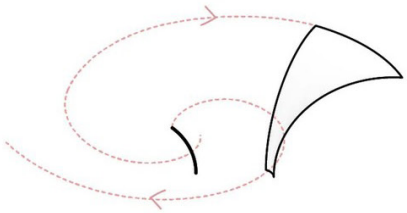
**18-Urban Park Micro Renovation / Atelier cnS + School of Architecture, South China University of Technology**

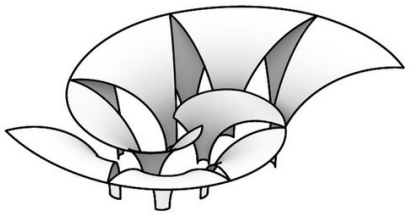
As the 3.0 and 4.0 versions of the bamboo pavilion, the Flower Pavilion and Embrace Pavilion continues the basic logic of combining the "shell-like" shape based on the design of the Changqi Bamboo Corridor and the Huanglong Waterfront Bamboo Corridor. The spiral line is used as the lofting control line to form the rhythm of the Flower Pavilion's structure which could create a spatial hierarchy that full of changes. Embrace Pavilion consists of two groups of reverse shell-like shape connected end to end to form a closed loop. Three-dimensional two-way curved surfaces are cantilevered on the structure to achieve a span of 12m. Through the scale change of the shape, a large-scale stage space is created and a small-scale waterfront viewing space is formed and it created a dramatic spatial twist at the transition between the two. [Archidaily]

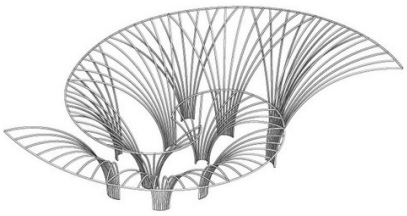


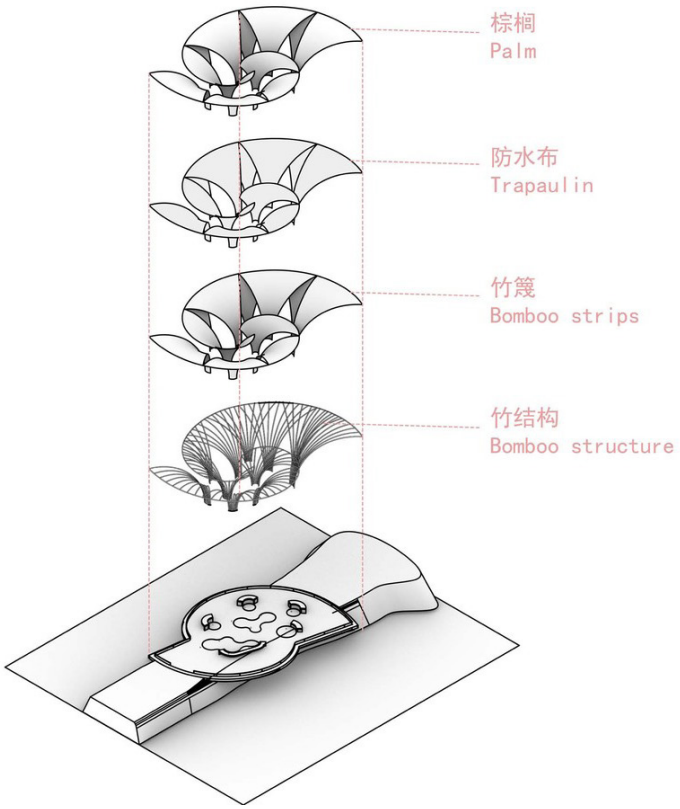

(Archidaily)

The bamboo structure material continues the construction logic of the whole series, adopting a curved cantilevered bamboo to form a shell-like shape, which is combined with traditional bamboo weaving skills, and the roof cladding is woven with bamboo strips which covered with the Palm Tree Bark. Because the roof is translucent, the light and shadow under the roof show the beauty of bamboo structure. The application of Palm Tree Bark ,which is inspired by straw rain cape coat, is a major breakthrough in the structure of bamboo pavilion. [Archidaily]





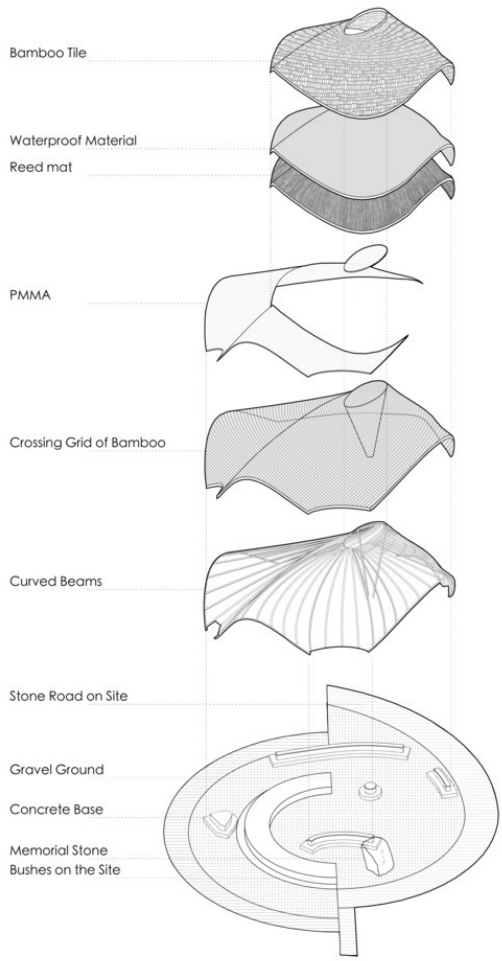


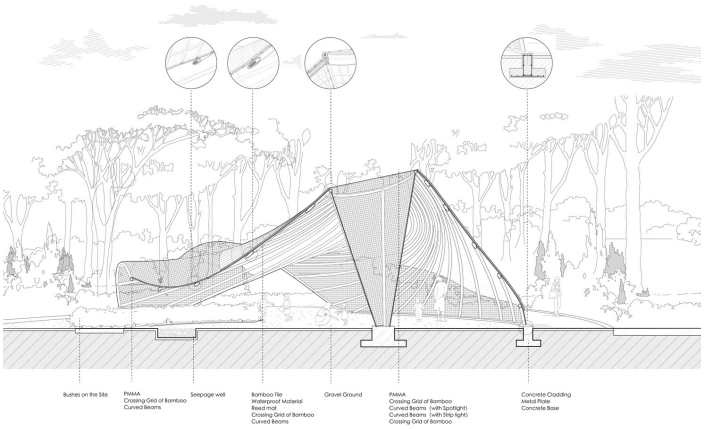



(Archidaily)

## 19-Swirling Cloud: Bulletin Pavilion for BJFU Garden Festival / SUP Atelier

Bamboo beams, the parameters of which were determined by digital simulation, were prefabricated and numbered in the factory, and then assembled on site. The bamboo beam and the ground were connected by metal fittings and strip foundation of cast-in-place concrete. Beams of different directions were connected in traditional ways of bamboo construction. Considering the need of natural light, rain-proofing, as well as the intention to create an atmosphere of intimacy with the partly curved roof, we selected bamboo tile and PMMA as roof materials with a waterproof membrane and reed mats underneath. The pavilion's central cone was not only a supporting structure but also a channel for daylight and artificial light. Sloped paving of permeable gravels on the site, together with pebble seepage pits dotted around the site, could avoid ponding at the joints where bamboo beams and the ground meet. [Archidaily]



(Archidaily)

## 5.2 Sustainable  system

### 01-Urban agriculture: bamboo urban vegetable garden

Jardins de Babylone has created a new creation and devoted particular attention to urban agriculture at the 'Jardins Jardin' show at the Tuileries  2011 in the 8th arrondissement of Paris: the bamboo urban vegetable garden. In Asia, bamboo scaffolding is used for the construction of buildings. This bamboo vegetable garden takes up this idea to create vertical urban vegetable gardens. It is made up of several distinct elements:

A total area of 50m2
The use of 90 bamboo canes 3m long for the construction of the structure.
Each bamboo placed horizontally has openings to accommodate the plants.
Each bamboo cane planted has been sealed beforehand thanks to drainage by fine gravel.
A layer of hydrophilic felt and a porous watering system.
The plants are thus irrigated several times during the day thanks to a studied programming.
Like a closed circuit, the overflow of water is collected in a tank serving as ballast for the structure. Fish provide nutrients for plants.
Installation of both vegetable plants (courgette, melon, pattypan squash, gherkin, tomato, strawberry, etc.) and aromatic and medicinal plants (Helichrysum, lemon balm, mint, chives, red basil, thyme, rosemary, etc.).[https://www.archiexpo.com/prod/jardins-de-babylone/product-158408-1949773.html]

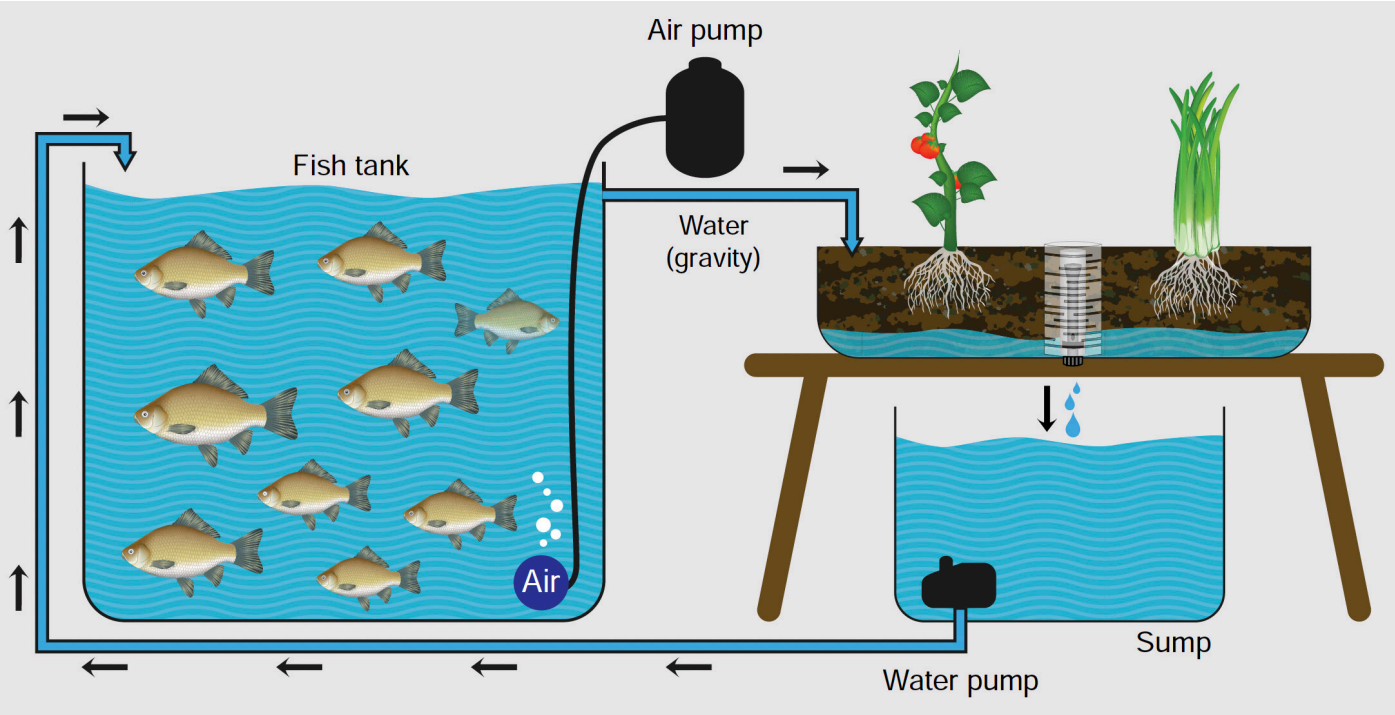



(https://www.archiexpo.com/prod/jardins-de-babylone/product-158408-1949773.html)

## 02-Aquaponics grow system-small media bed unit

### Simple aquaponic unit

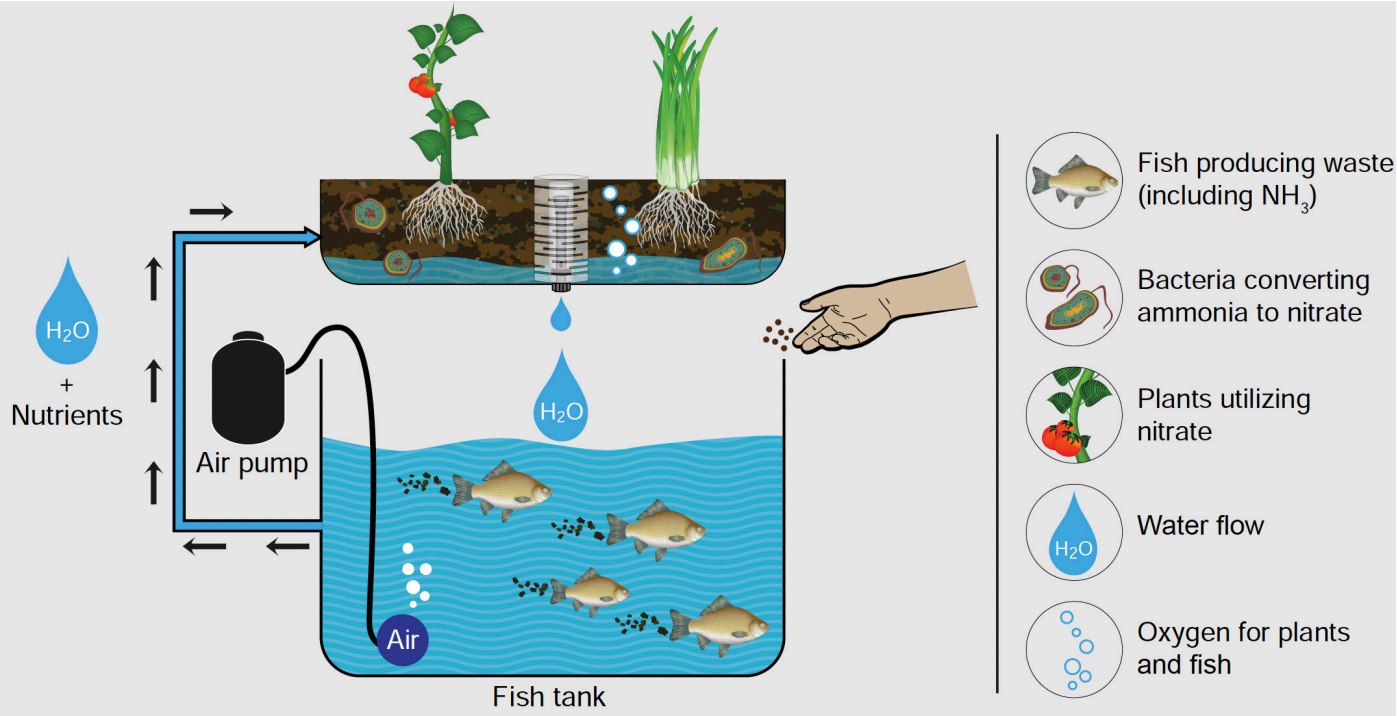
Aquaponics is the integration of **recirculating aquaculture and hydroponics** in one production system. In an aquaponic unit, water from the fish tank cycles through filters, plant grow beds and then back to the fish. In the filters, the fish wastes is removed from the water, first using a mechanical filter that removes the solid waste and then through a biofilter that processes the dissolved wastes. The biofilter provides a location for bacteria to convert ammonia, which is toxic for fish, into nitrate, a more accessible nutrient for plants. This process is called nitrification. As the water (containing nitrate and other nutrients) travels through plant grow beds the plants uptake these nutrients, and finally the water returns to the fish tank purified. This process allows the fish, plants, and bacteria to thrive symbiotically and to work together to create a healthy growing environment for each other, provided that the system is properly balanced. [31,Somerville]




(31,Somerville)

### The biological components in the aquaponic process: fish, plants and bacteria

In one continuously recirculating unit, culture water exits the fish tank containing the metabolic wastes of fish. The water first passes through a mechanical filter that captures solid wastes, and then passes through a biofilter that oxidizes ammonia to nitrate. The water then travels through plant grow beds where plants uptake the nutrients, and finally the water returns, purified, to the fish tank. The biofilter provides a habitat for bacteria to convert fish waste into accessible nutrients for plants. These nutrients, which are dissolved in the water, are then absorbed by the plants. This process of nutrient removal cleans the water,preventing the water from becoming toxic with harmful forms of nitrogen (ammonia and nitrite), and allows the fish, plants, and bacteria to thrive symbiotically. [31,Somerville]




(31,Somerville)

(31,Somerville)

**Water quality in aquaponics**

Water is the life  blood of an aquaponic system. It is the medium through which plants receive their nutrients and the fish receive their oxygen. It is very important to understand water quality and basic water chemistry in order to properly manage aquaponics.

There are five key water quality parameters for aquaponics: **dissolved oxygen(-DO), pH, water temperature, total nitrogen concentrations and hardness (KH).** [31,Somerville]

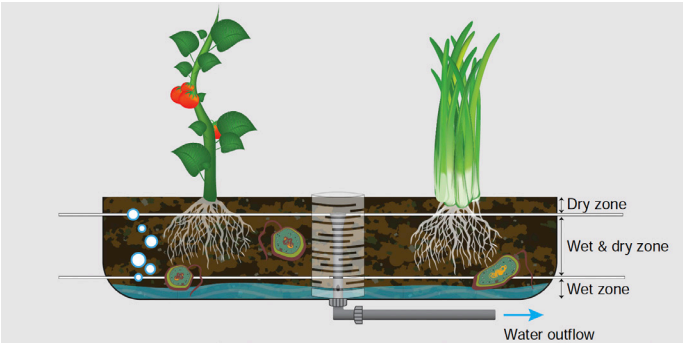
| | |
|---|---|
| pH | 6–7 |
| Water temperature | 18–30 °C |
| DO | 5–8 mg/litre |
| Ammonia | 0 mg/litre |
| Nitrite | 0 mg/litre |
| Nitrate | 5–150 mg/litre |
| KH | 60–140 mg/litre |

(31,Somerville)

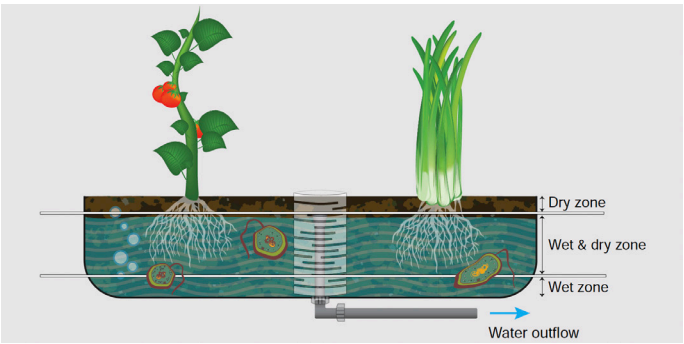
## A small media bed unit

Media-filled bed units are the most popular design for small-scale aquaponics. This method is strongly recommended for most developing regions. These designs are efficient with space, have a relatively low initial cost and are suitable for beginners because of their simplicity. In media bed units, the medium is used to support the roots of the plants and also the same medium functions as a filter, both mechanical and biological. [31,Somerville]

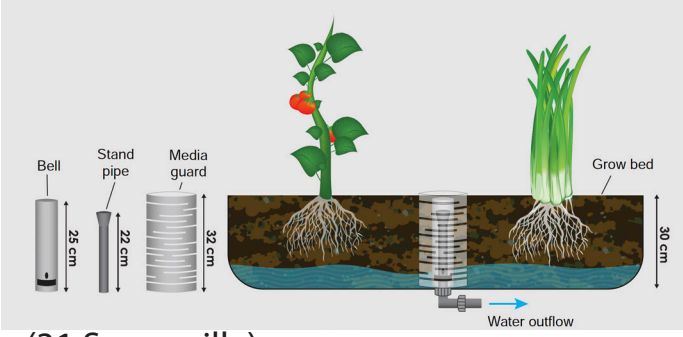
(31,Somerville)




a (31,Somerville)




b (31,Somerville)




c (31,Somerville)

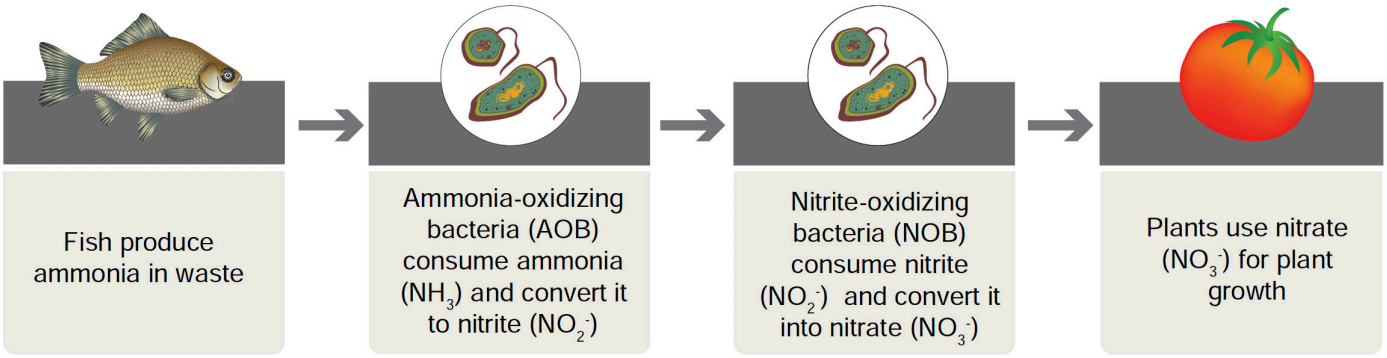
(a)The three zones of a media bed during the drain cycle

(b)The three zones of a media bed during the flood cycle

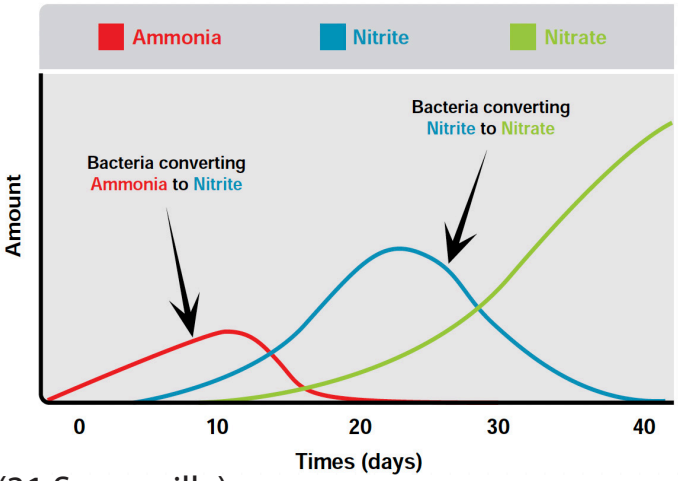
(c)Diagram of a bell siphon and components installed in a grow bed

## Bacteria in aquaponics

In aquaponic, ammonia must be oxidized into nitrate to prevent toxicity to fish. The nitrification process is a two step bacterial process where ammonia-oxidizing bacteria convert **ammonia (NH3)** into **nitrite (NO2-)**, and then nitrite-oxidizing bacteria convert nitrite into **nitrate(NO3-)**. [31,Somerville]




(31,Somerville)




(31,Somerville)

## RAS Aquaponic in Italy

The research, which has been carried out this year at the University's Experimental Farm in six independent systems (3 replicates x 2 treatments), assessed **lettuce growth**,quality and food safety issues at different fish stocking densities/diets against standard hydroponics. The fish species under study was **Nile tilapia**(Oreochromis niloticus) from Nam Sai farms,Thailand and from Vulcittica, Italy. [32, Edoardo Pantanella]

(32, Edoardo Pantanella)

## Plants in aquaponics

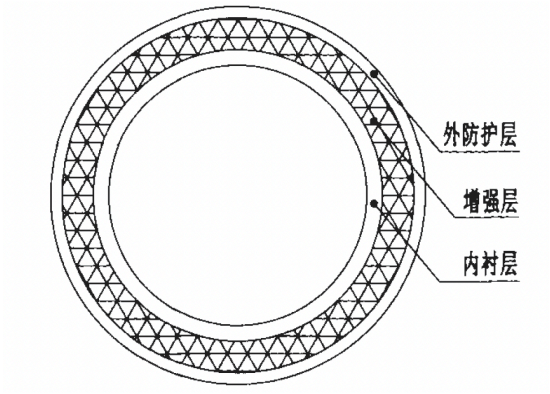
The major adventages of aquaponic over soil agriculture are: (i) no wasted fertilizer; (ii) lower water use; (iii) higher productivity/quality; (iv) ability to utilize non-arable land; and (v) offset of tillage, weeding and other traditional agricultural tasks. Plants require sunlight, air, water and nutrients to grow. Essential macronutrients include nitrogen, phosphorus, potassium, calcium, magnesium and sulphur;Micronutrients include iron, zinc, boron, copper, manganese and molybdenum.Deficiencies need to be addressed by supplying the limiting nutrients with supplemental fertilizer or increasing mineralization. [31,Somerville]

## Fish in aquaponics

Tilapia, carp, and catfish are highly suitable for aquaponics in tropical or arid conditions as they grow quickly and can survive in poor quality water and at lower DO levels. Trout grow well in cold water, but require better water quality. Water quality needs to be maintained for fish. Ammonia and nitrite must be close to 0 mg/litre as they are toxic at any detectable levels. Nitrate should be less than 400 mg/litre. DO should be 4–8 mg/litre. [31,Somerville]

## 5.3 Chinese bamboo technologies

### 01-Bamboo winding composites




Composite structure(33, Jiang Zehui)

Bamboo winding pipe gallery (33, Jiang Zehui)

Bamboo winding integral modular house (33, Jiang Zehui)

Winding high-speed rail carriages (33, Jiang Zehui)

Bamboo winding composites is a new bio-based matedal independently developed by China with the independent and complete intellectual property rights.Bamboo winding composites is a green,renewable and environmental material with light weight and high strength,which has the characteristics of flame retardance,thermal insulation,energy saving and IOW carbon emission.It can be widely used in the fields of **transportation, municipal administration,water conservancy,construction and military industry**,and its industry chain runs through the primary,secondary and tertiary industries of the national economy.Bamboo winding composites has been developed since 2007,which has undergone the initial sample production and detection,small sized trial and provincial 1evel appraisal of new products to the ministerial 1evel demonstration and application ,pilot production line development and evaluation as ministerial 1evel achievements,finally to the industrialization equipment in operation,the construction and operation of demonstration manufacturing plant.Meanwhile,the compilation and implementation of industry standards and national standards for the product,the recognition and endomement of the technology and project by related ministries and commissions have also been completed,which marks the completion of all the ground work of a new industry before industrialization. [33, Jiang Zehui]

Video:https://www.youtube.com/watch?v=K-sY26Dr4mk

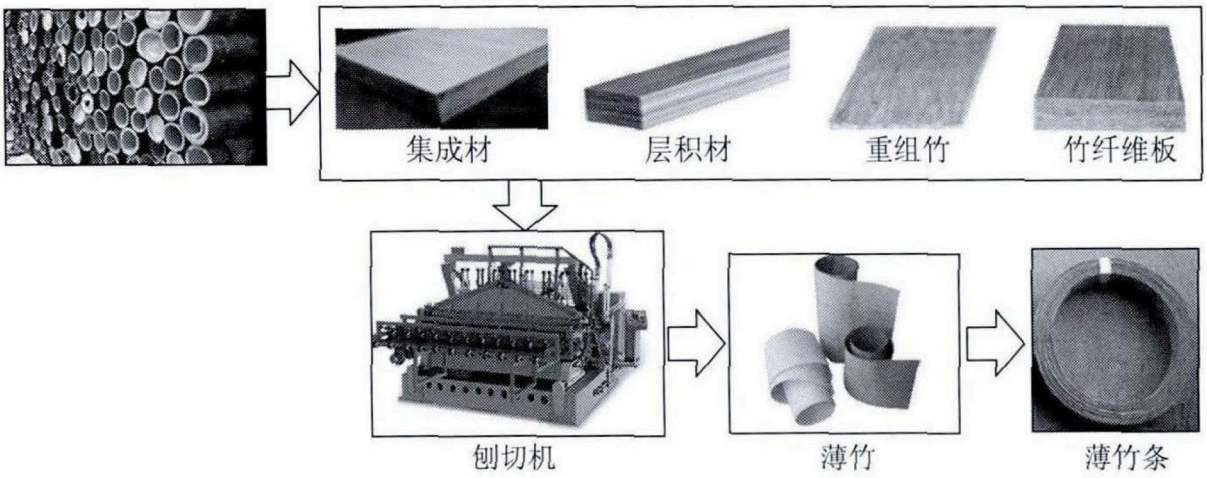



图 1　薄竹材加工示意图

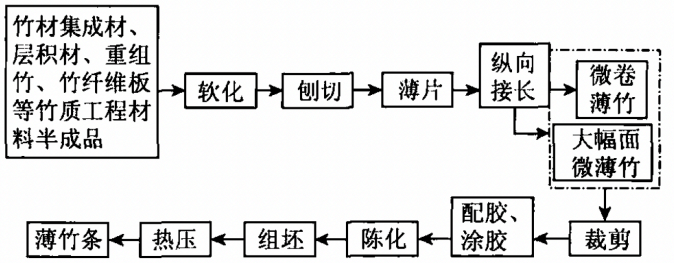



图 2　薄竹材加工流程图

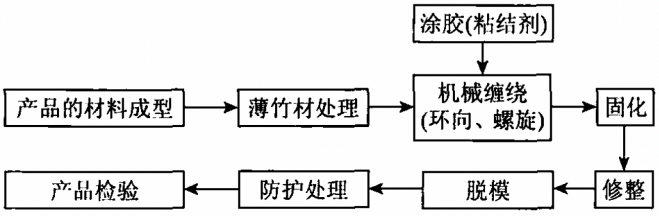
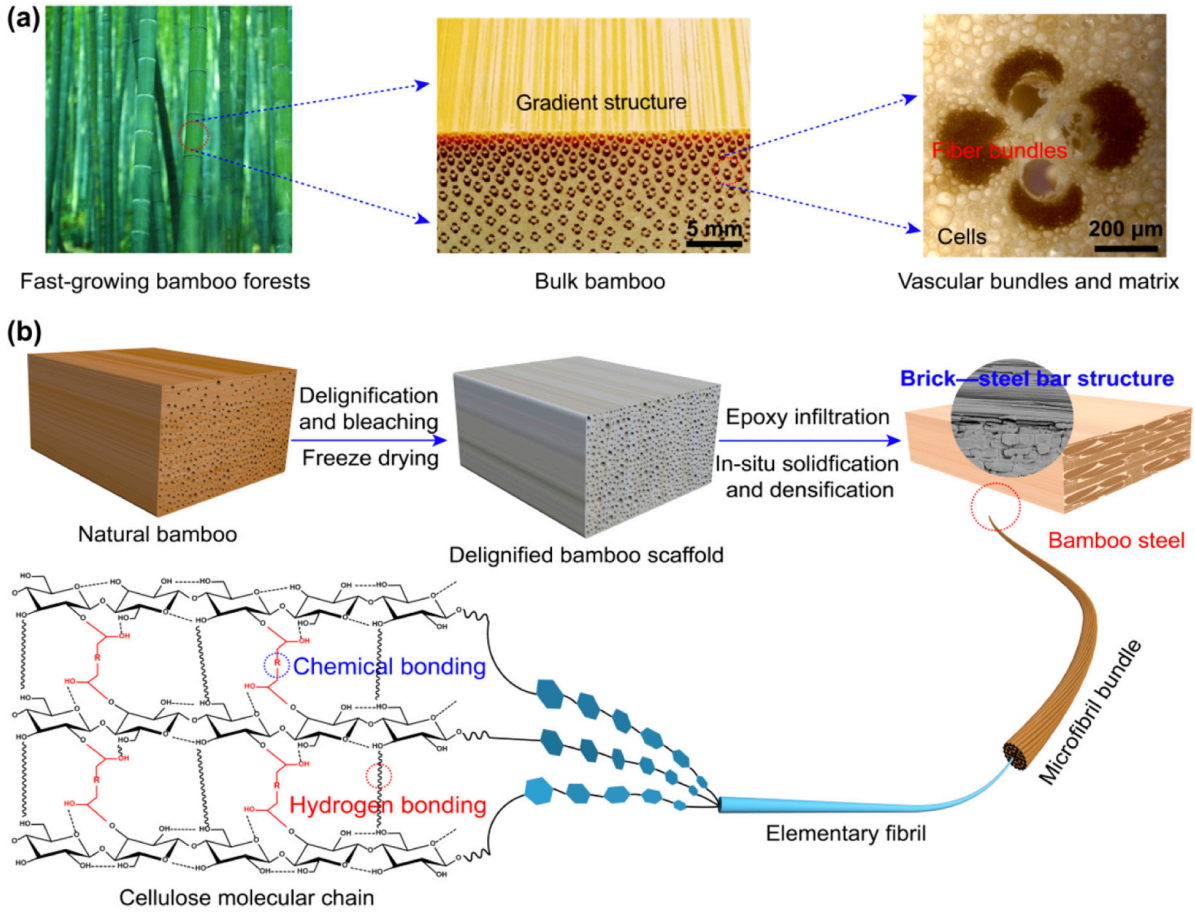



图 3　薄竹缠绕工艺流程

(34,Song Shasha)

## 02-Bamboo Steel



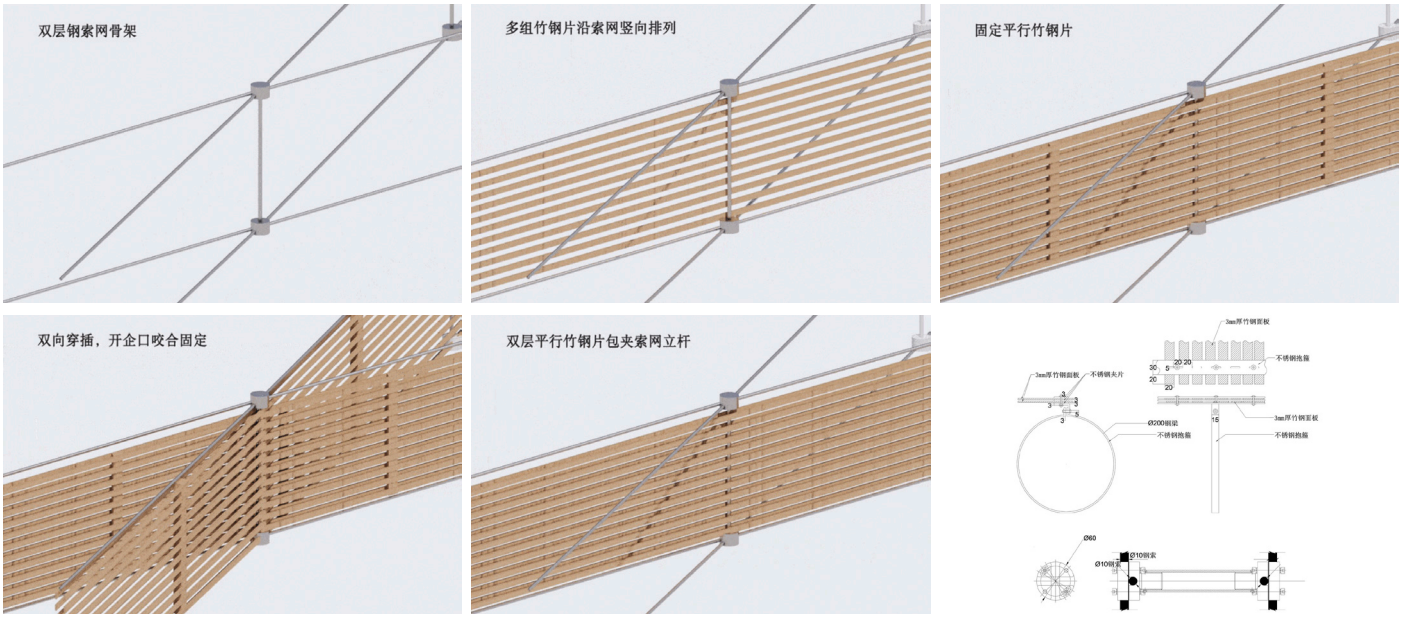

(a) Gradient structure of natural bamboo.

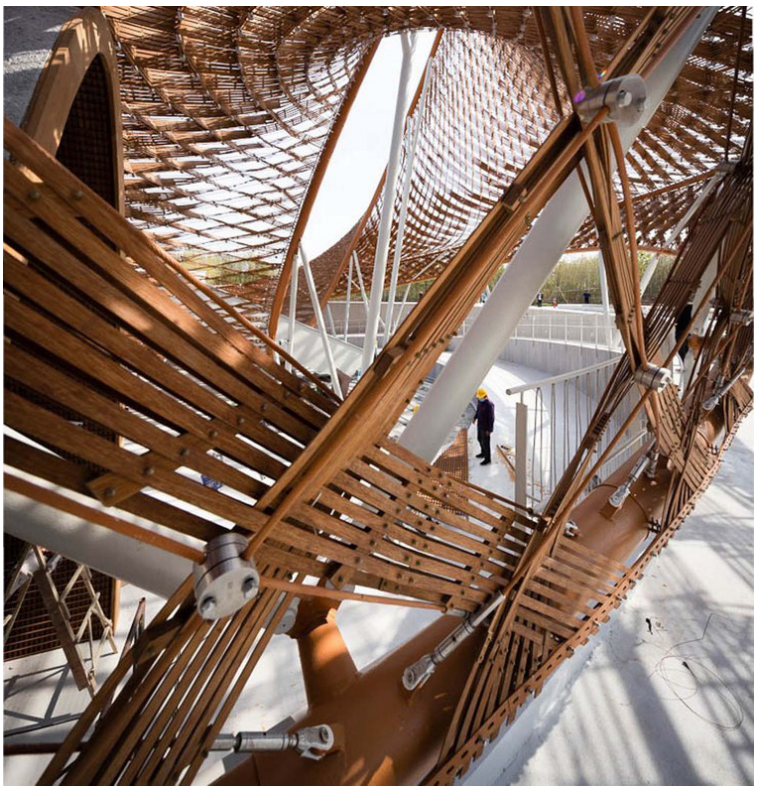
(b) Schematic illustration of the design and the **fabrication process** of bamboo steel.

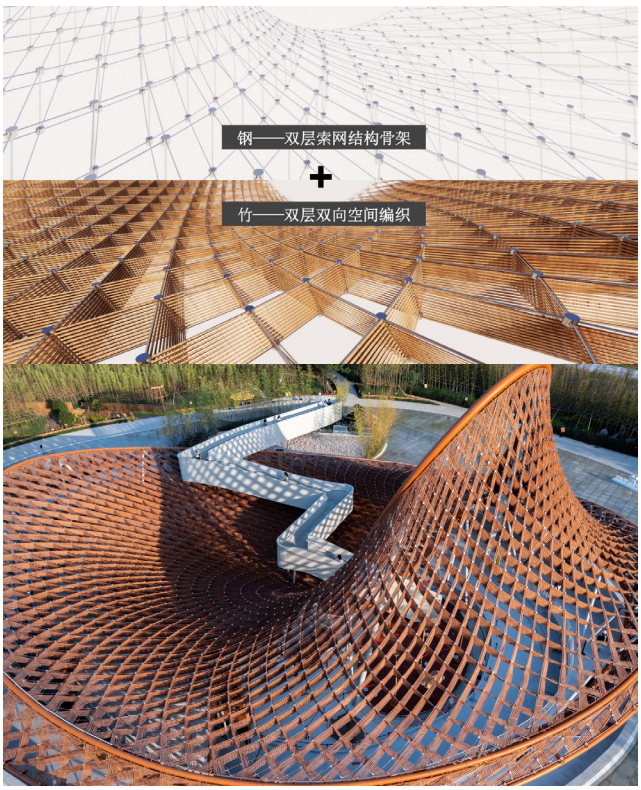
(35,Wang YouYong)

In this work, a high-performance epoxy composite with high-content bamboo fibers of the well-preserved bamboo structure, named as **bamboo steel**, is demonstrated with a facile yet effective top–down approach.The lignin and hemicellulose in bulk bamboo, which seldom contribute to the strength, were first removed by a **chemical delignification** and bleaching process. Then, the porous bamboo as the reinforcement scaffold was directly impregnated with the **epoxy resin**. Finally, the bamboo steel was fabricated with a hot-pressing-induced **densification and in situ solidification process**, which exhibits remarkable mechanical properties including a tensile strength of 407.6 MPa, a record flexural strength of 513.8 MPa, and a high toughness of 14.08MJ/m3. [35,Wang YouYong]

**Bamboo and Rattan Pavilion of the 10th China Flower Expo / Creation Research Center of Huajian Group Shanghai Architectural Science and Technology Innovation Center.** [https://www.archdaily.com/]



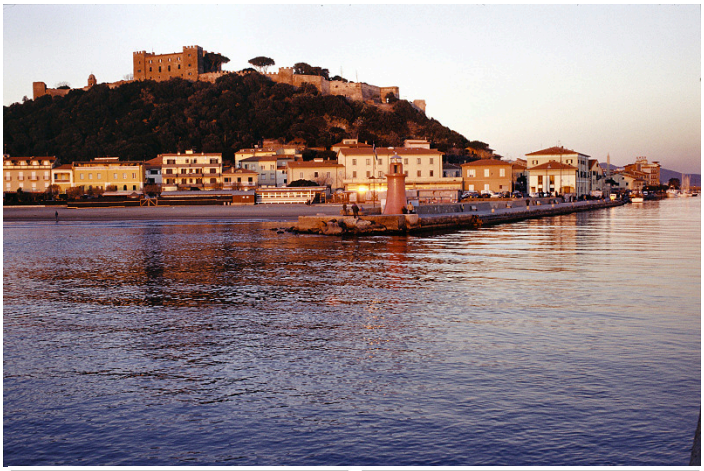



(Archdaily)

# 6.Bamboo Architectural Design Proposal

Castiglione Della Pascaia is a beautiful seaside city in the remote area of Tuscan, where Forever Bamboo project is trying to plant bamboo forests in there. Less population and inconvenient transportation let this area lose attraction for younger people. The site for designing bamboo farming area and greenhouse is located on northern side of city, closed to river and swampland. After fully understanding urban tissues and urban typology and components, the design proposal would like to consider urban metabolism system, for which paper, bamboo bio-waste, plastic, and clothes can be collected from community, and greenhouse can reuse sunlight and rainfall, generate vegetables and fishes for local. Also, park, pavilion, benches, and playground spaces provide multi-function uses for local inhabitants. Construction will be started from planting bamboo in the area beside greenhouse, harvesting bamboos after 3 years in the period of mature. And then it can be use after treating them completely. The second step is to collect waste and transfer to bamboo reinforced paper crates, plastic coating, curtains, and fertilizers. After that, it will work with local school and create a workshop for students, starting to fix steel skeletons, bamboo frames, and plastics. Finally, it will become a creative spaces not only for generating fish or vegetable, but providing spaces for eating, playing, and cooperating with schools as education classrooms.

# 6.1 Location&Context

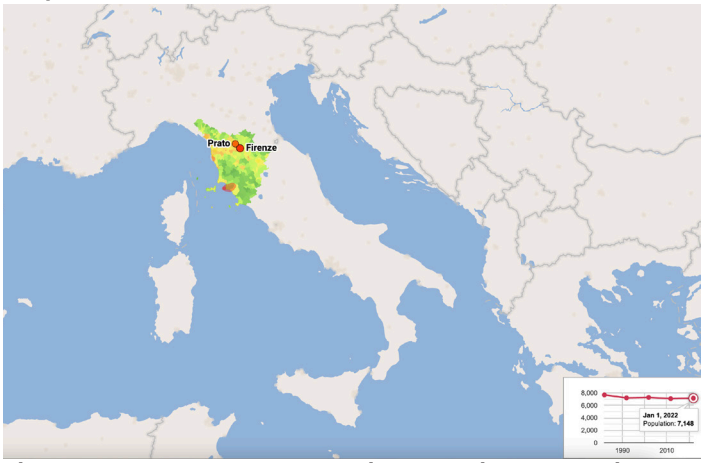


| TERRITORY | | DEMOGRAPHIC DATA (YEAR 2020) | |
|---|---|---|---|
| Region | Toscana | Inhabitants (N.) | 7,134 |
| Province | Grosseto | Families (N.) | 3,658 |
| Sign Province | GR | Males (%) | 49.2 |
| Hamlet of the municipality | 12 | Females (%) | 50.8 |
| Surface (Km2) | 209.10 | Foreigners (%) | 8.1 |
| Population density (Inhabitants/Kmq) | 34.1 | Average age (years) | 51.0 |
| | | Average annual variation (2015/2020) | -0.48 |

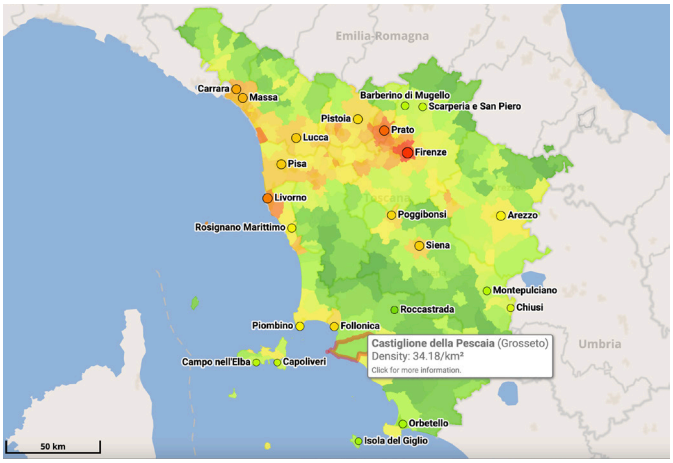
(https://ugeo.urbistat.com/AdminStat/en/it/demografia/dati-sintesi/castiglione-della-pescaia/53006/4)

## Castiglione della Pescaia

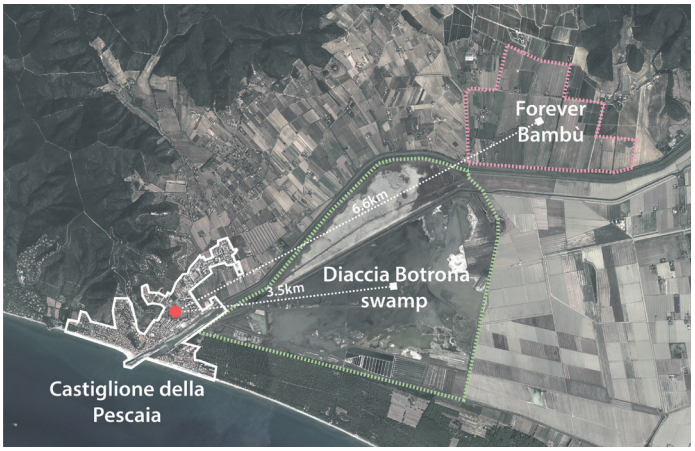
This place seems suspended in time. Castiglione della Pescaia, a small and sweet village in the province of Grosseto. There are **7148 inhabitants** living in this city in 2022. They call it "little Switzerland", probably because it sits quietly, with its intersection of characteristic alleys. Castiglione della Pescaia gives the impression of flanking the coast rather than being part of it. Along the road that leads to the beaches there are many small fishing boats, some of which are seen moving away towards the open sea. (https://www.italiani.it/en/Castiglione-della-Pescaia-very-sweet-Tuscany/?cn-reloaded=1)

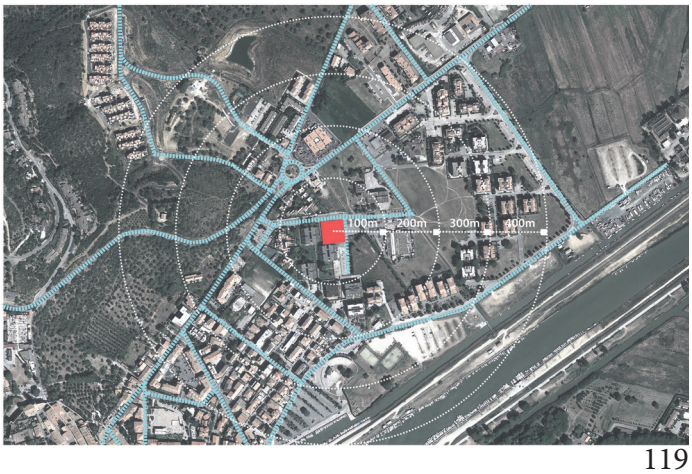



(https://www.citypopulation.de/en/italy/toscana/)

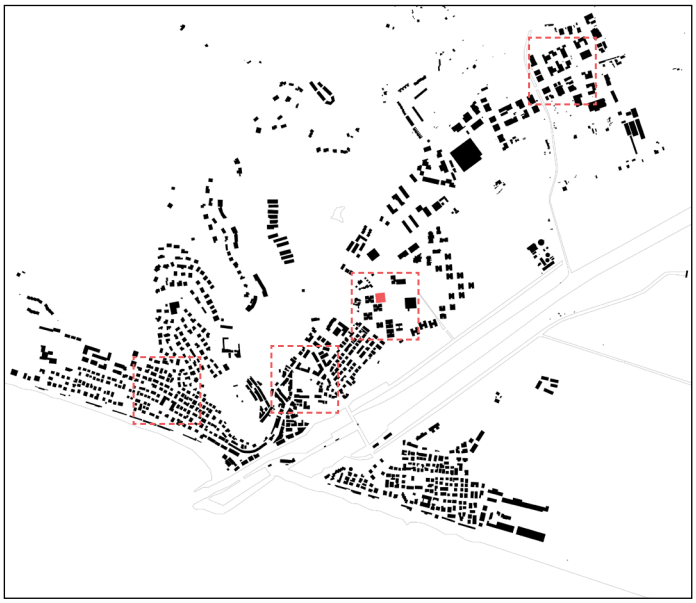



## Site Location

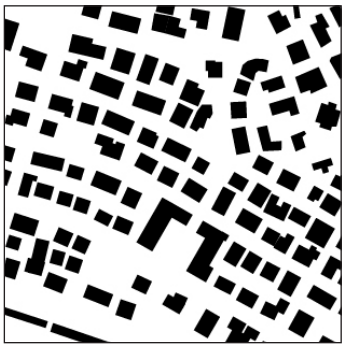


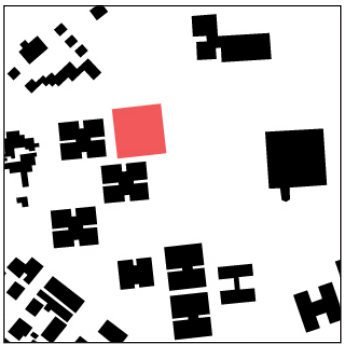



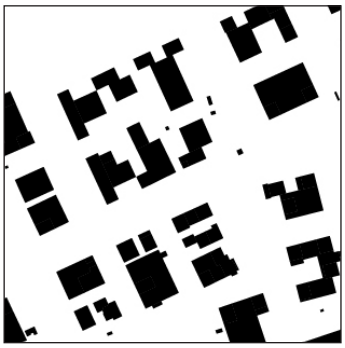
## Urban scale-Morphology



## Urban tissues







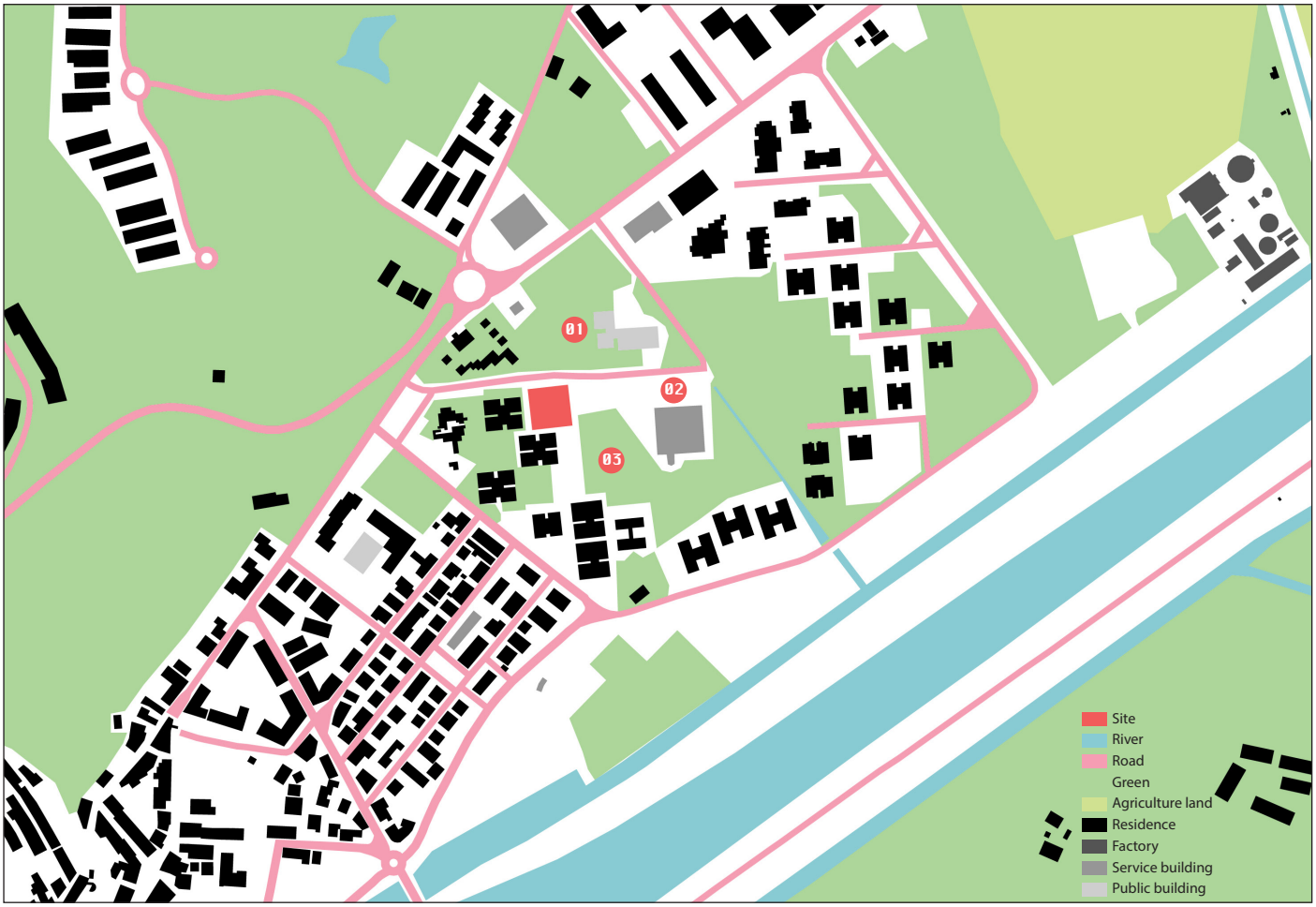


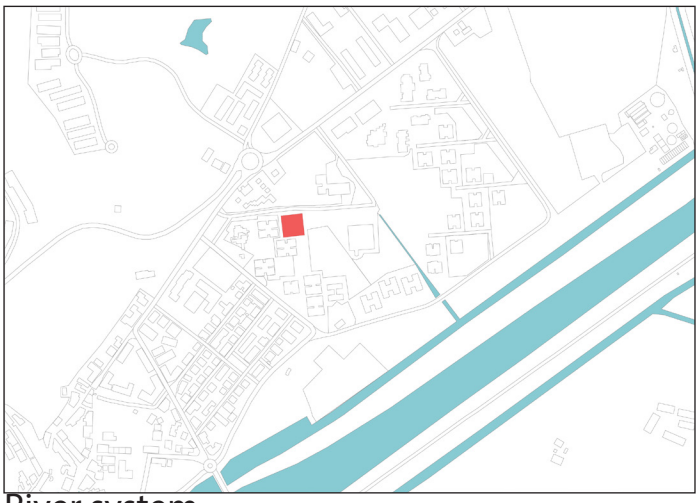

## Context scale-Typology

01-School (google)

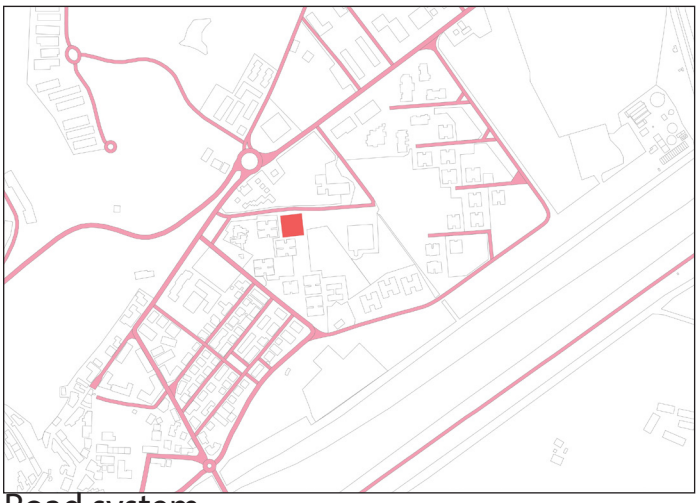
02-Supermarket (google)

03-Greenness (google)

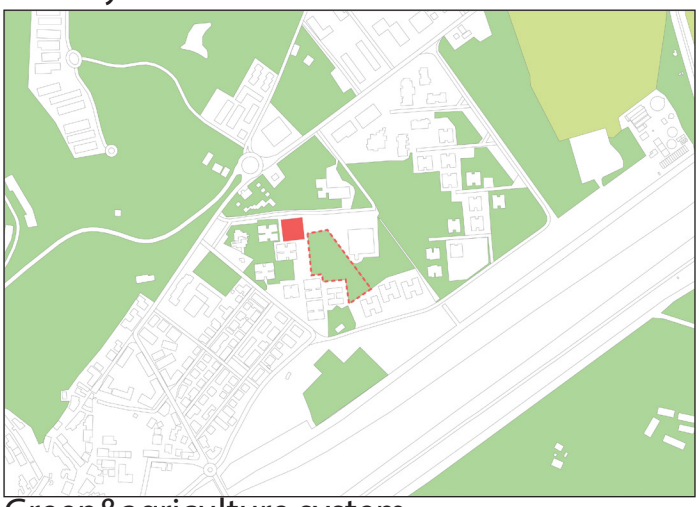


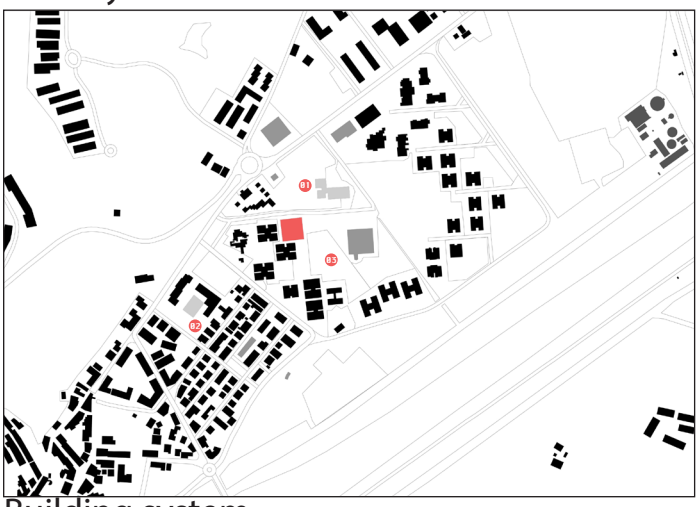
River system



Road system



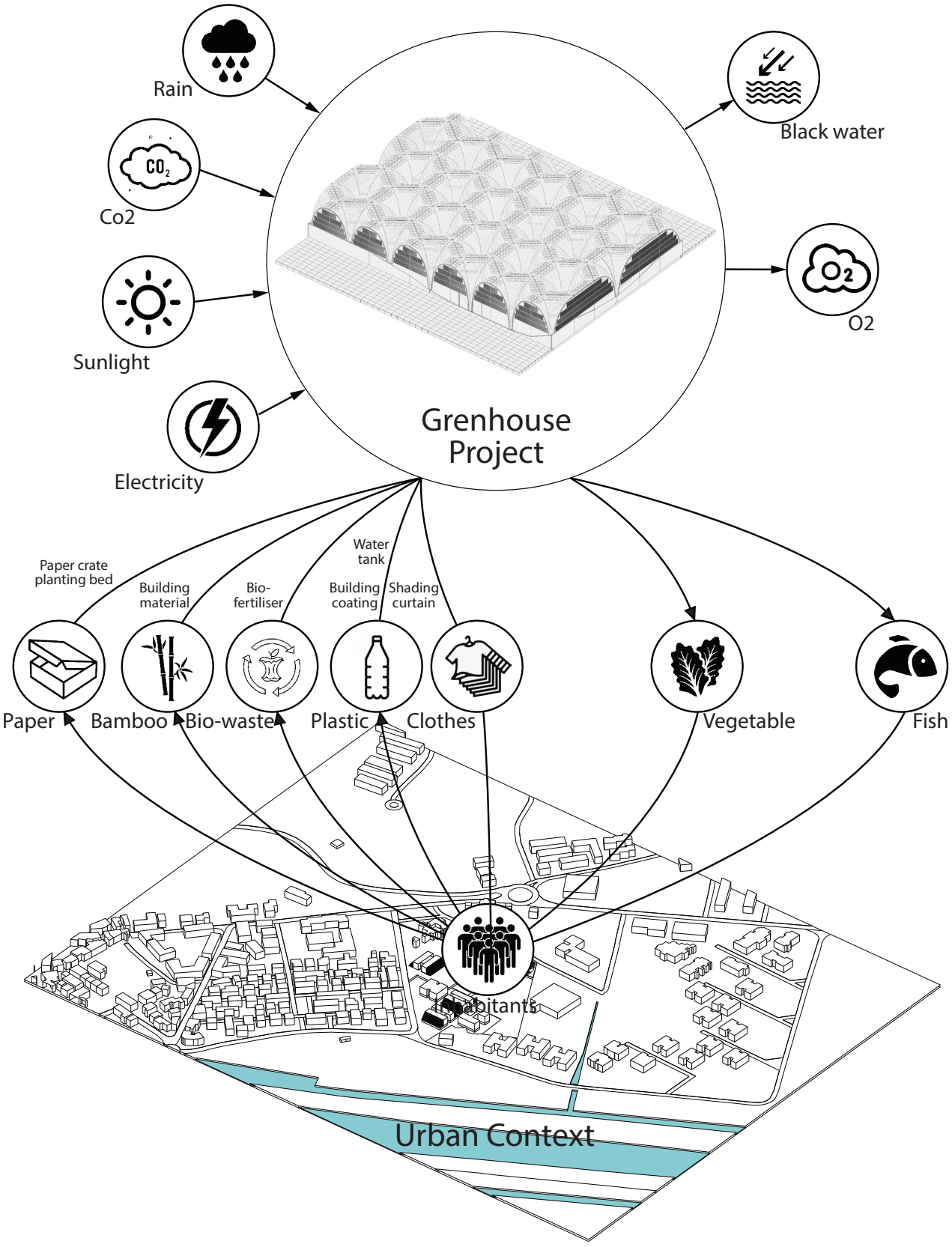
Green&agriculture system



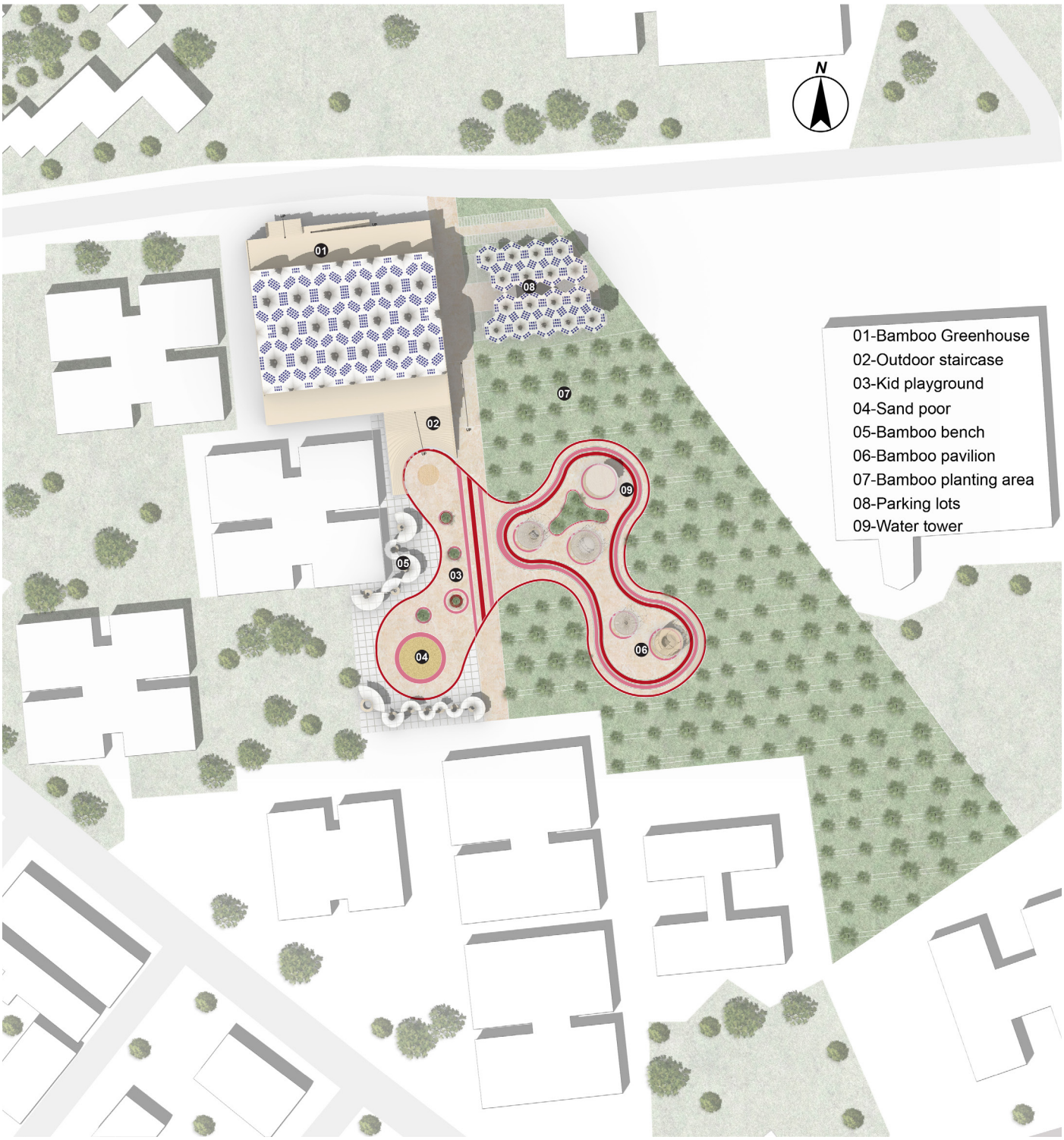
Building system

# 6.2 Design concept

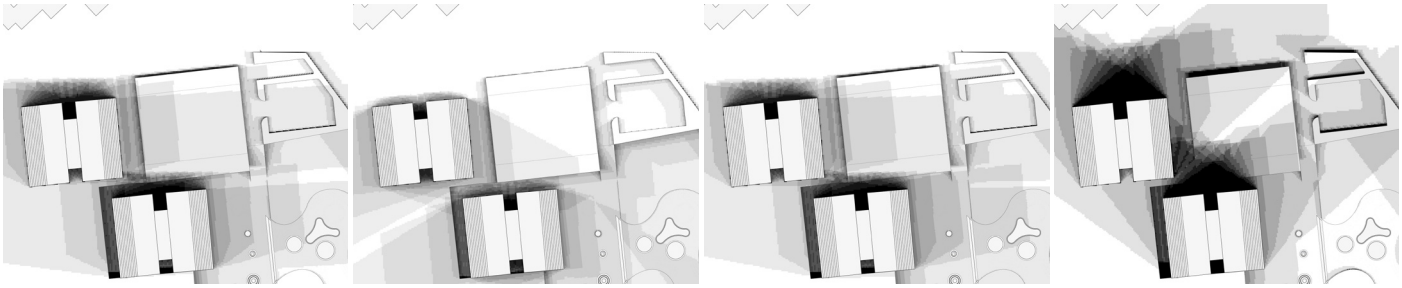
## Urban matebolism



## Masterplan



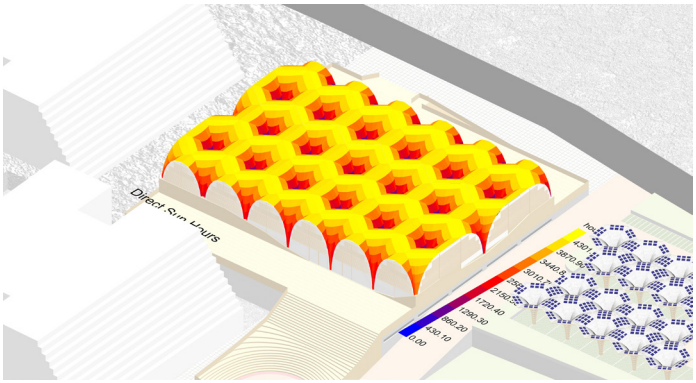

## Shadow in site

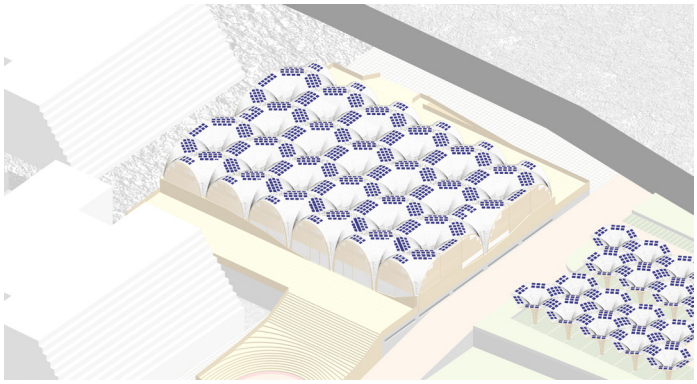


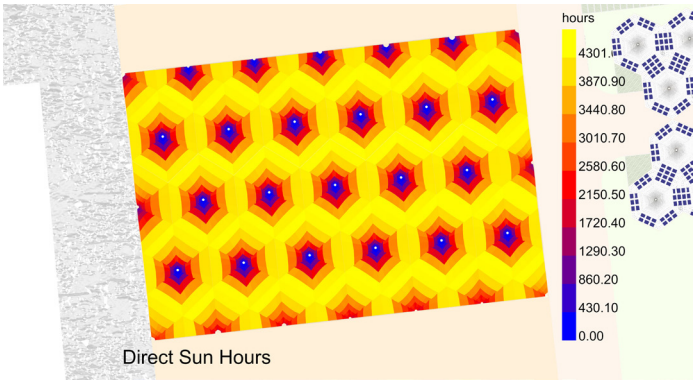
21/03 22/06 21/09 22/12

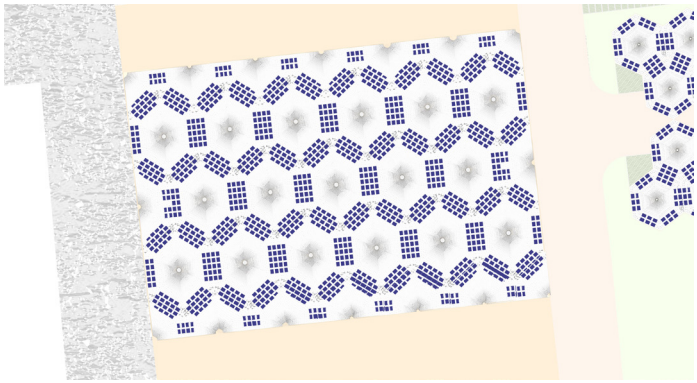
# Greenhouse Roof

## 01-Electricity system







Direct Sun hours during a whole year

Solar Panel on the Roof

PV Modules Size: 420*330*3 mm PV Modules Quantity: 1316
Maximum power(Pmax):20W

PVGIS-5 estimates of solar electricity generation:

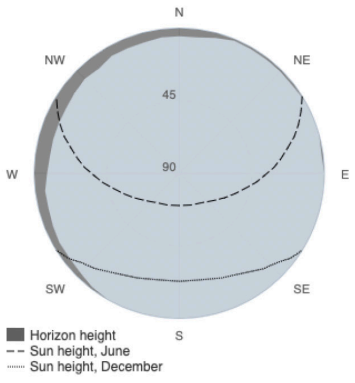
**Provided inputs:**

| | |
|---|---|
| Latitude/Longitude: | 42.768,10.886 |
| Horizon: | Calculated |
| Database used: | PVGIS-SARAH2 |
| PV technology: | Crystalline silicon |
| PV installed: | 26.32 kWp |
| System loss: | 14 % |

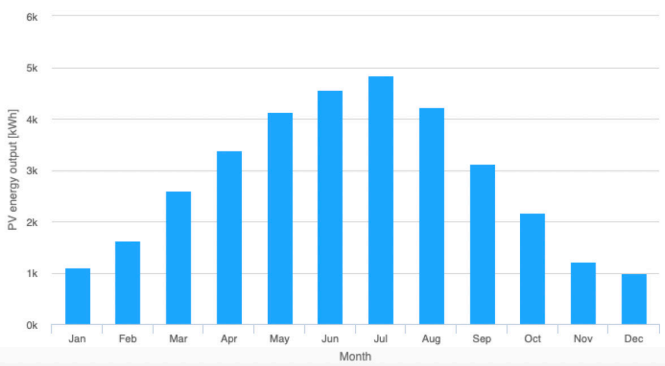
**Simulation outputs**

| | |
|---|---|
| Slope angle: | 0 ° |
| Azimuth angle: | 0 ° |
| Yearly PV energy production: | 33938 kWh |
| Yearly in-plane irradiation: | 1616.9 kWh/m² |
| Year-to-year variability: | 859.33 kWh |
| Changes in output due to: | |
| Angle of incidence: | -3.69 % |
| Spectral effects: | 0.44 % |
| Temperature and low irradiance: | -4.14 % |
| Total loss: | -20.25 % |

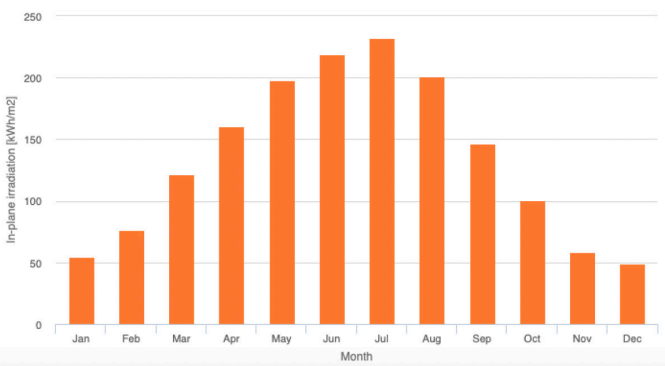
**Outline of horizon at chosen location:**



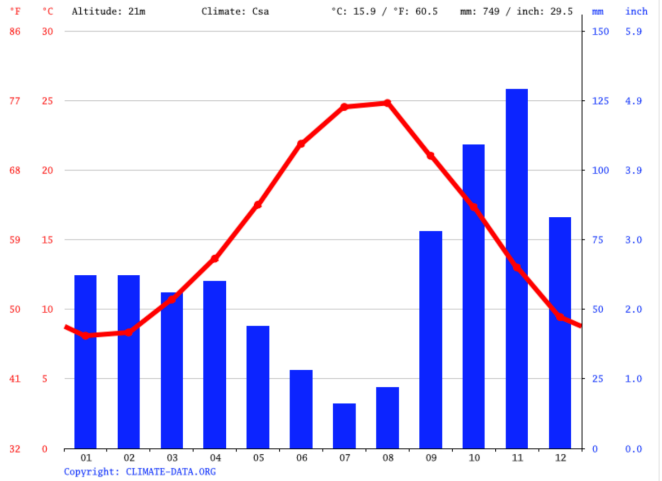

**Monthly energy output from fix-angle PV system:**



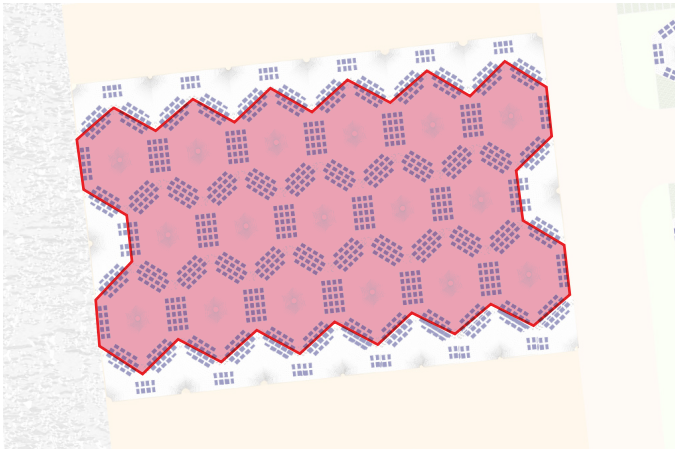

**Monthly in-plane irradiation for fixed-angle:**



## 02-Rain recycling system




https://en.climate-data.org/europe/italy/tuscany/castiglione-della-pescaia-500283/

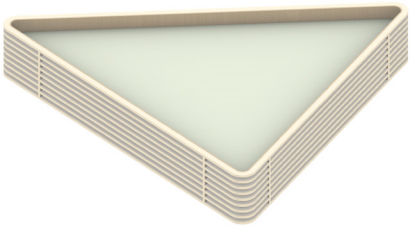


Catchment area: 707.2 m2;
Annual rainfall: 749 mm;
Collection efficiency: 90%;
Rain fall harvest: 476.72 m3:

## Local Recycling

### 01-Paper

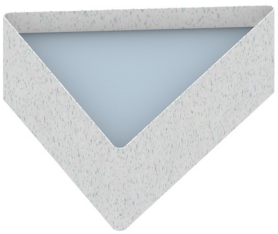
Paper crates& Laminated Bamboo



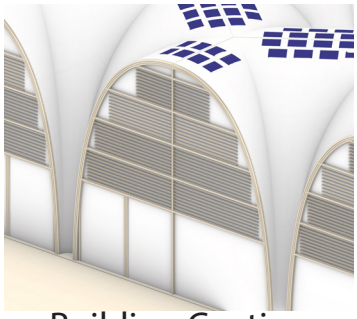
Planting bed

### 02-Plastic

Plastic bottles

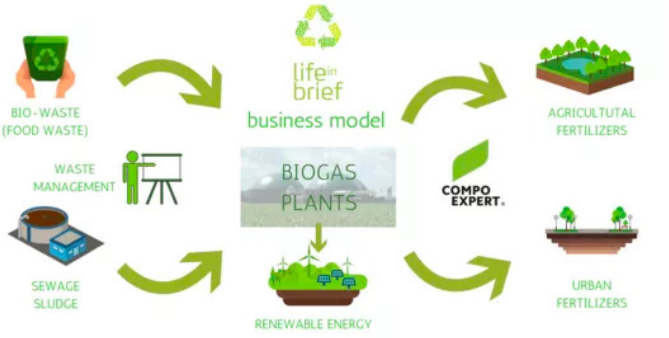


Fish Tank



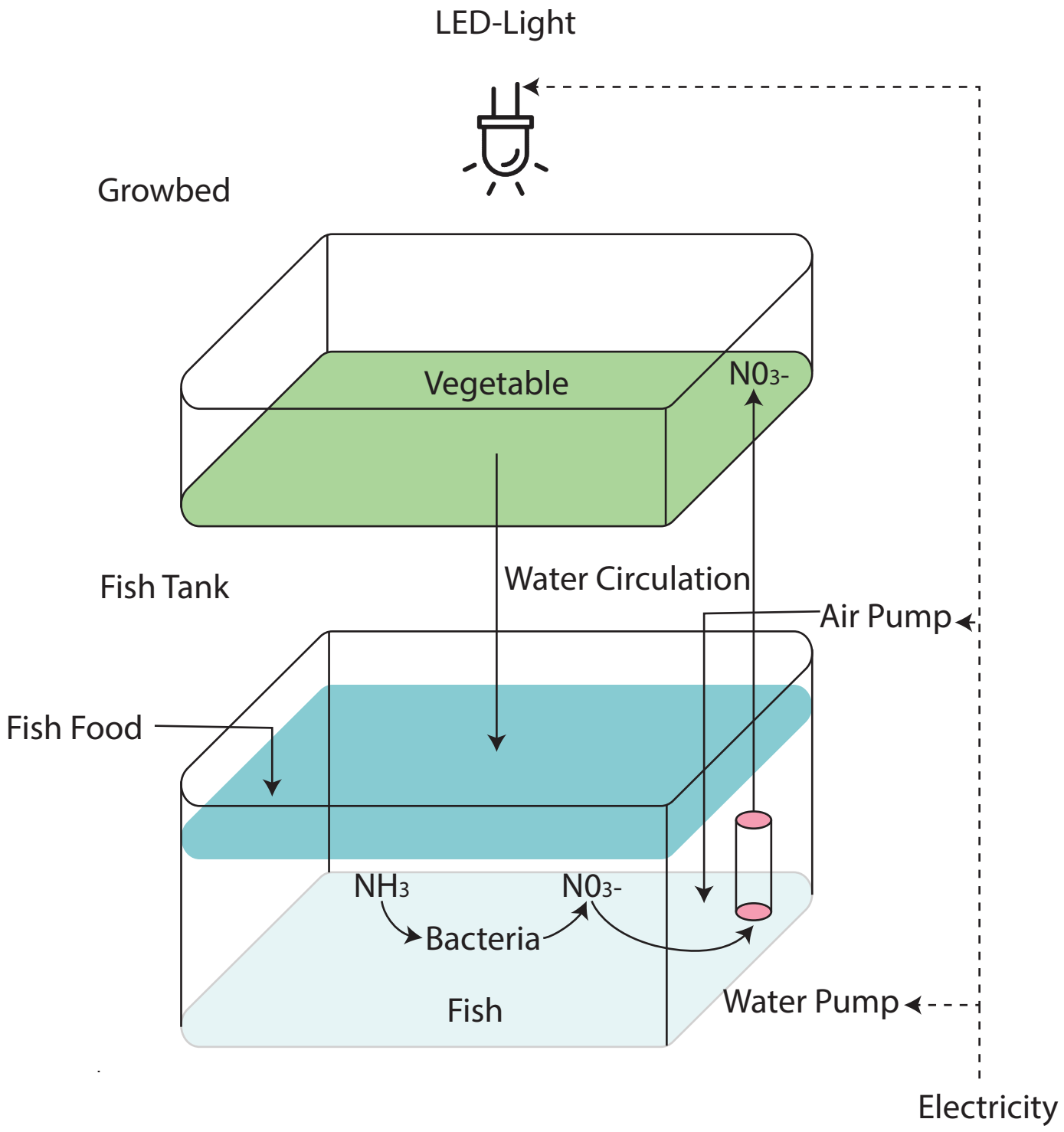
Building Coating

### 03-Bio-waste




New Fertilizers from Biowaste-Project:LIFE In-BRIEF (LIFE14 ENV/ES/000427)

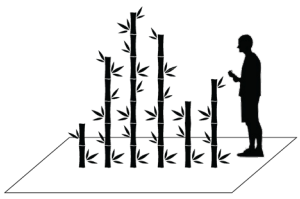
**Aquaponic system in project**



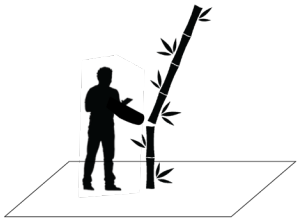

| Element | Feature | Detail |
|---|---|---|
| Growbed | 46 units Bamboo-reinfored paper crates(0.798 $m^3$/unit) | 36.708 $m^3$ |
| Fish Tank | 23 units x Recycled Plastic Tanks(1.596 $m^3$/unit) | 36.708 $m^3$ |
| Vegetable | Tomato, Mint, Chilly, Lettuce, Basil(15-30 kg/ $m^3$/ year) | 550.62-1101.24 kg/ year |
| Fish | Monosex Tilapia (Oreochromis niloticus) and Pangasius (Pangasiandon hypophthalmus)50/$m^3$ x 0.75kg x 90% x 2 circles | 2477.79 kg/ year |
| Fish Food | Bio-fertiliser | - |
| LED-Light | 46 units x 2 x 15w red/blue LED x 6 hours/ day | 3022.2 KW/ year |
| Water Pump | 23 units x 10.4W x 12 hours operation time | 1047.7 KW/ year |
| Air Pump | 23 units x 45W x 24 hours operation time | 9066.6 KW/ year |
| Electricity | LED-Light+Water Pump+Air Pump | 13136.5 KW/ year |

## Construction process

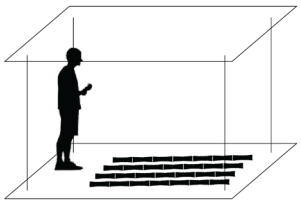
### Phase 01: Preparing Bamboo



Planting bamboo



Harvesting bamboo

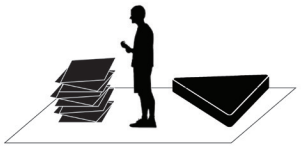


Treatment

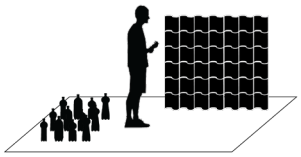
Shipping bamboo

### Phase 02: Collecting Urban Waste

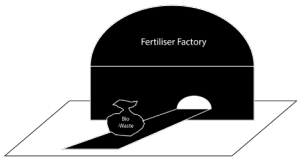

Recycling waste



Paper crate



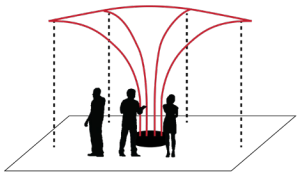
Plastic facade



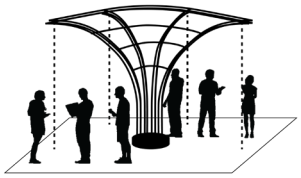

Fertiliser

### Phase 03: Constructing Building

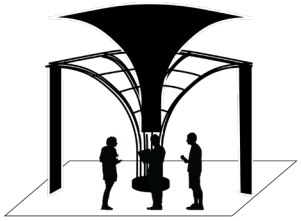
Students workshop



Steel skeleton

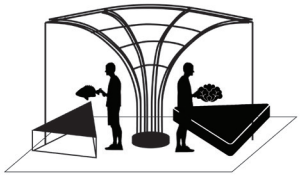


Baoboo frames

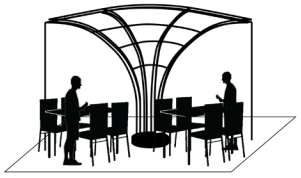


Plastic surfaces

### Phase 04: Operating for community

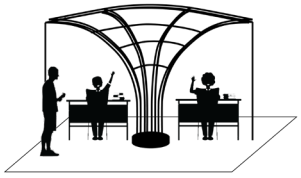


Fish&vegetable



Eating

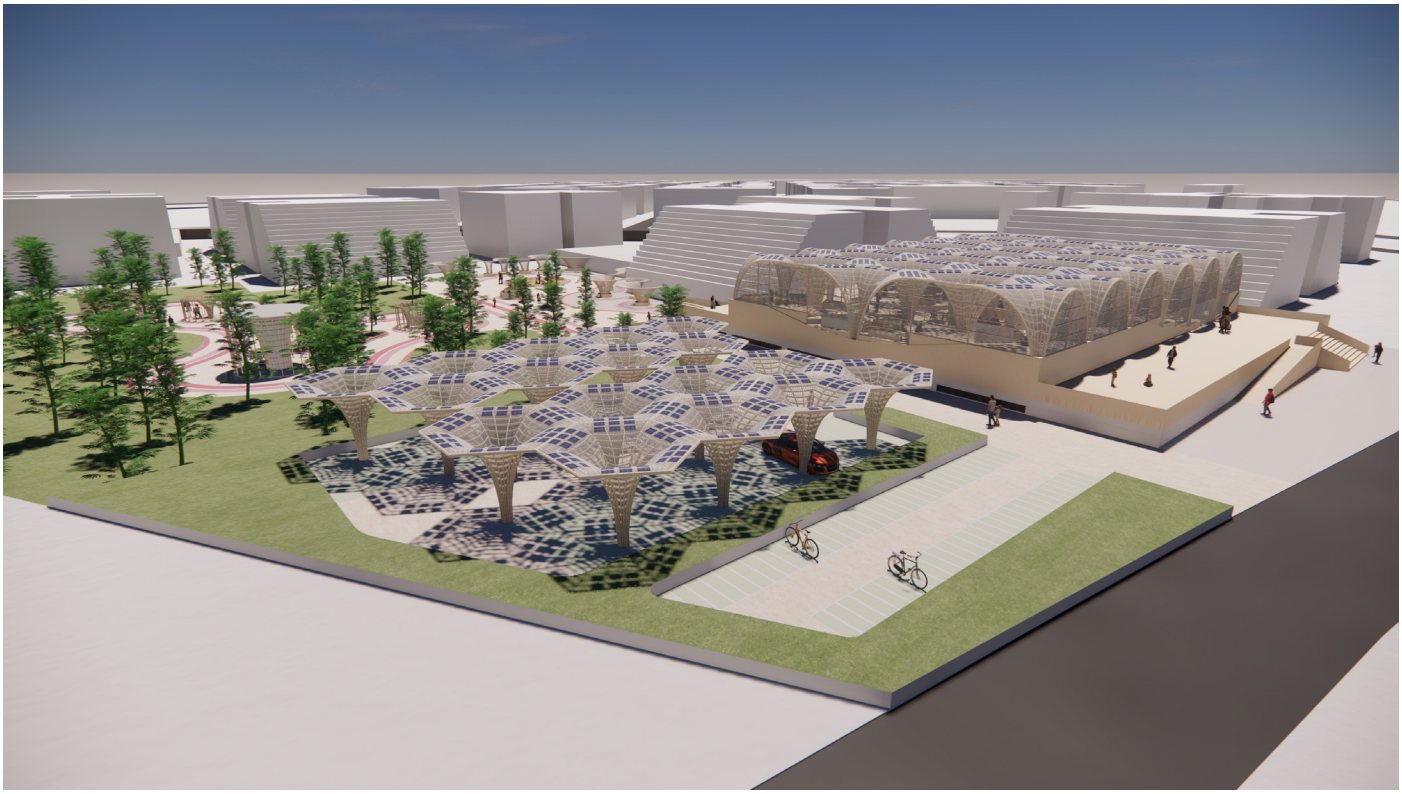
Playground



Education

## Aerial view 01

## Aerial view 02



## Aerial view 03

## Aerial view 04

## Landscape 01

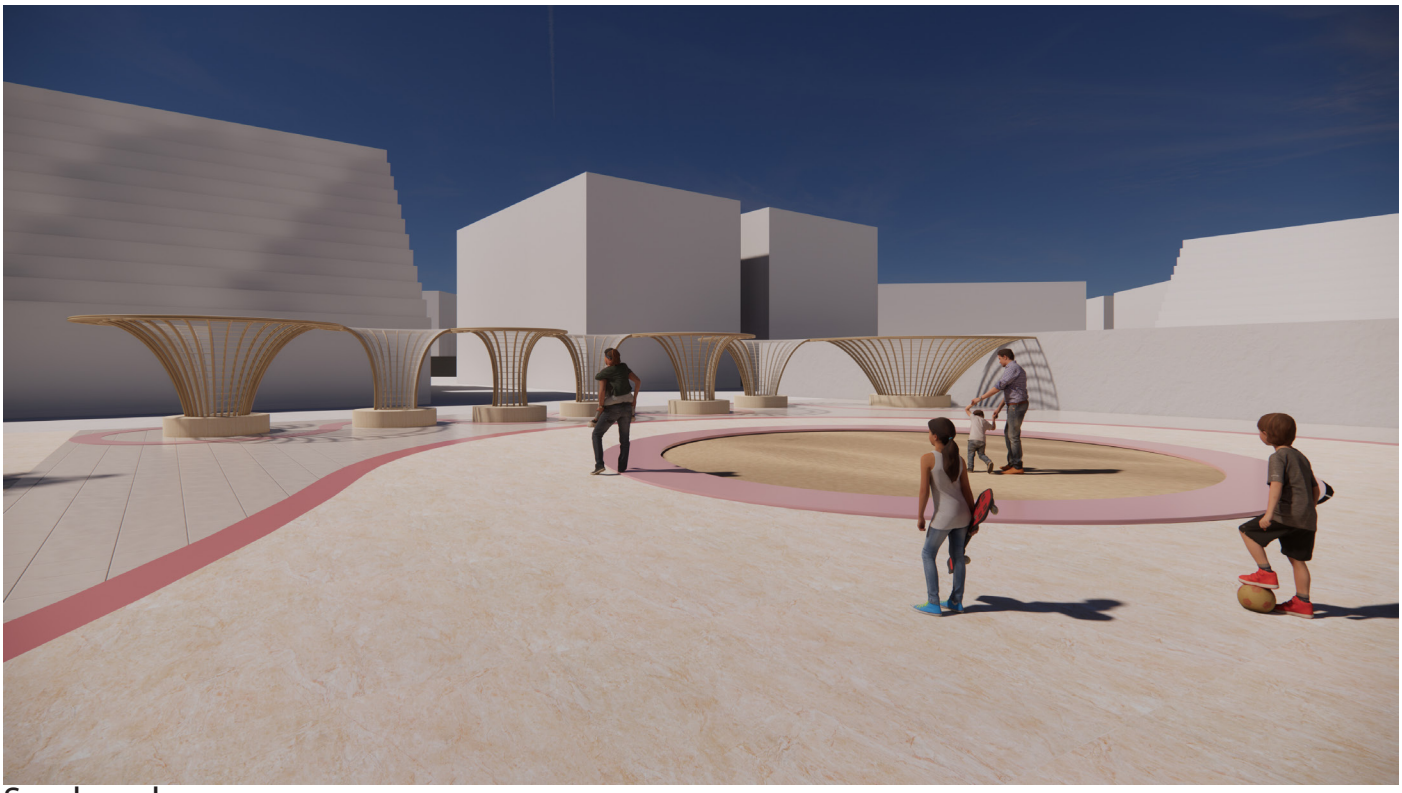
Outdoor staircase

Outdoor staircase

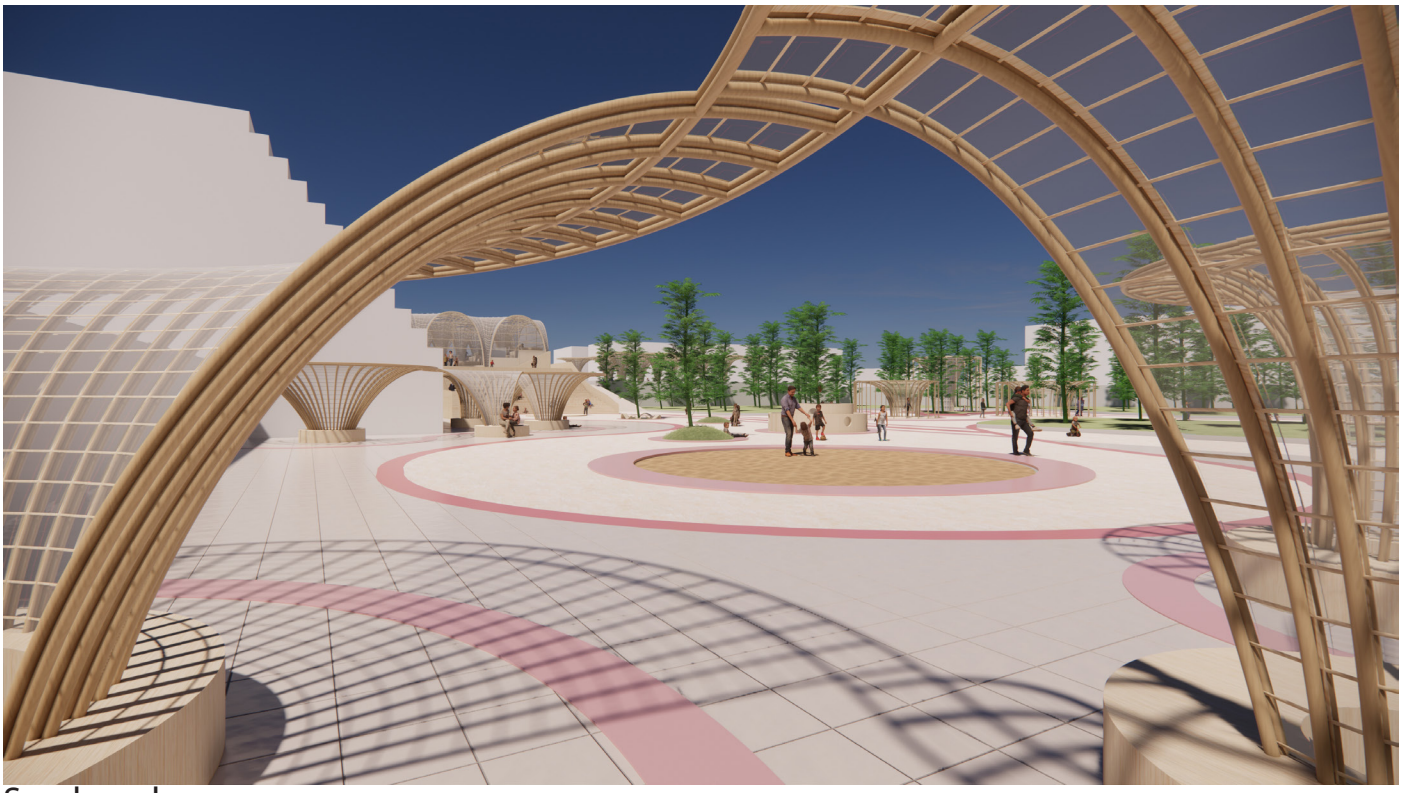
Outdoor staircase

## Landscape 02

Playground

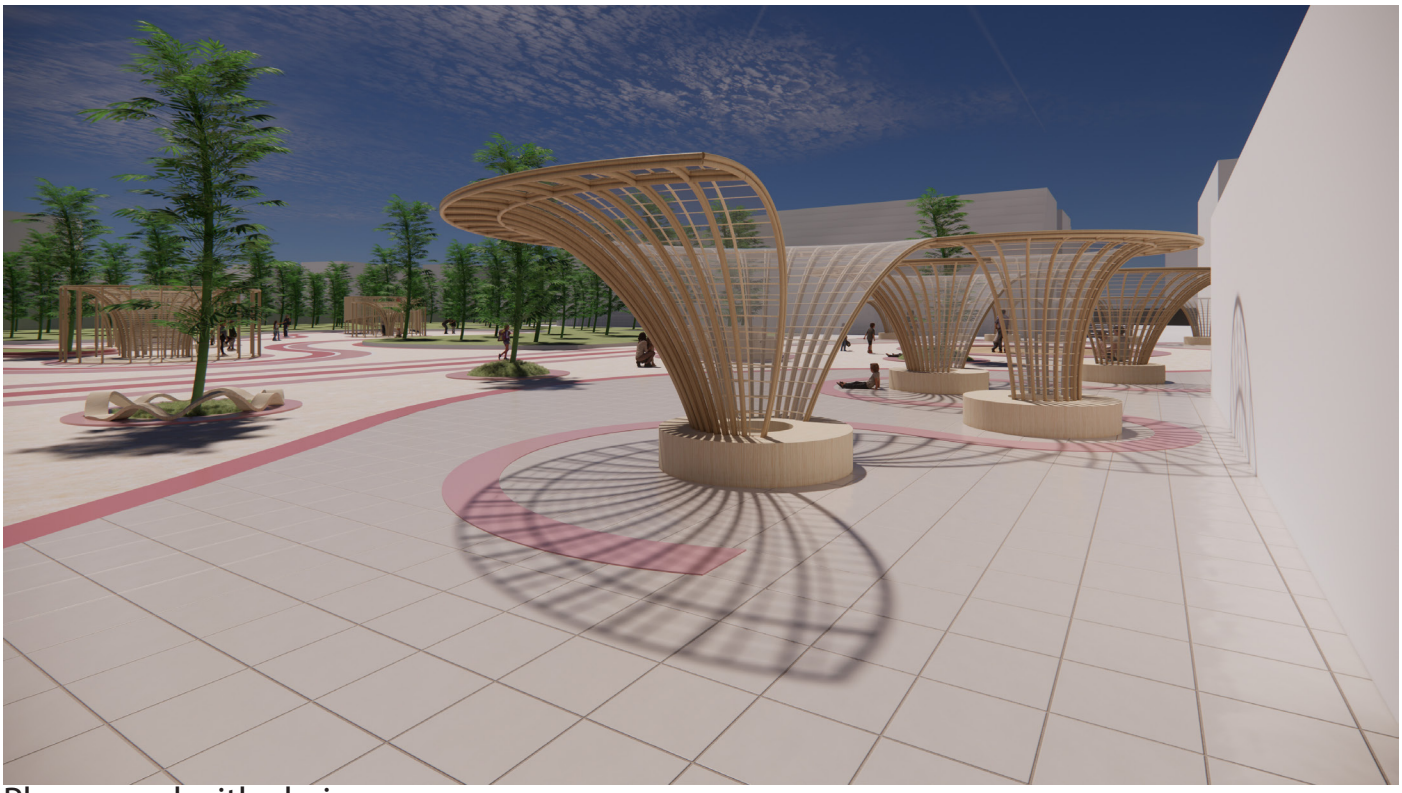


Sand pool



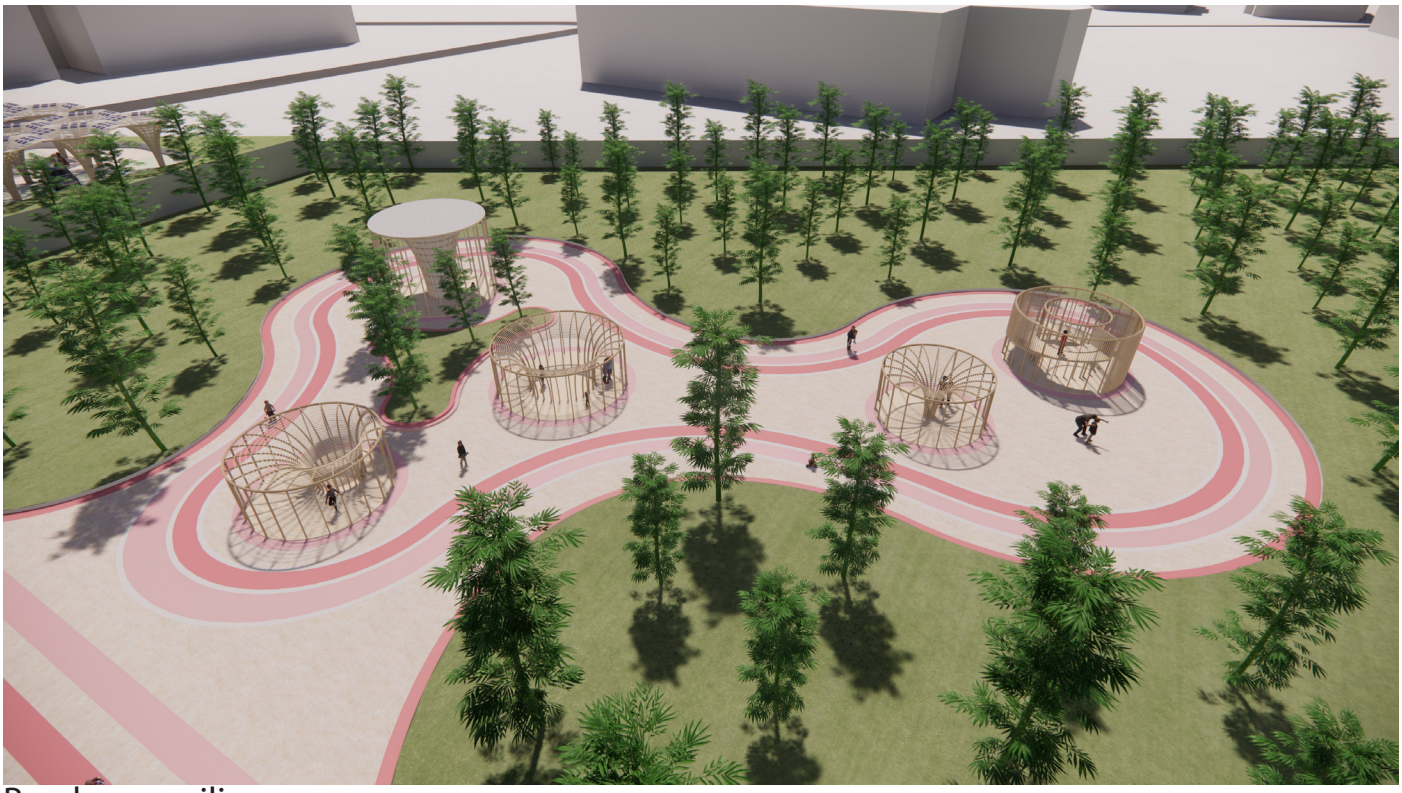
Sand pool

Sidewalk



Playground with chairs

## Landscape 03

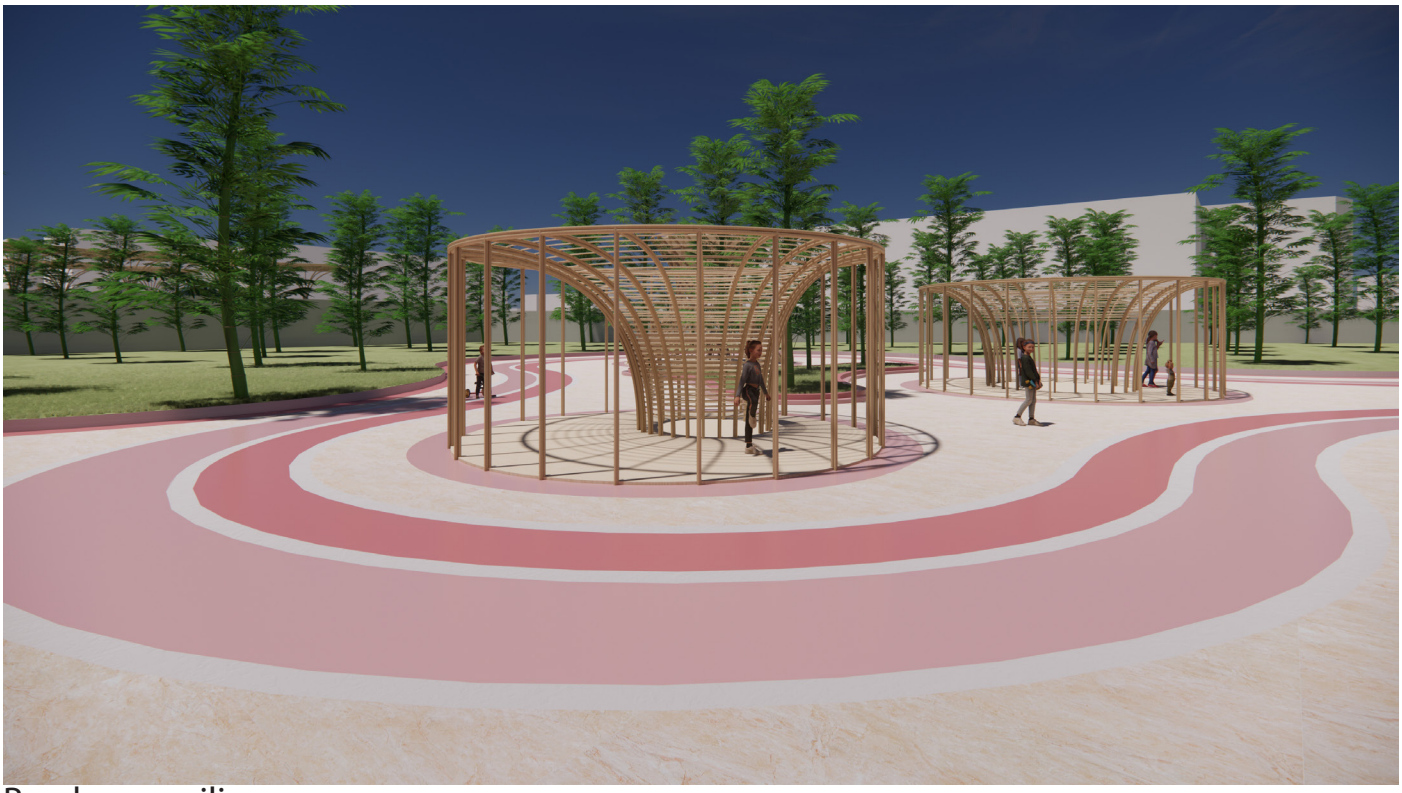


Bamboo pavilion

Water Tower

Bamboo Tower

Bamboo Tower

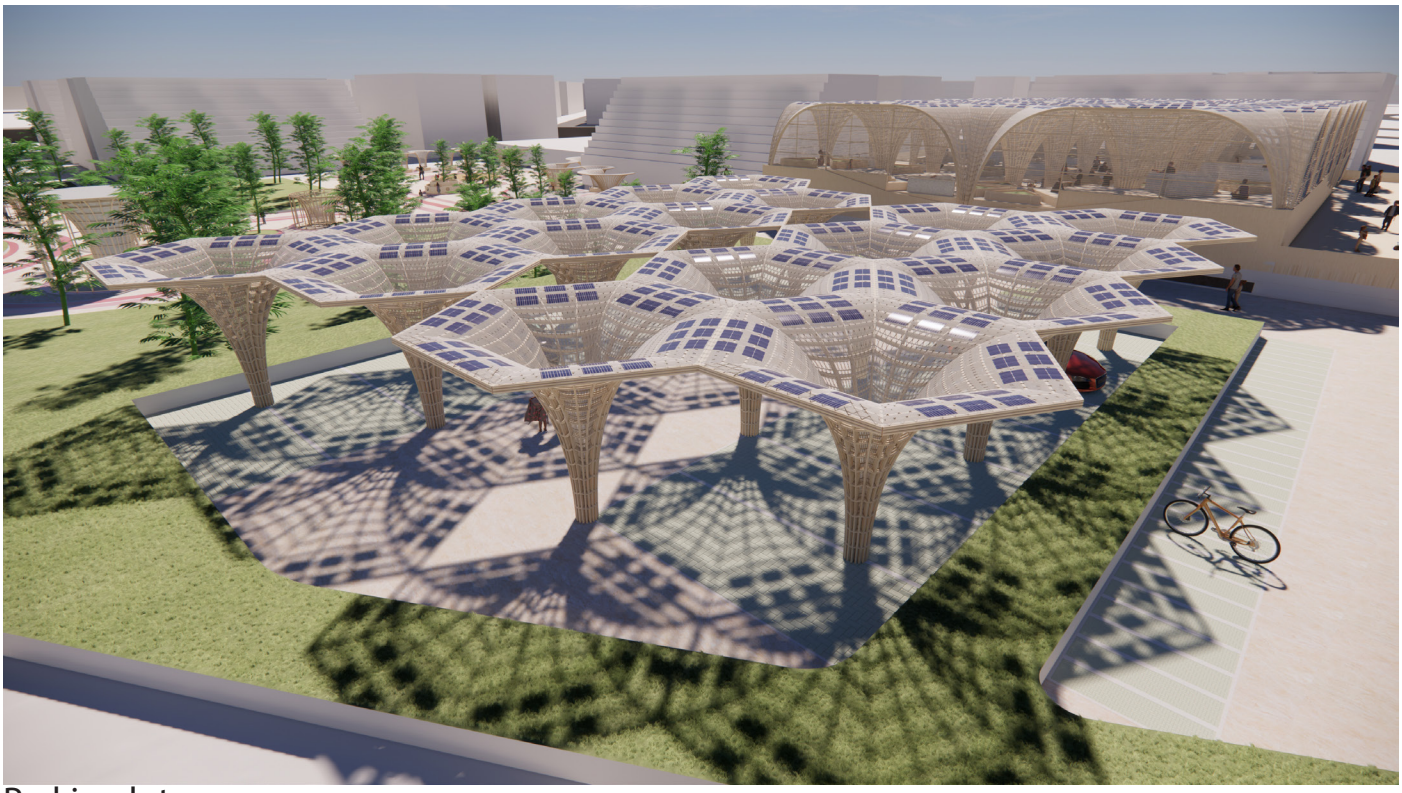


Bamboo pavilion

Bamboo pavilion

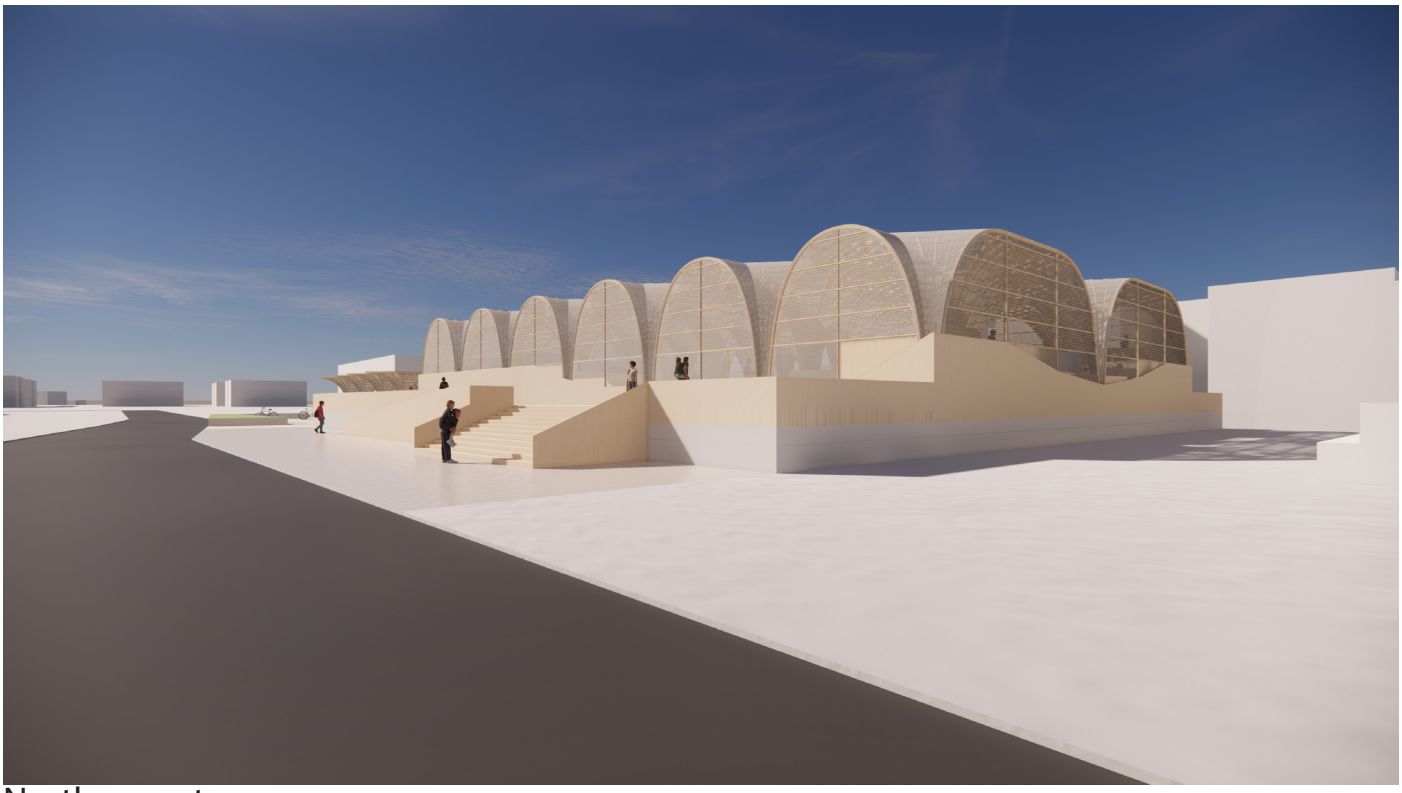
## Landscape 04

Parking lots

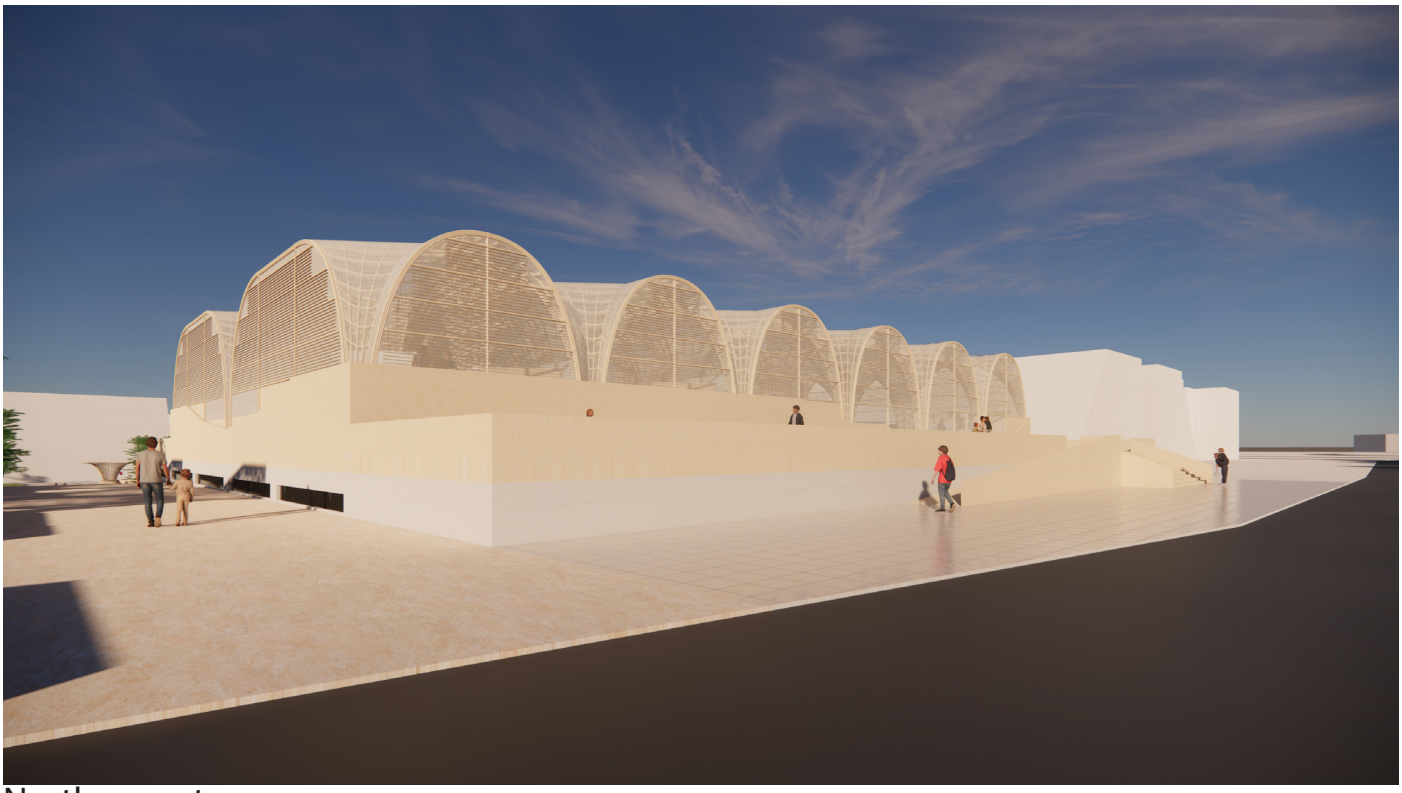


Parking lots

## Greenhouse

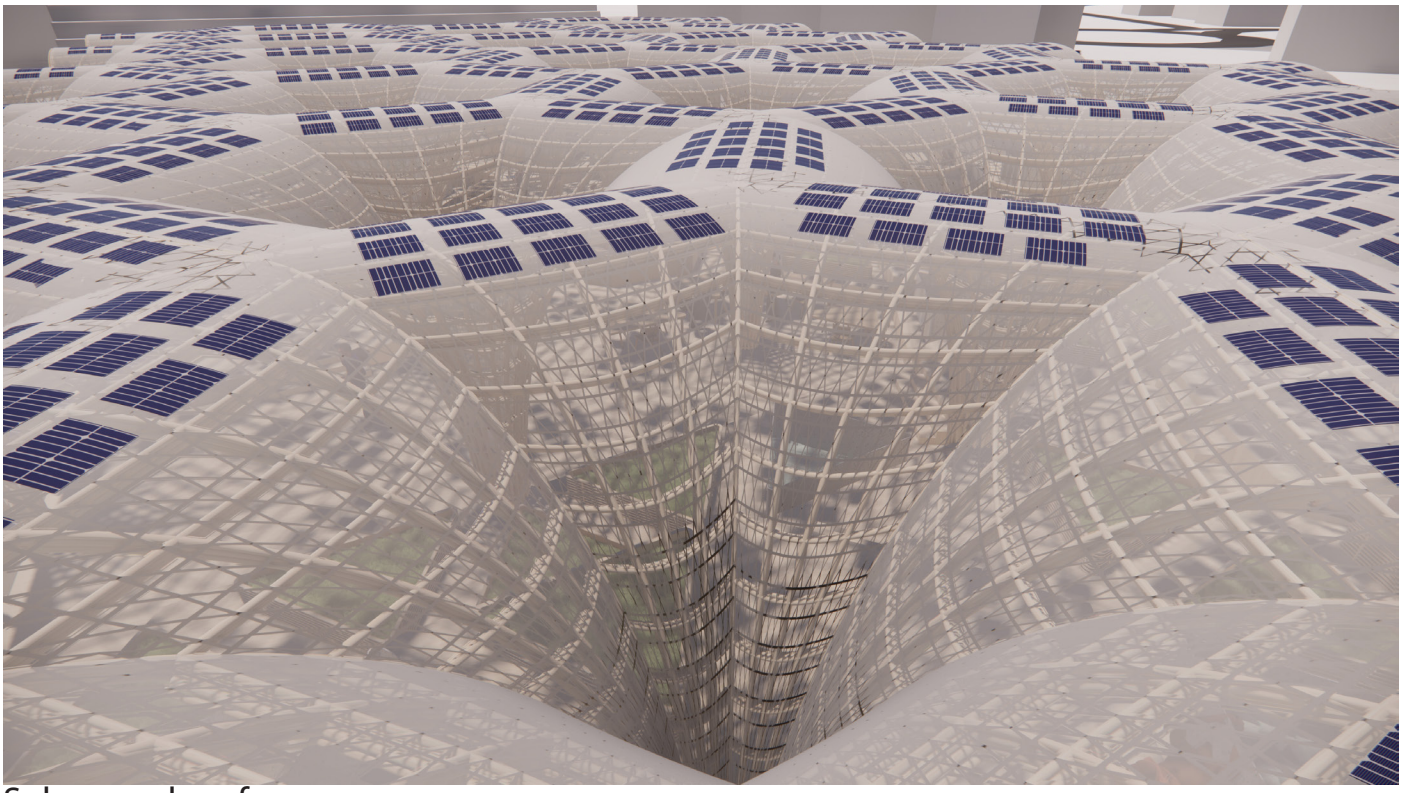


Northern entrance

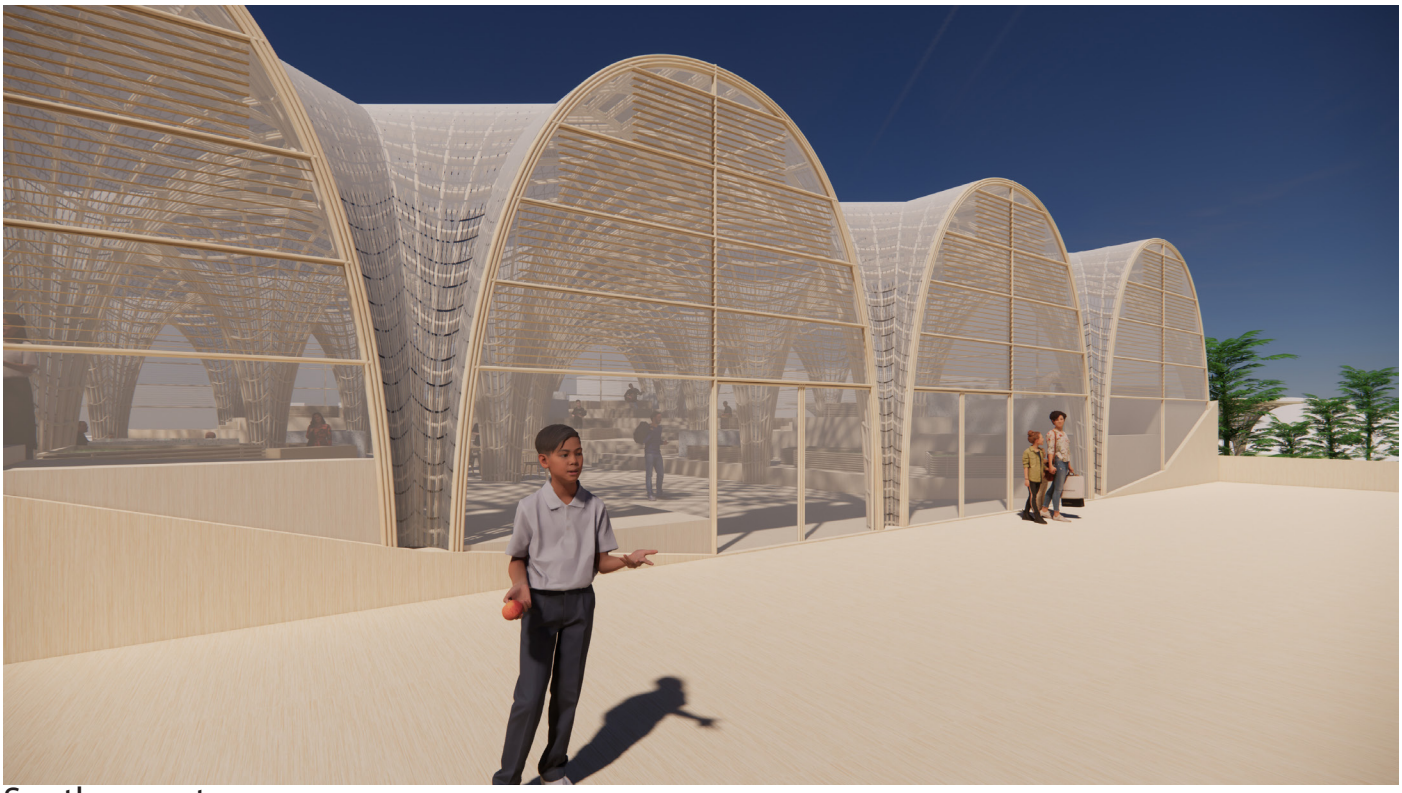


Northern entrance

Northern entrance



Solar panel roof

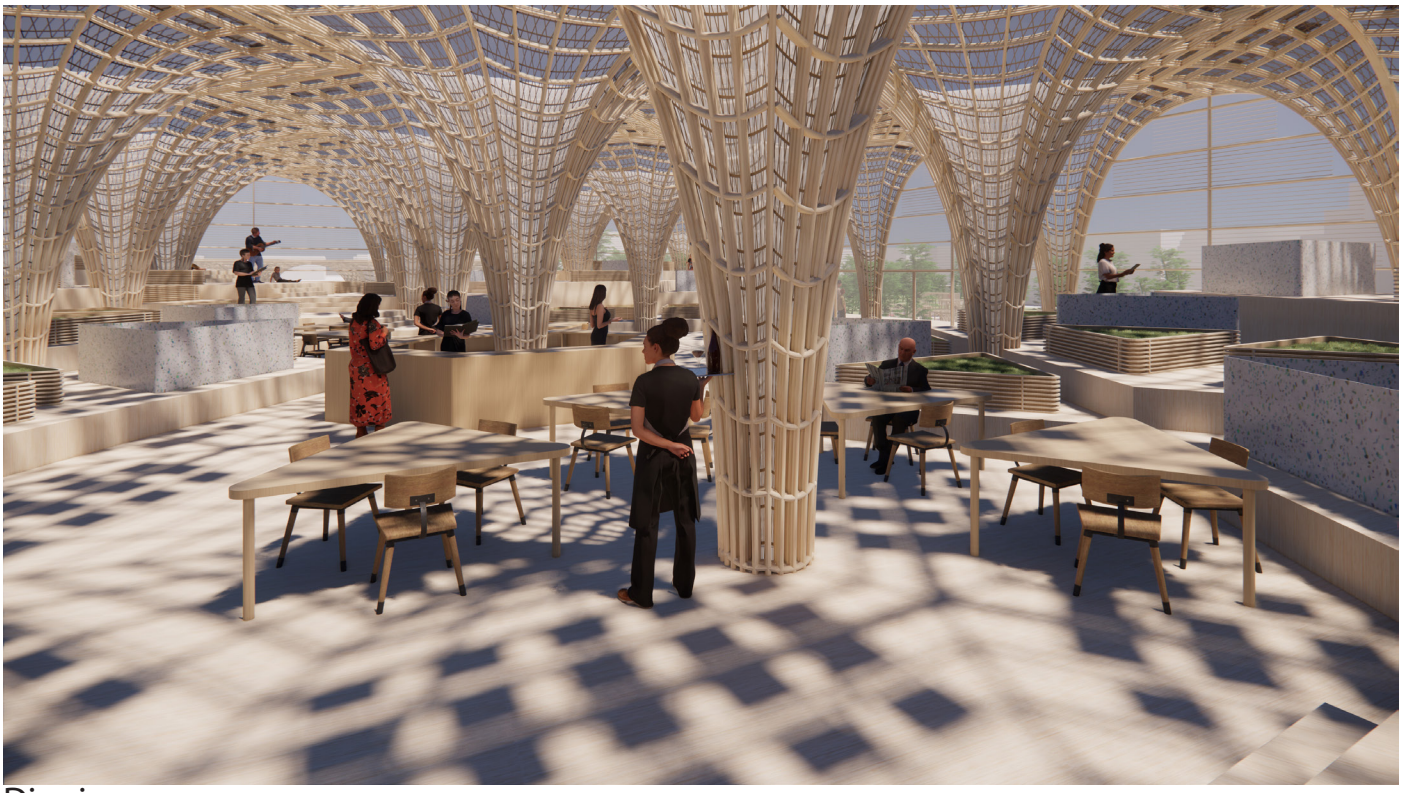


Southern entrance

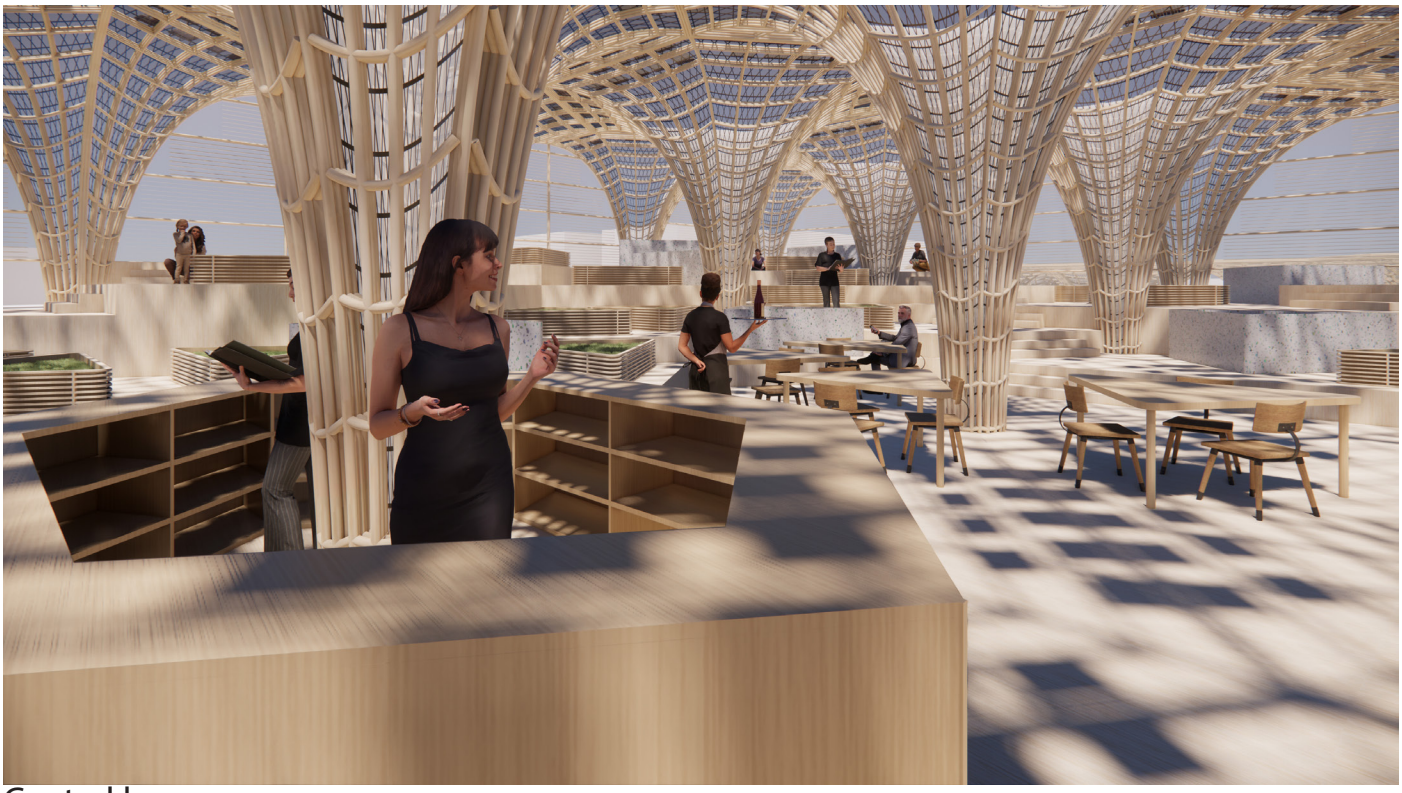
Side walk

Interior view

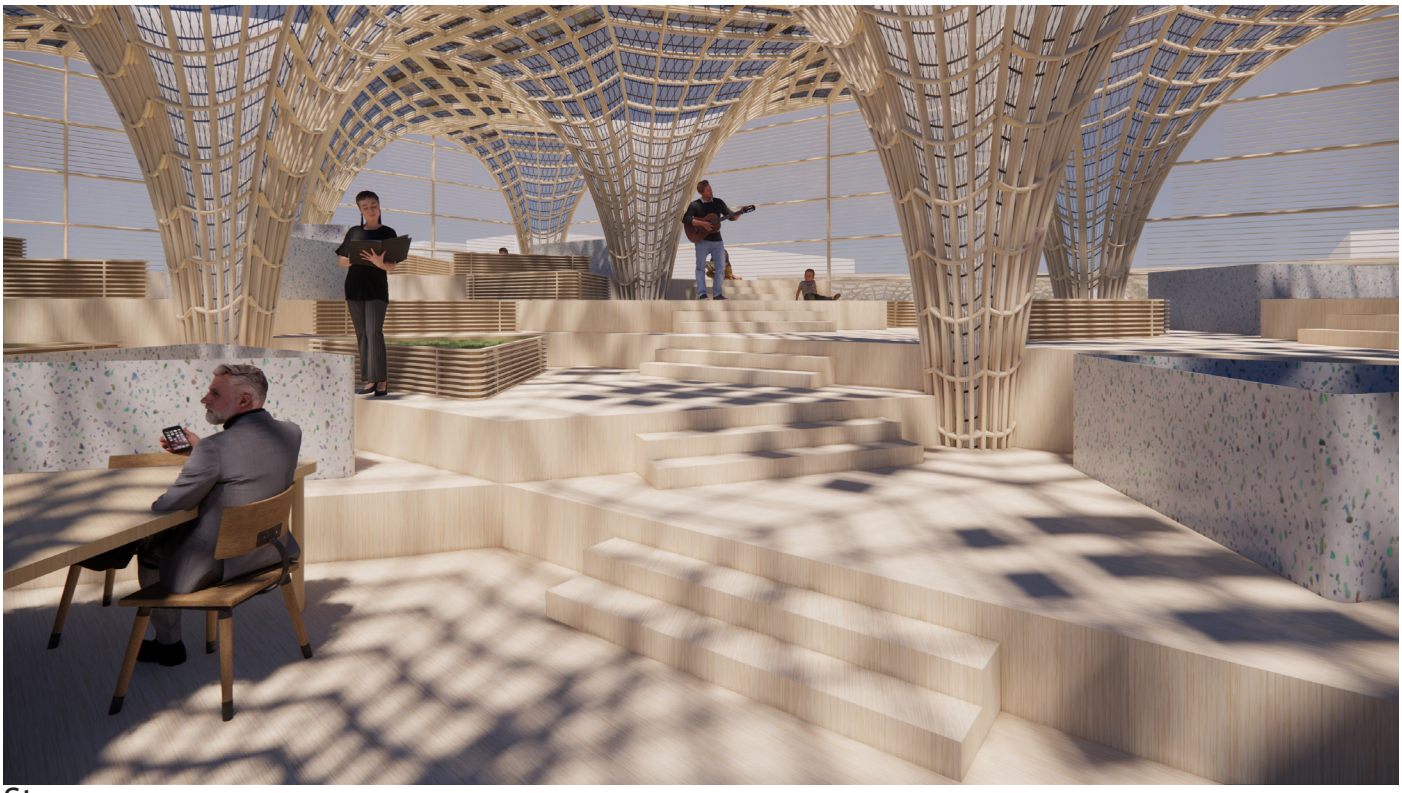
Interior view



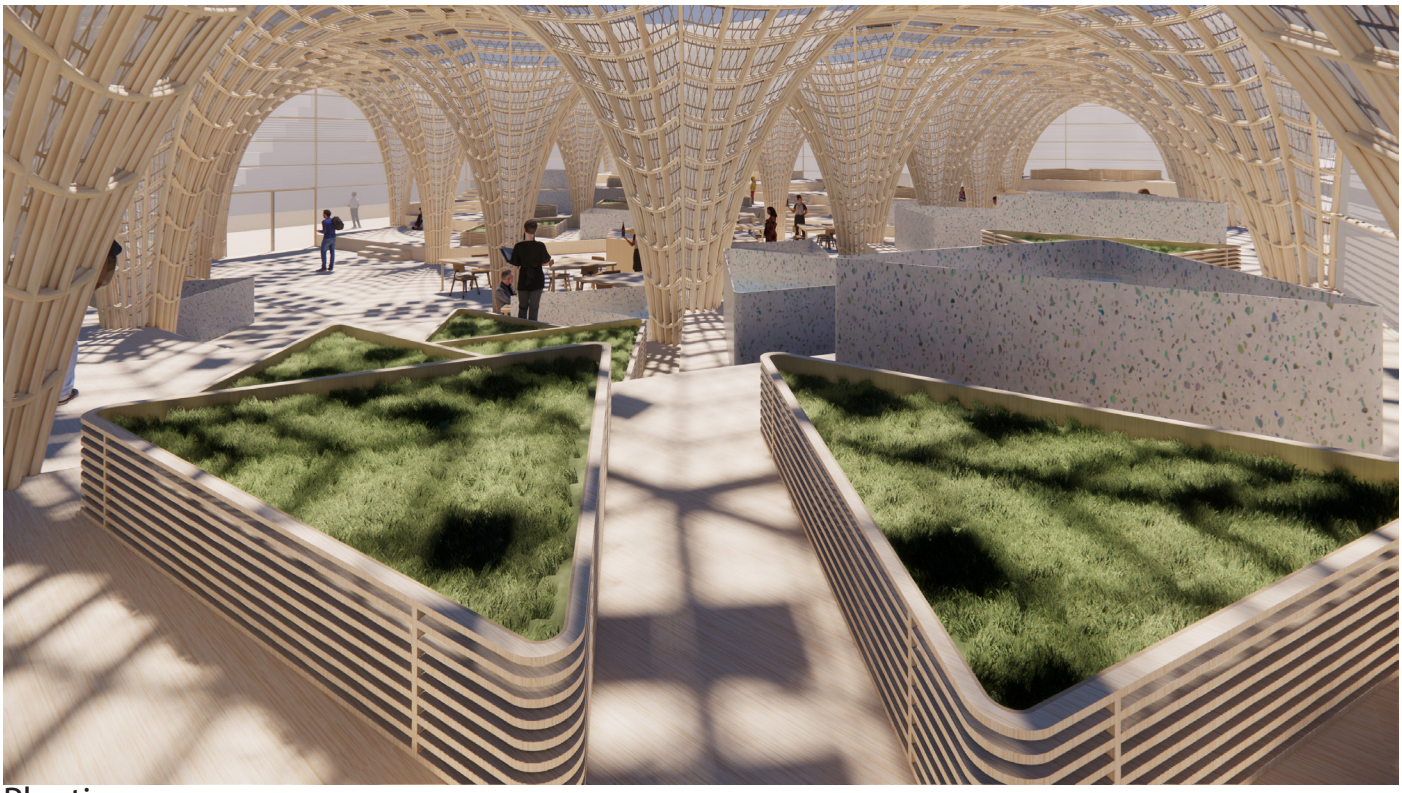
Dinning area



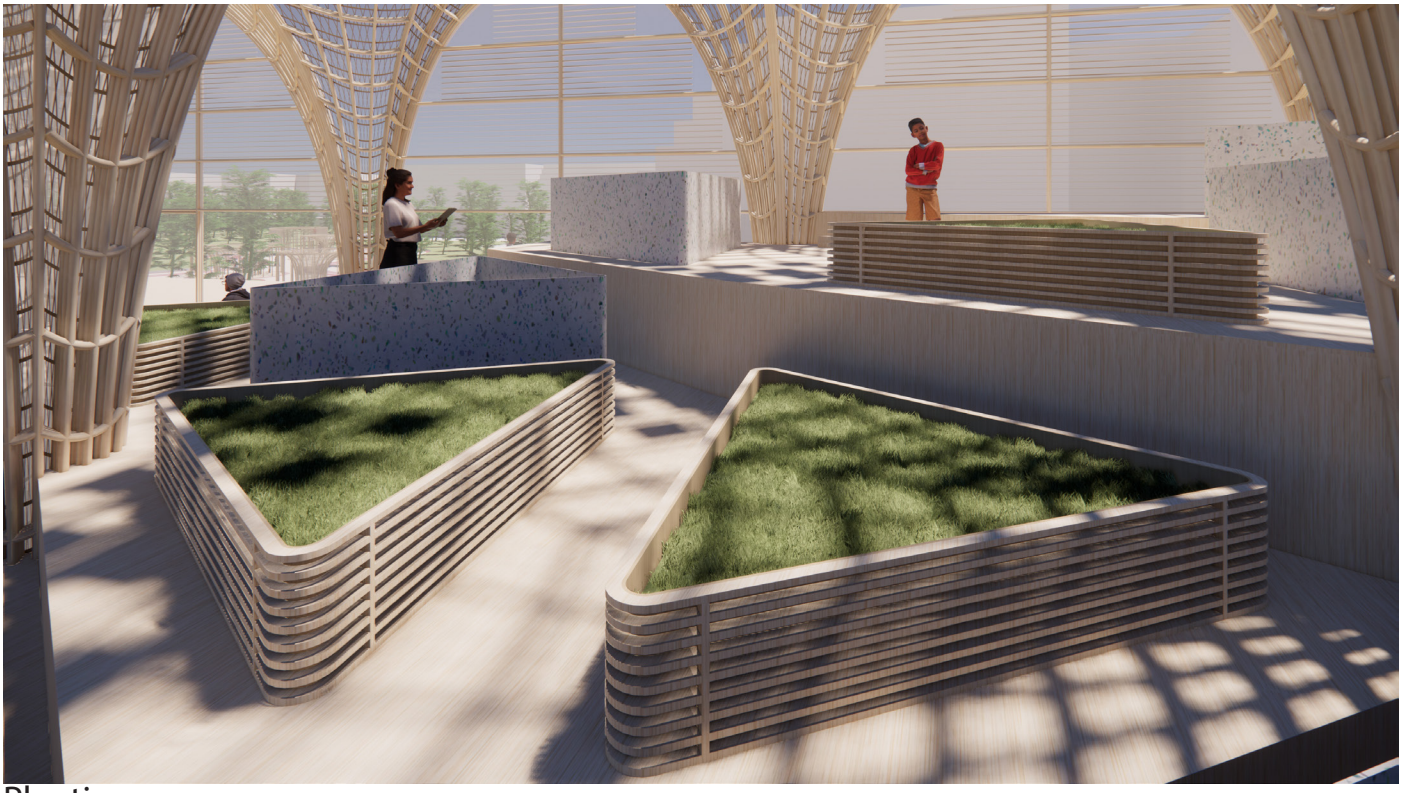
Central bar



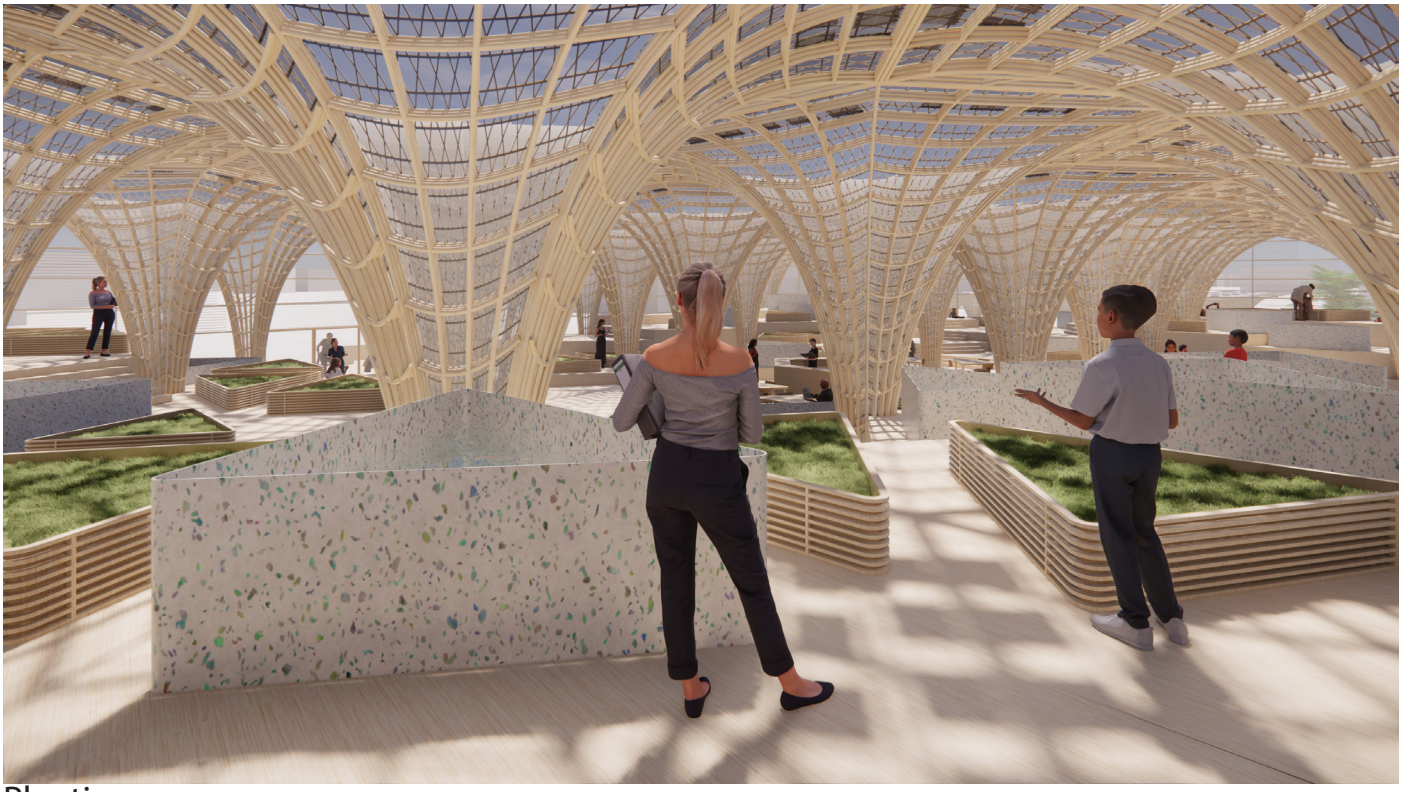
Step



Planting area

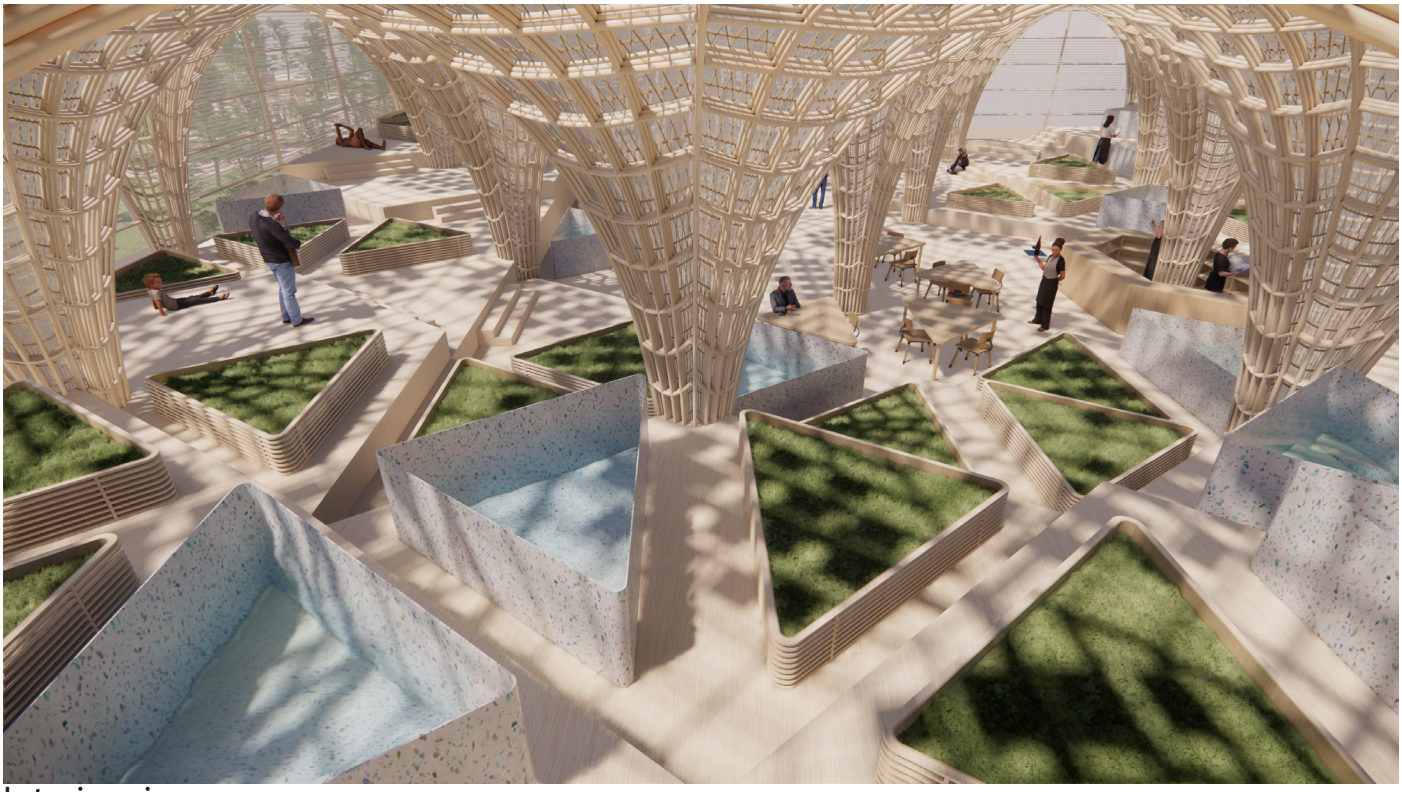


Planting area



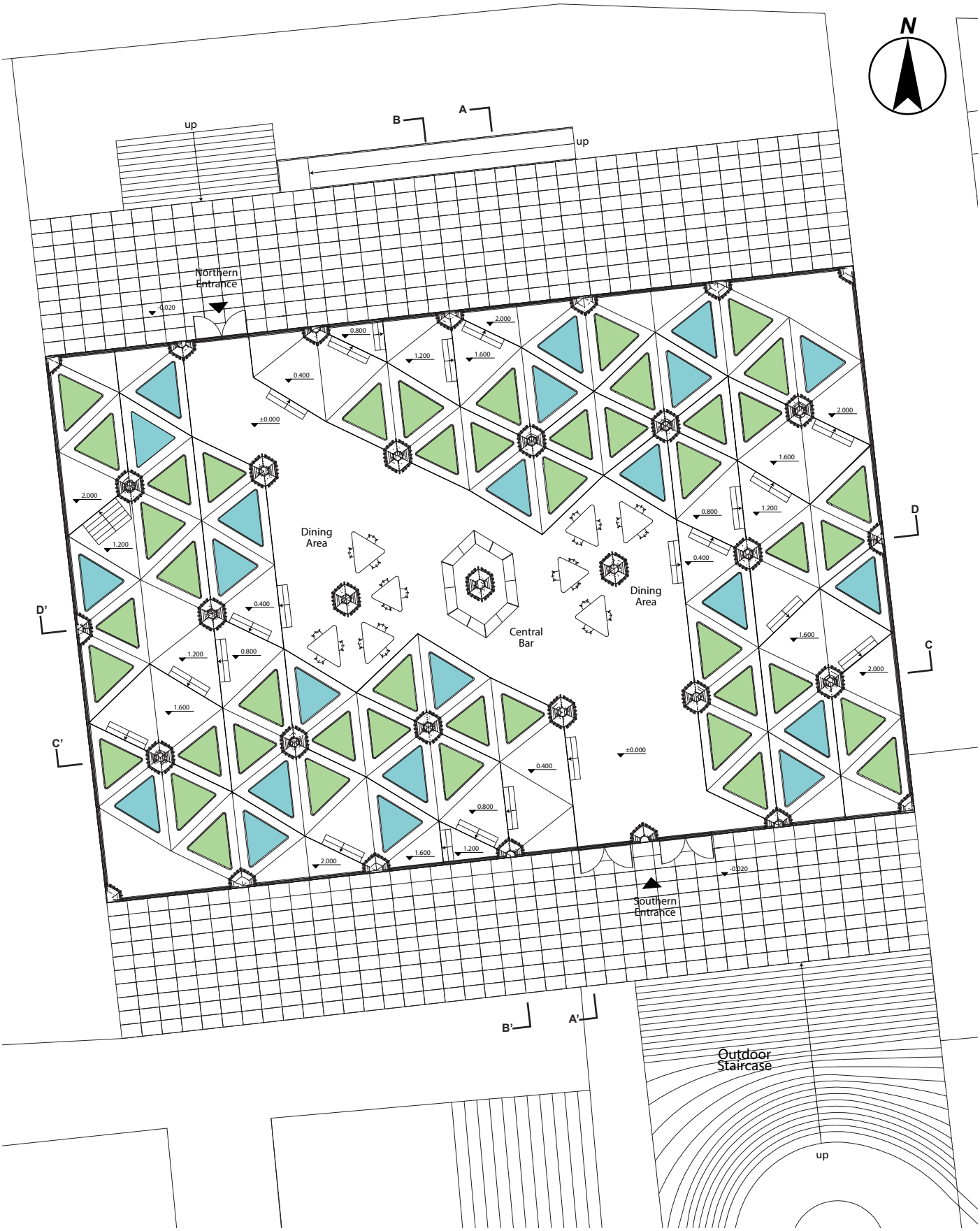
Planting area

Interior view

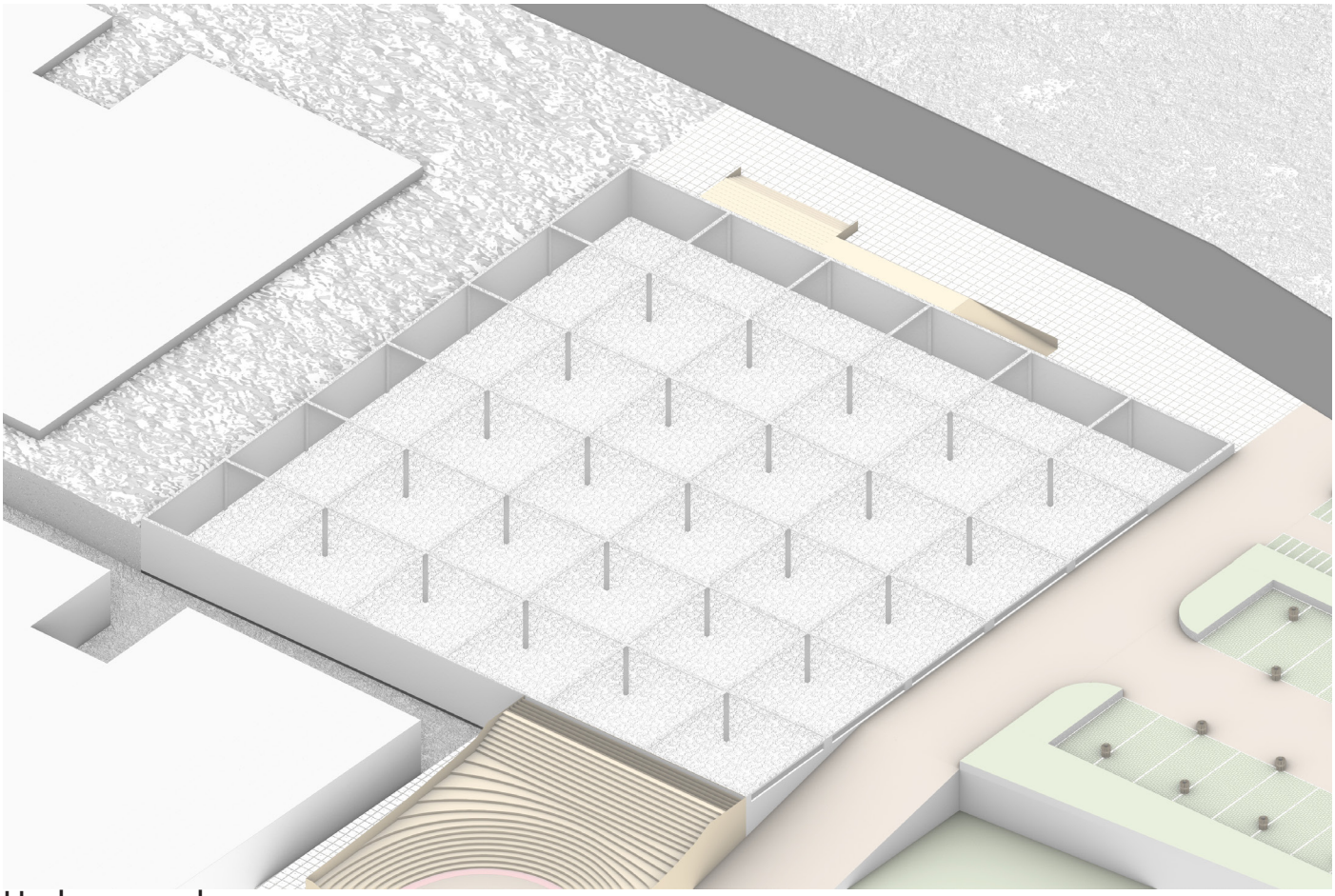


Interior view

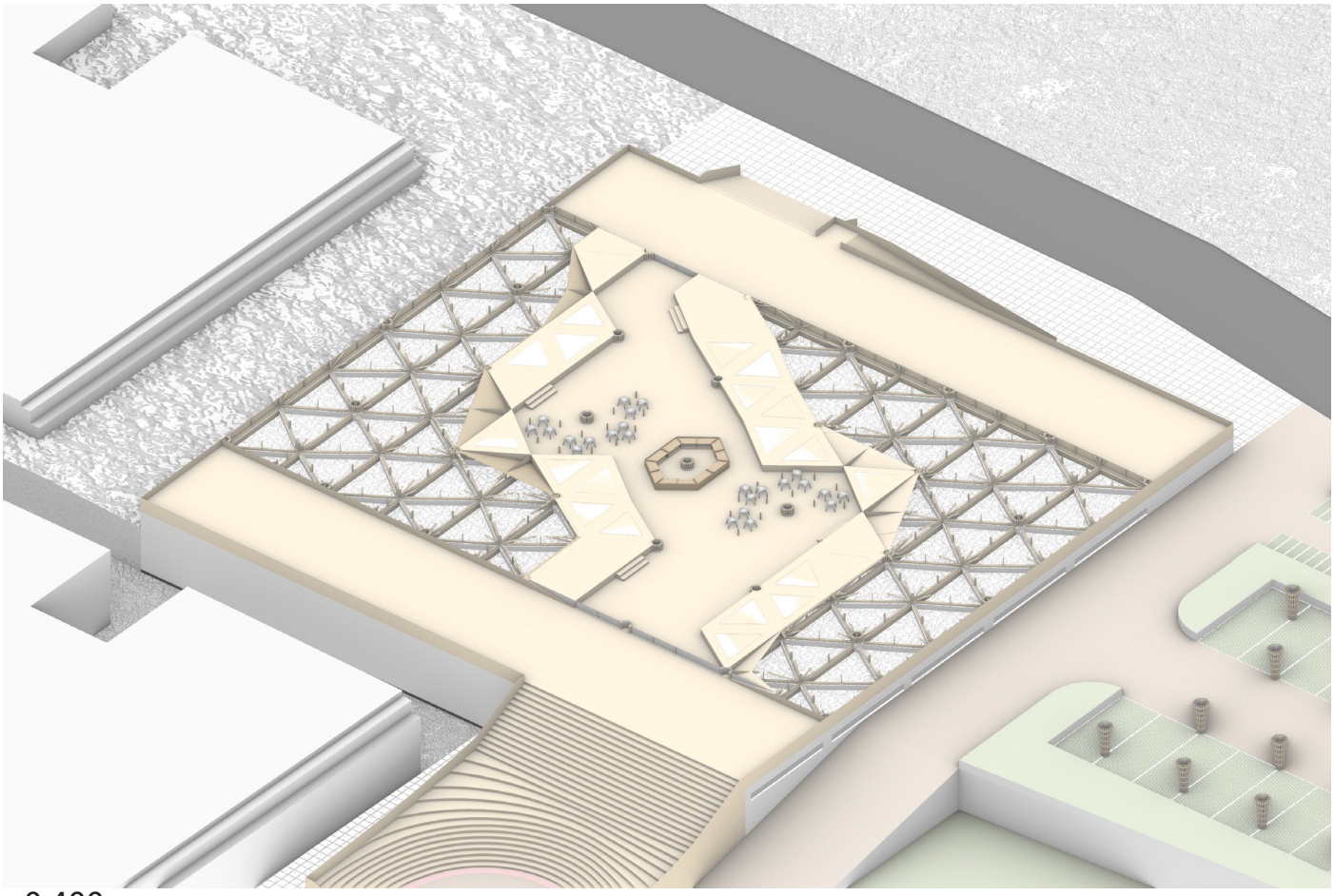
## Floor plan 1:250



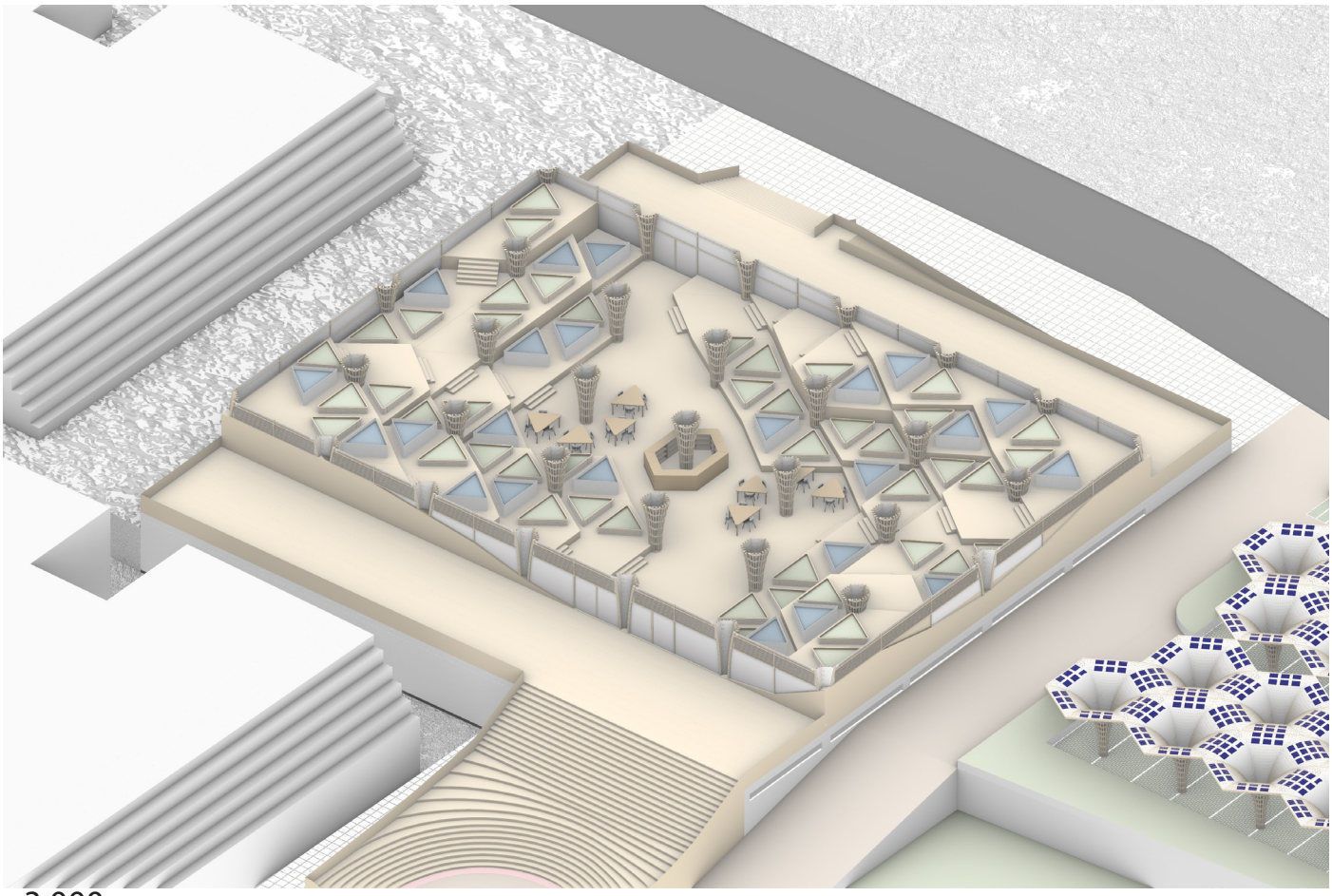
## Isometric view



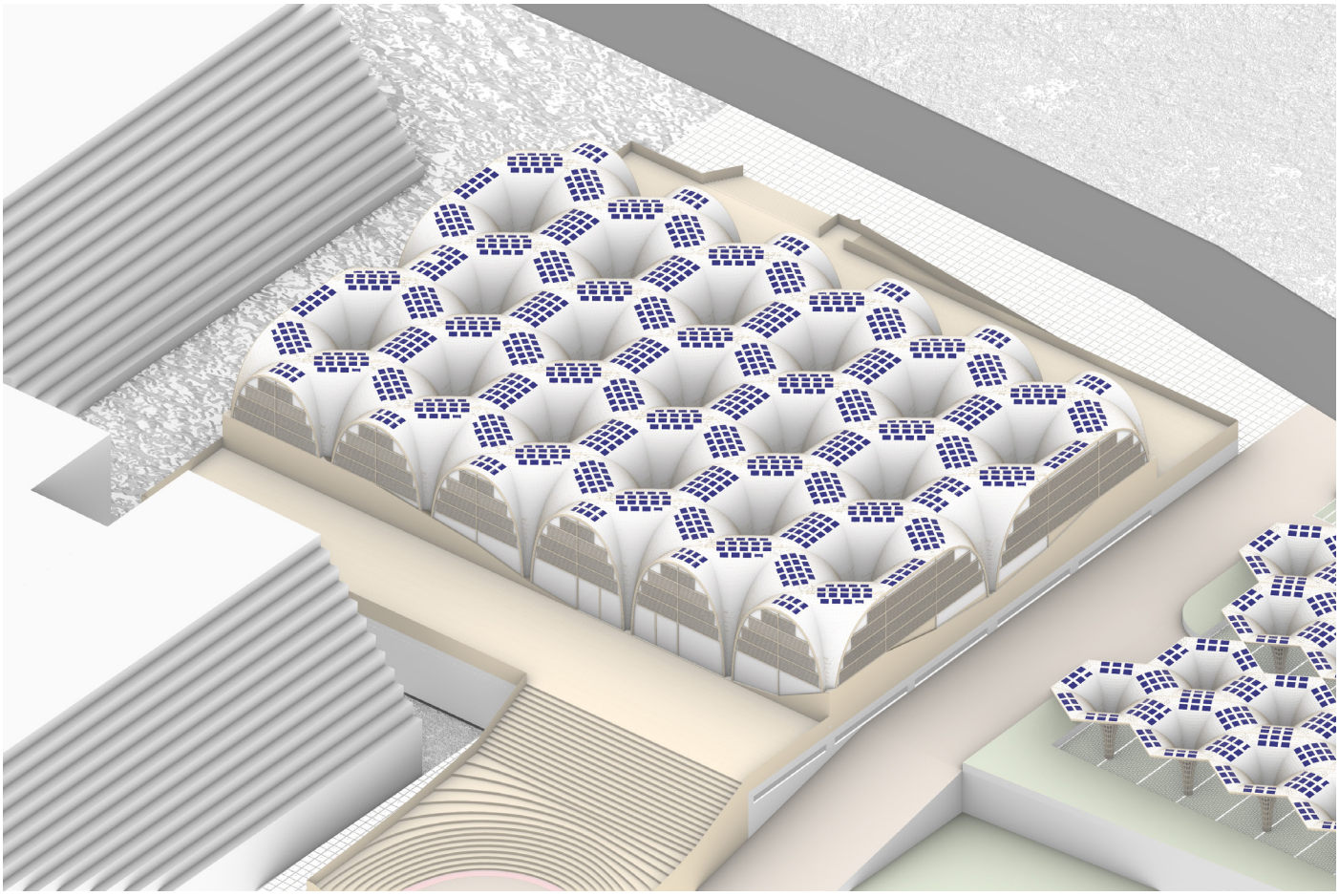
Underground



+0.400



+3.000



## Deconstruction diagram

Plastic and Waterproof Surface&Solar Panel

Bamboo Strips

Bamboo Roof as Collector of Rain-fall&Steel Skeleton

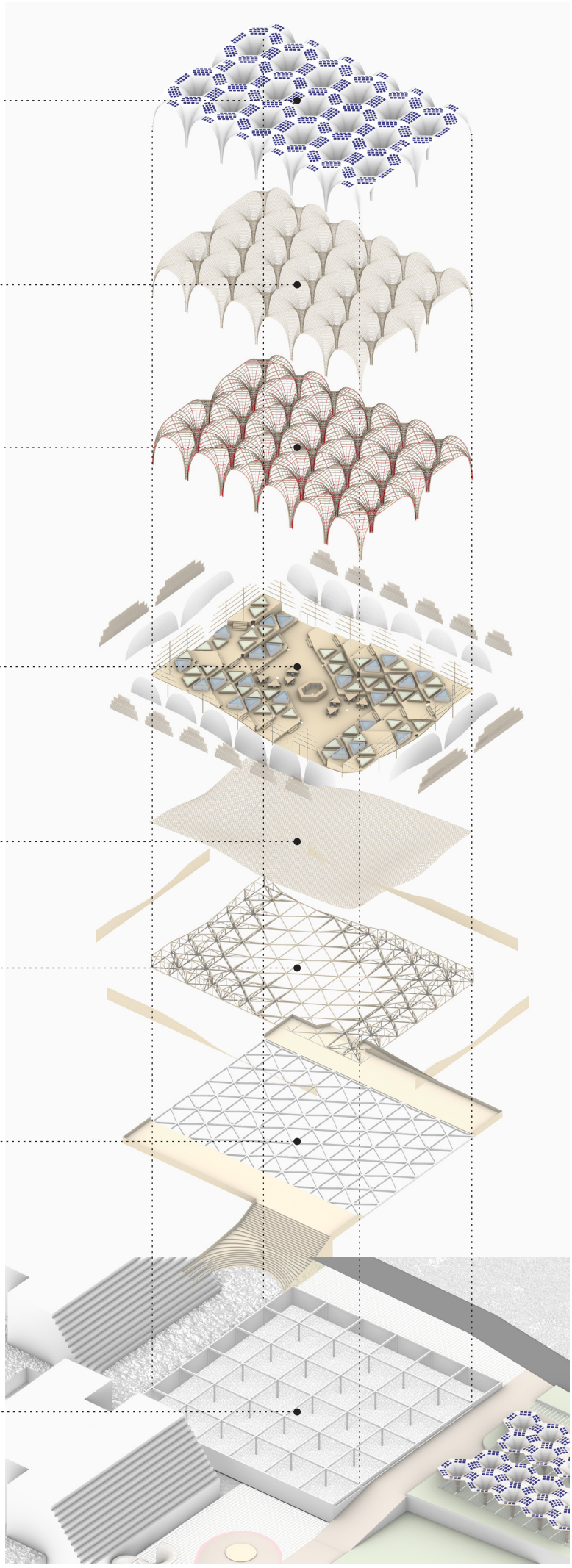
Bamboo Panels&Planting Bed&Fish Tank&Interior Furniture&Plastic Facade&Bamboo Shading

Bamboo Strips

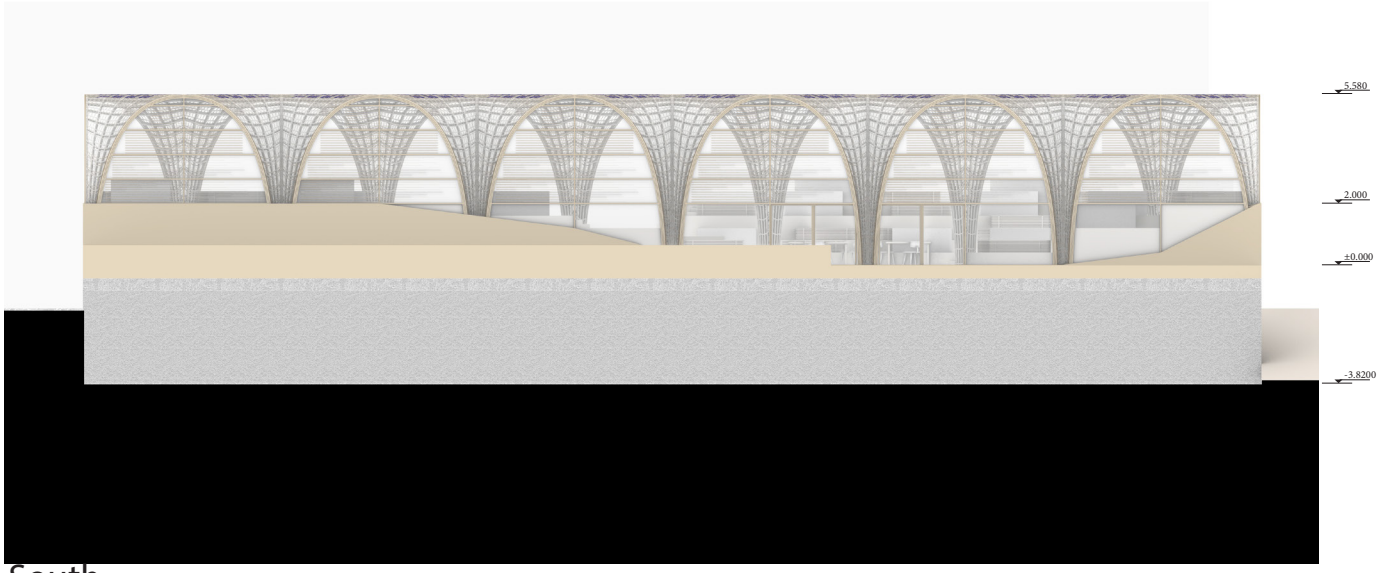
Bamboo Triangle Grid Frames

Concrete Foundation&Bamboo Pavement

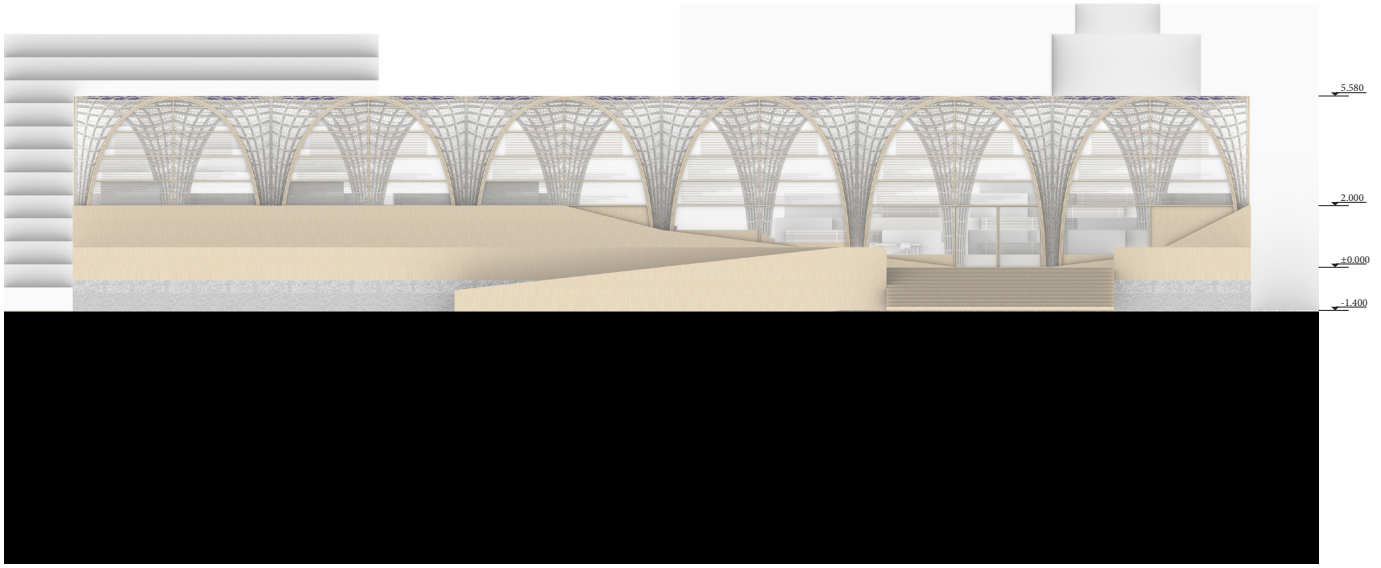
Existing Parking Lots with Concrete Structure



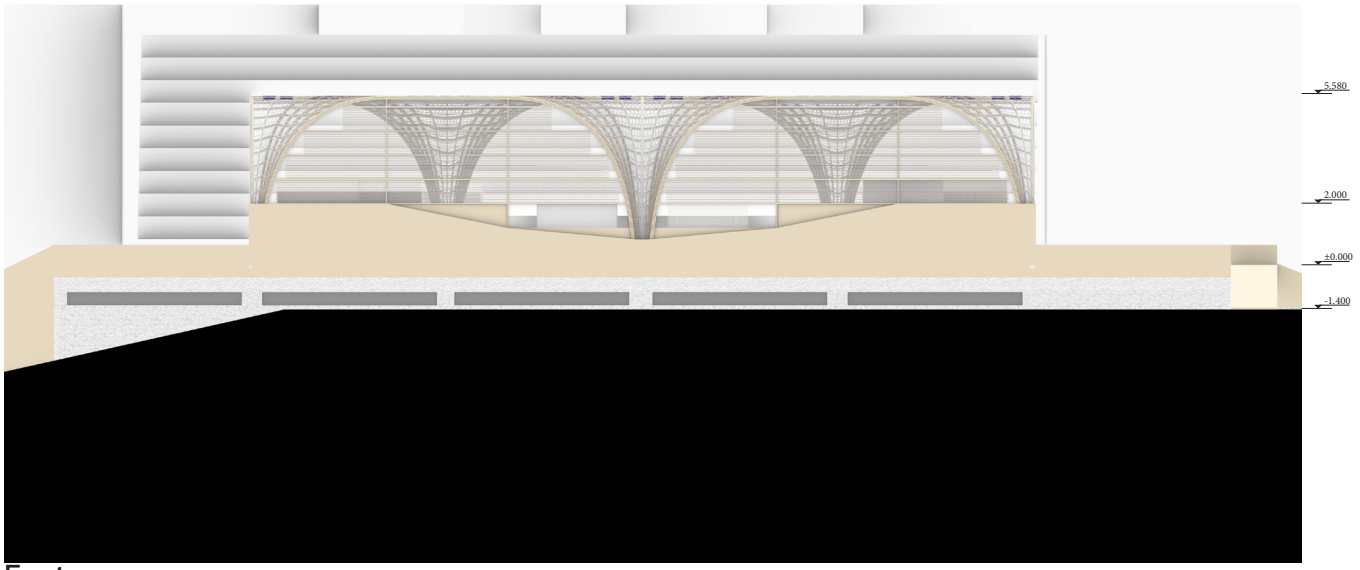
## Elevation 1:250



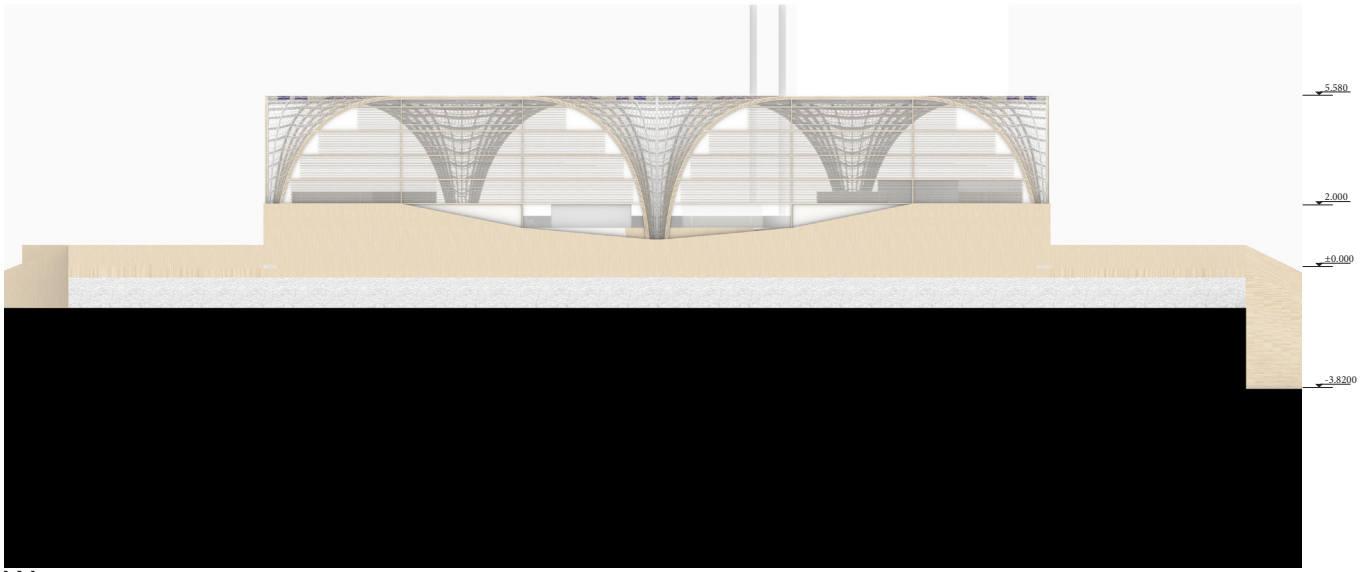

South




North



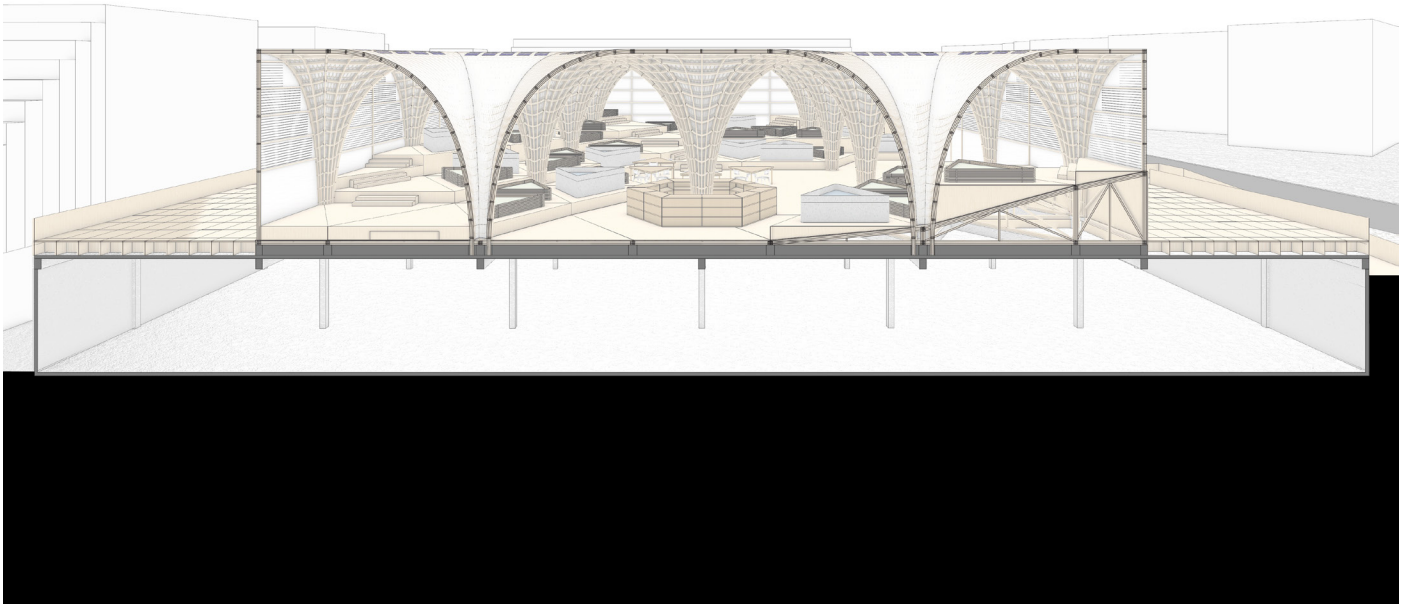

East




West

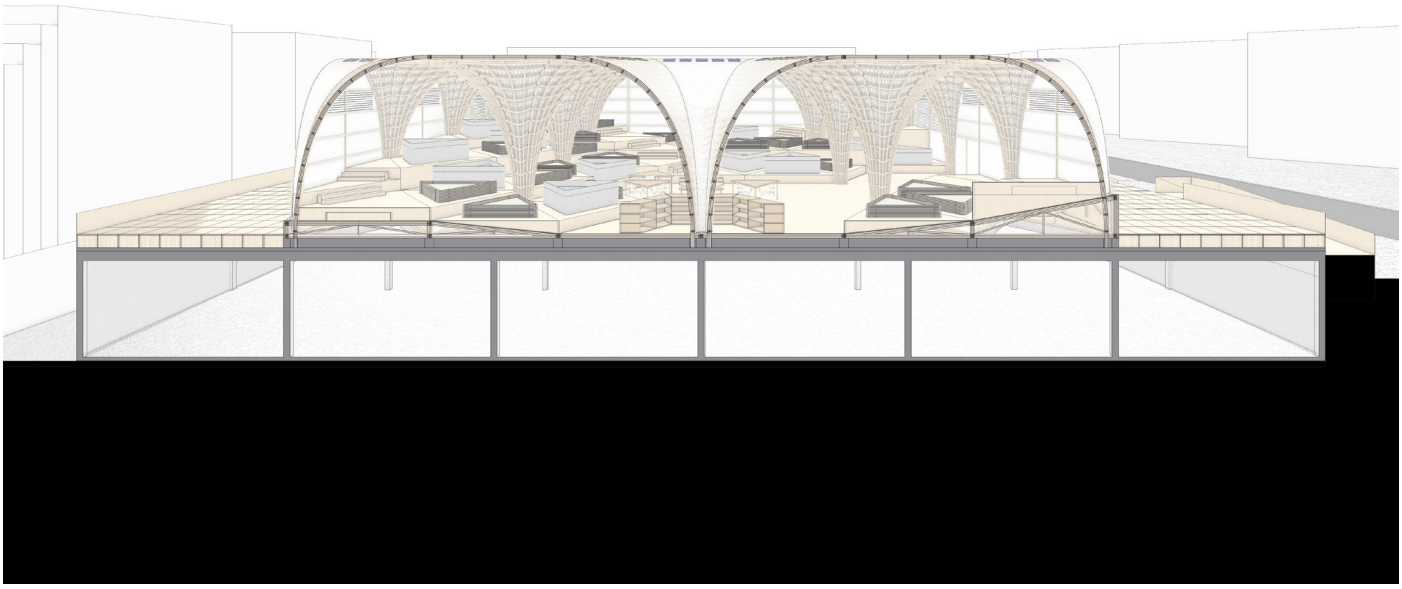
## Cross Section A-A’1:250


## 3D cross section view A-A’

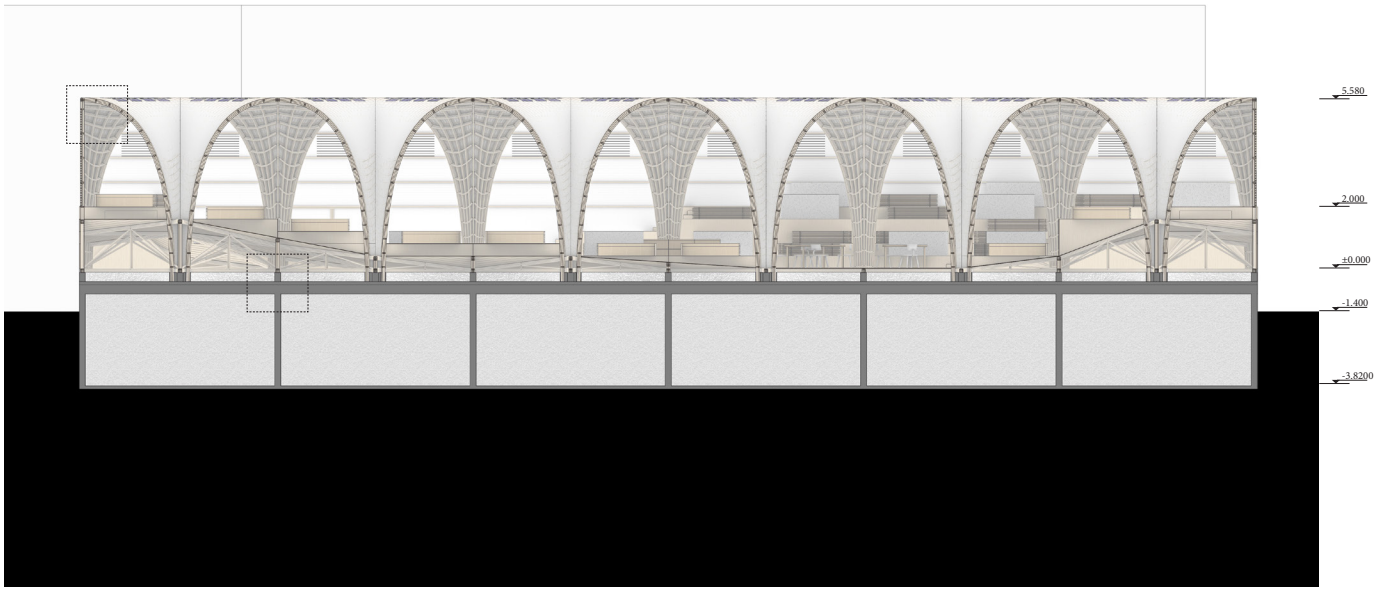


## Cross Section B-B’1:250


## 3D cross section view B-B’



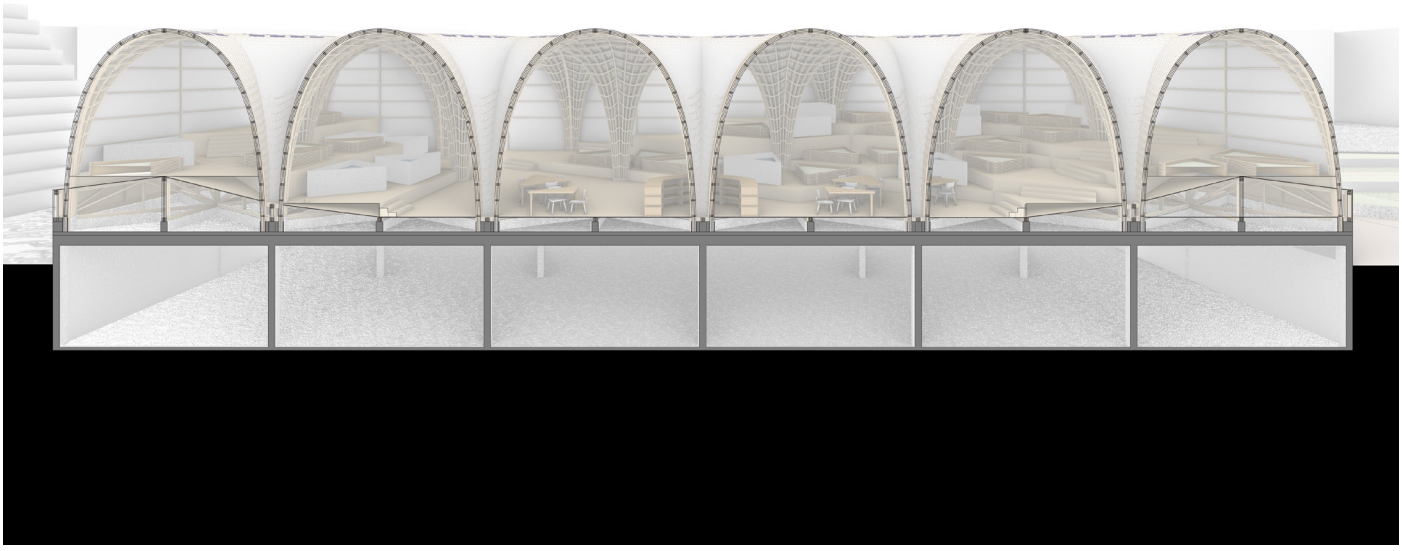
## Cross Section C-C' 1:250



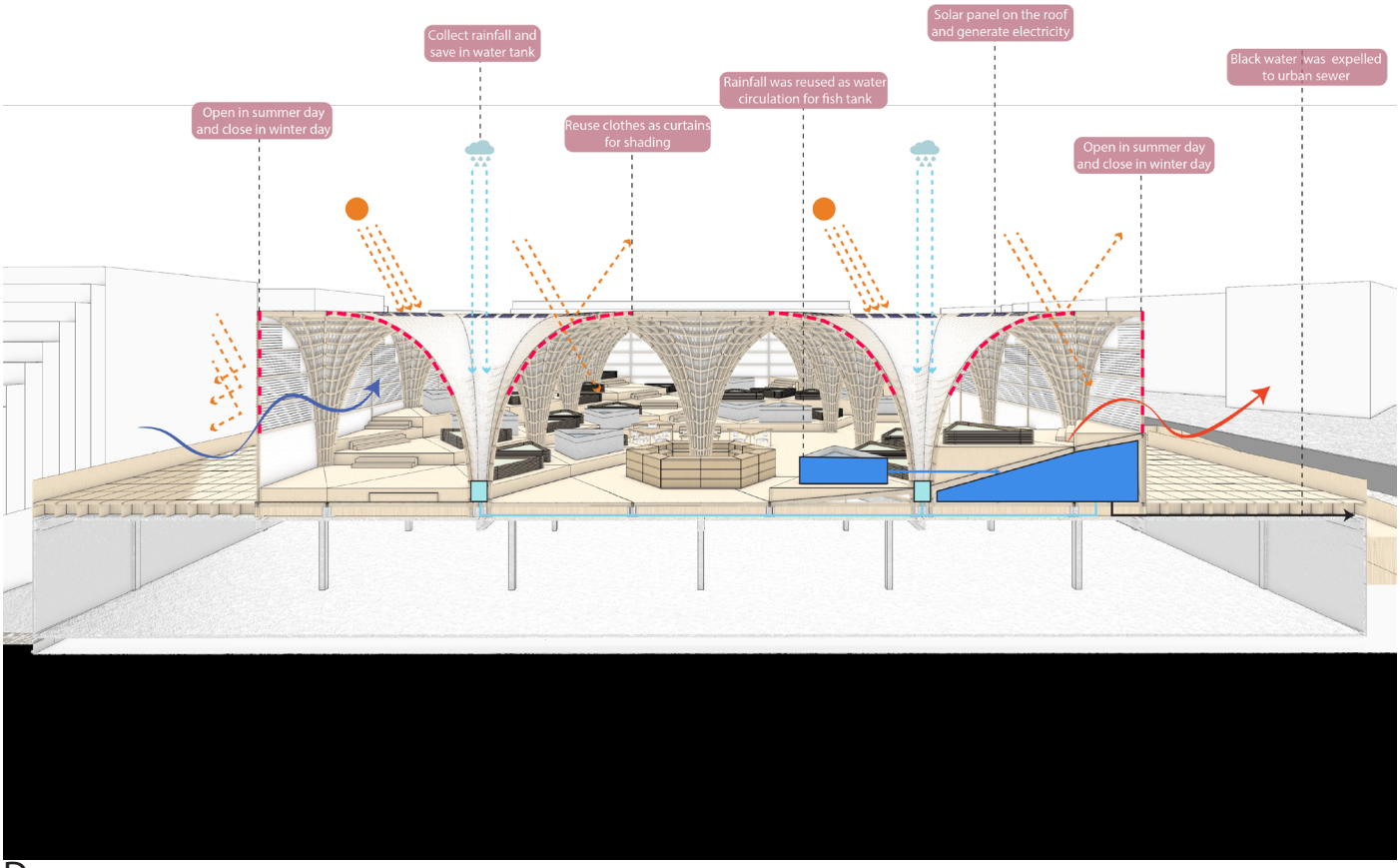

## 3D cross section view C-C'

## Cross Section D-D' 1:250

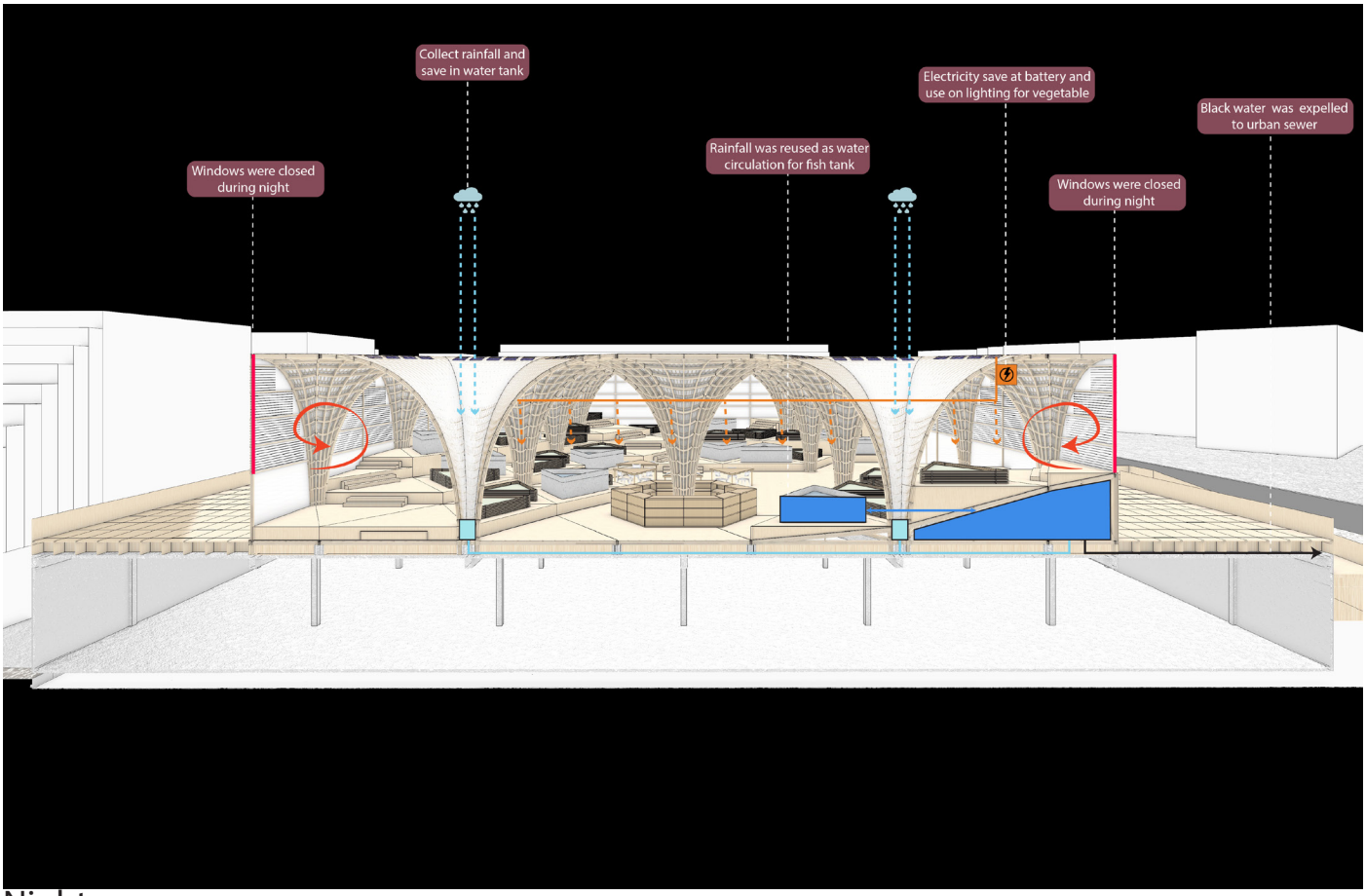

## 3D cross section view D-D'



# Sustainable strategy diagram



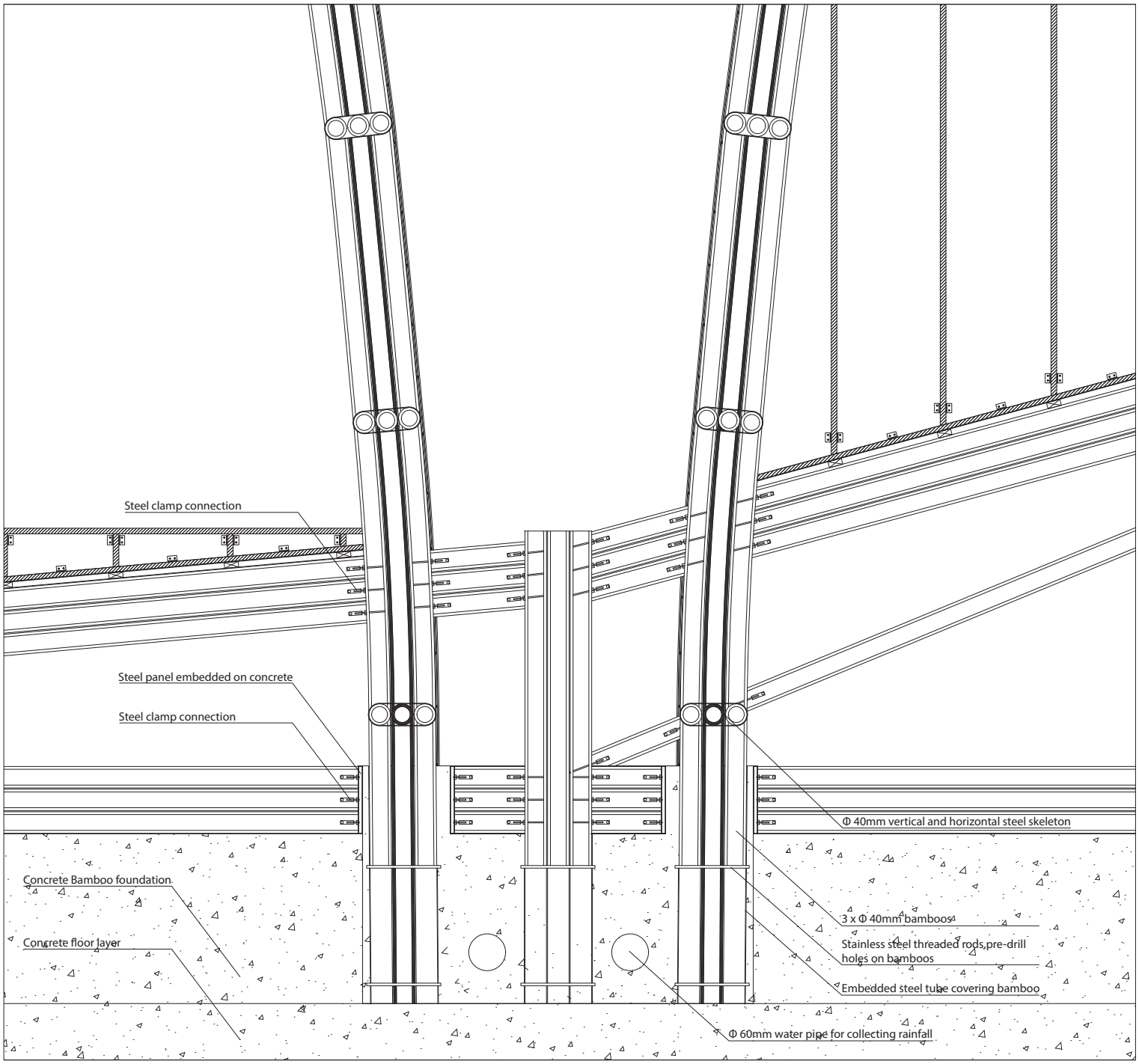

Day



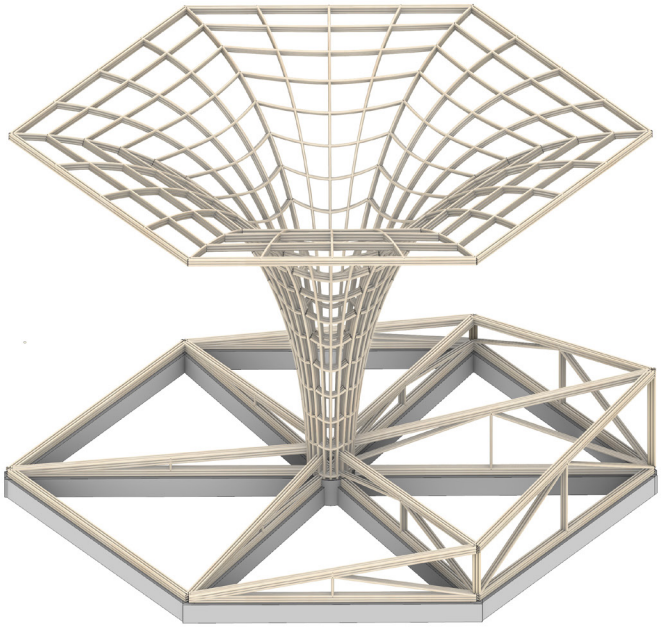

Night

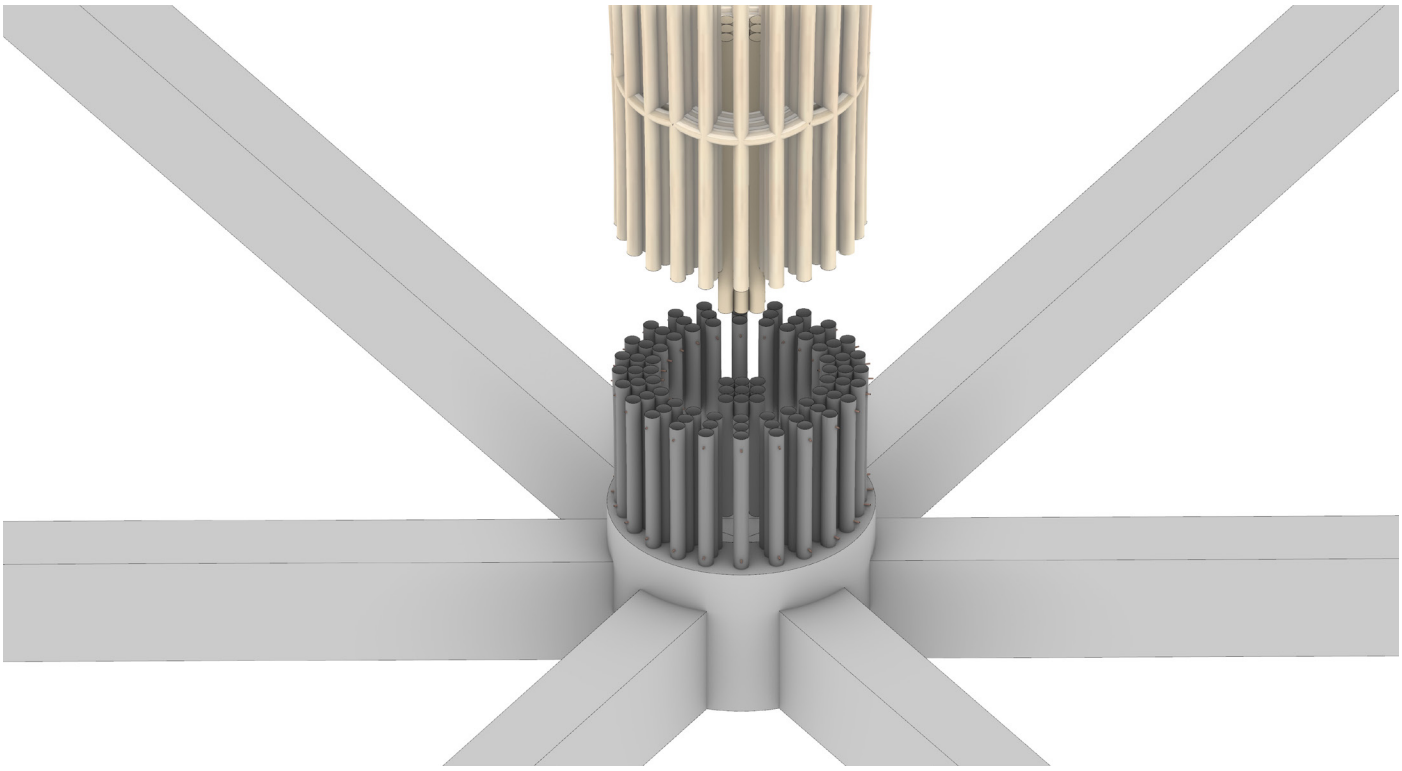
# 6.3 Construction detail

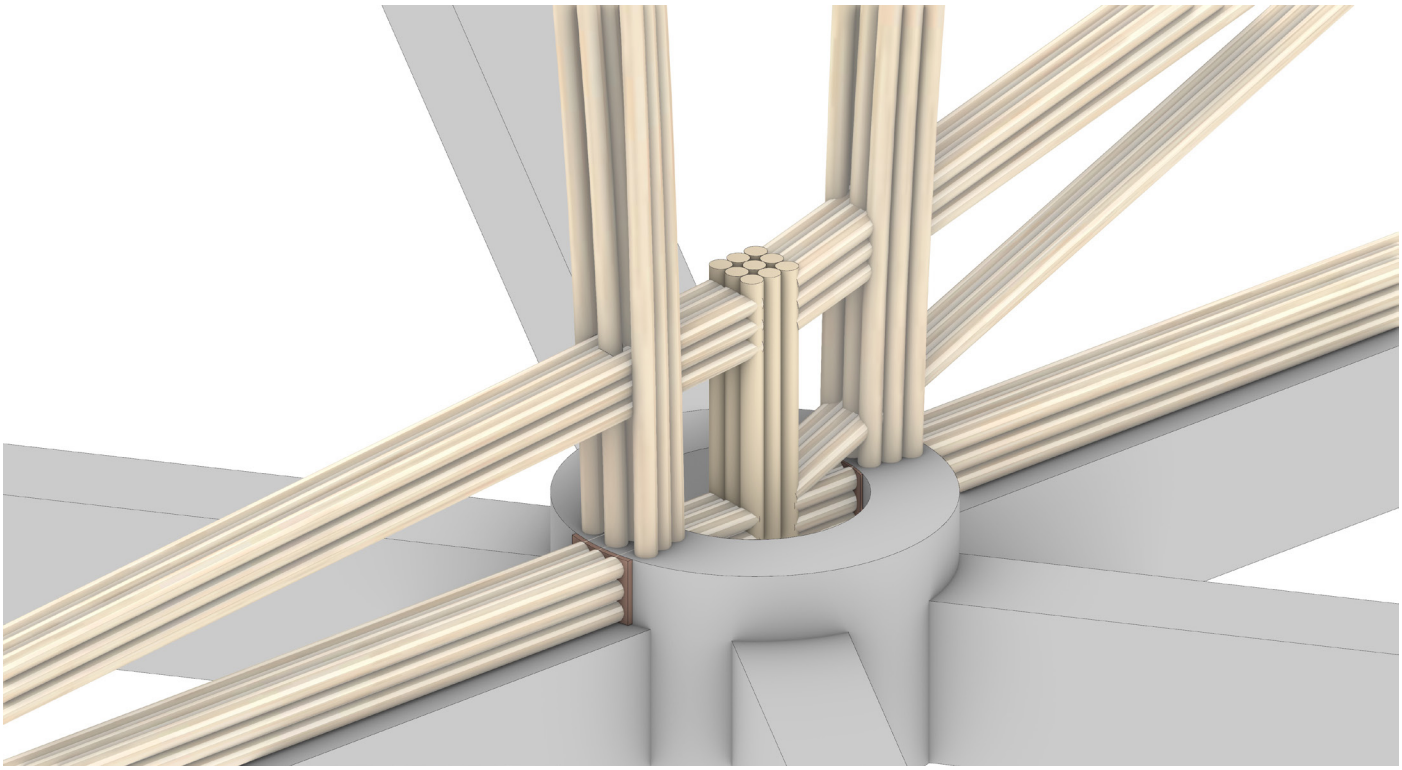
## Detail 01 1:10

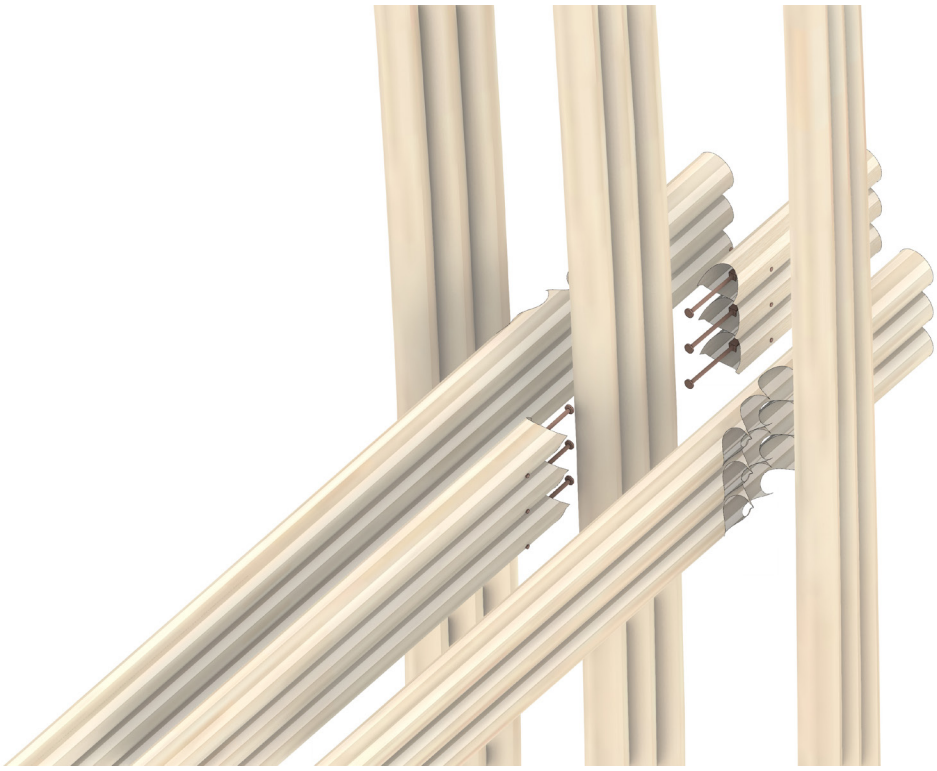


## Detail 01-3D diagram

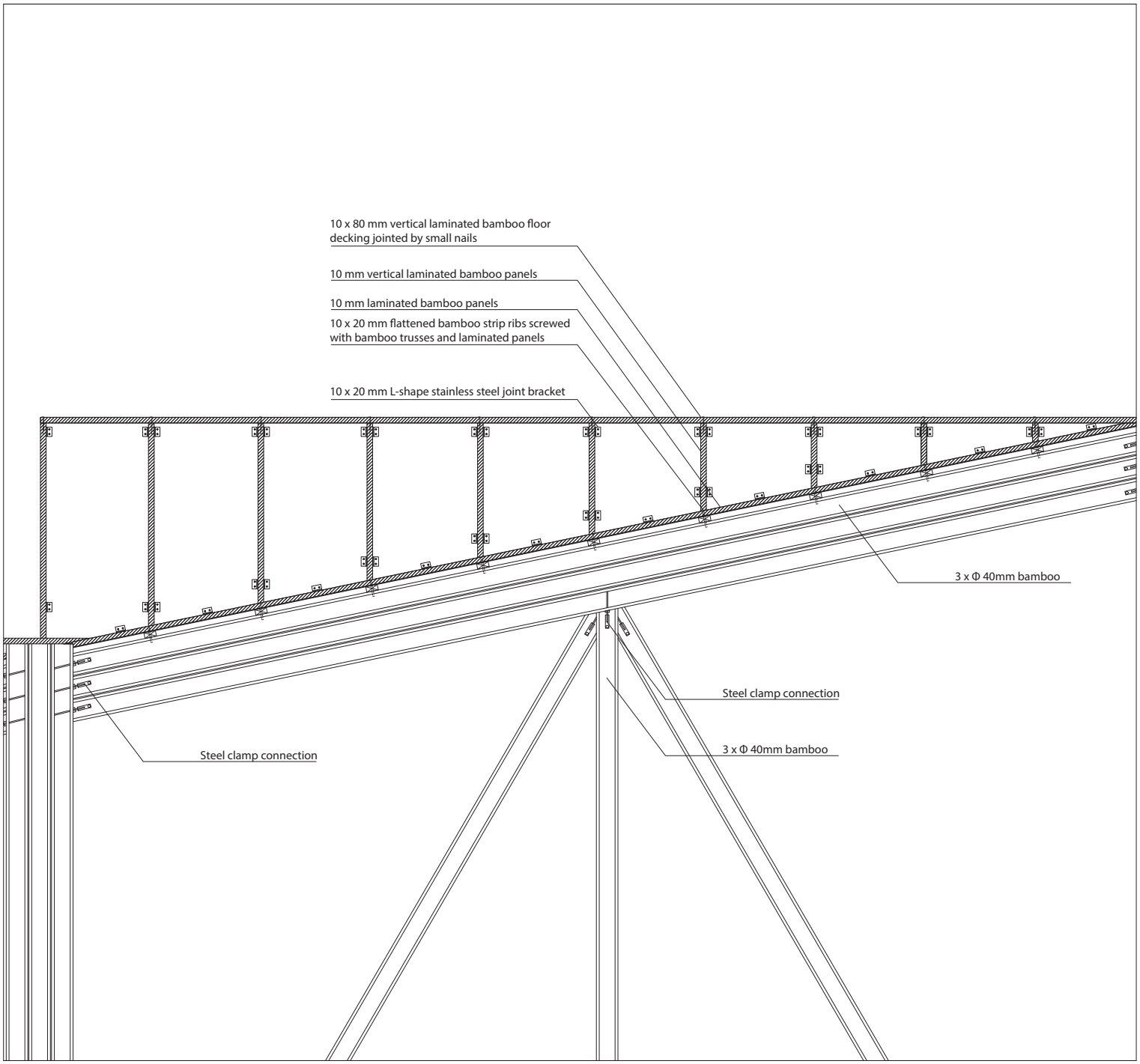




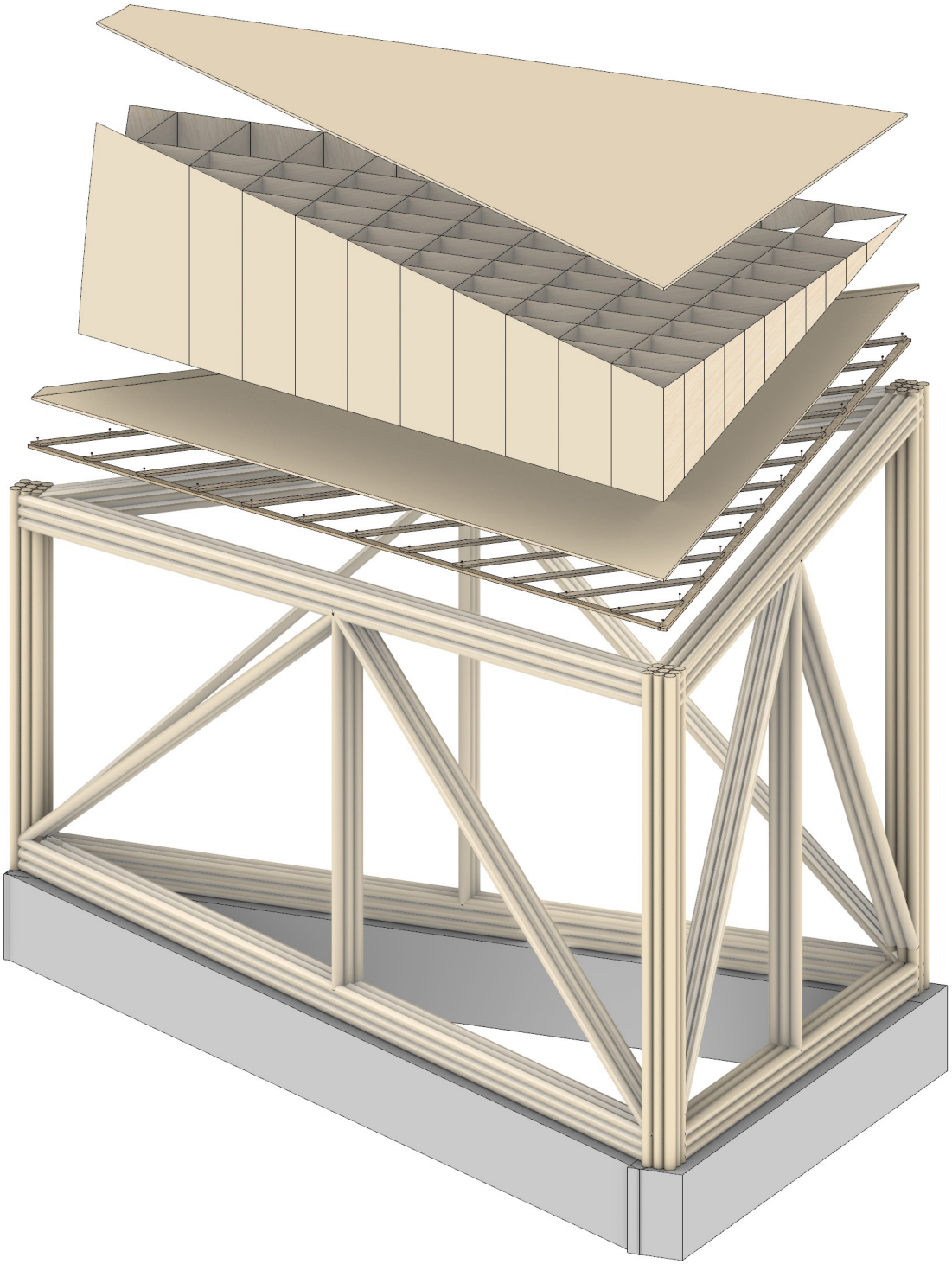


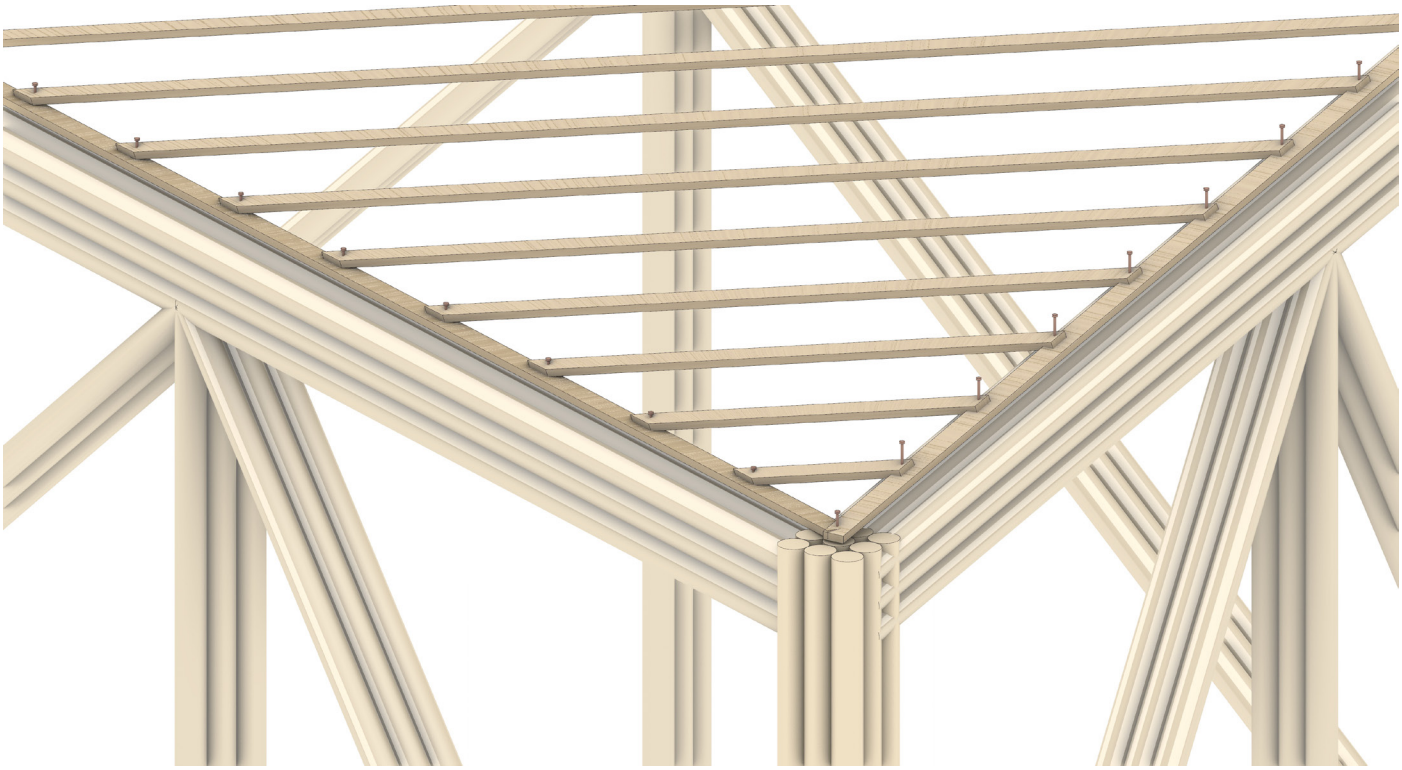


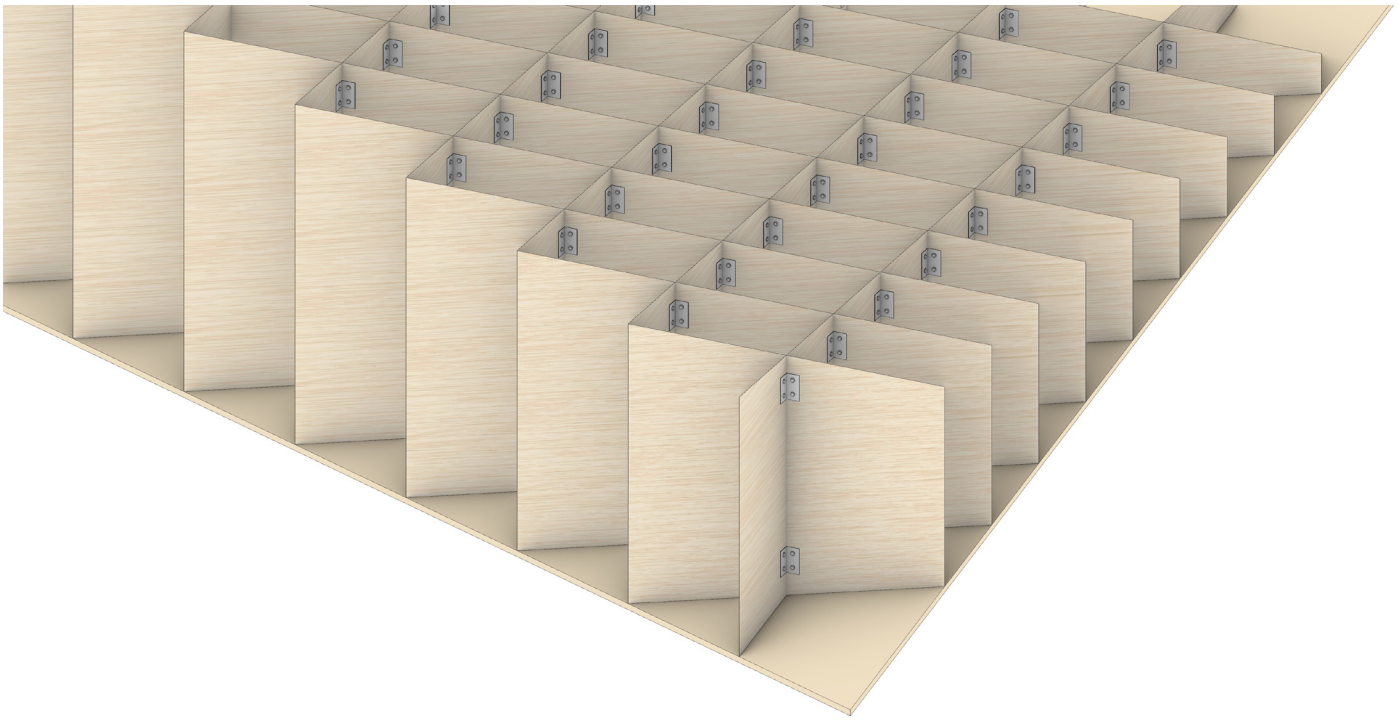
# Detail 02 1:10



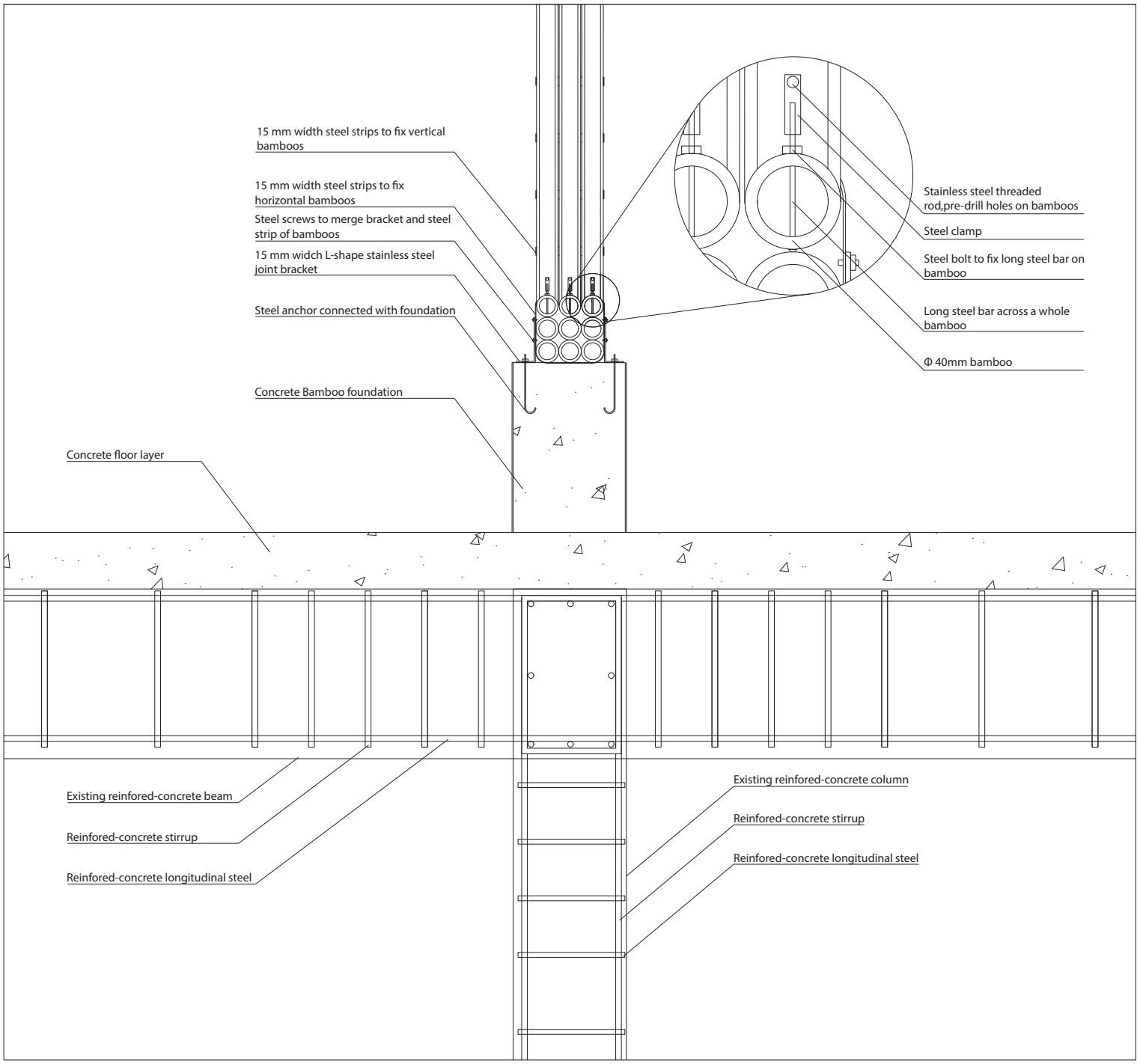
## Detail 02-3D diagram



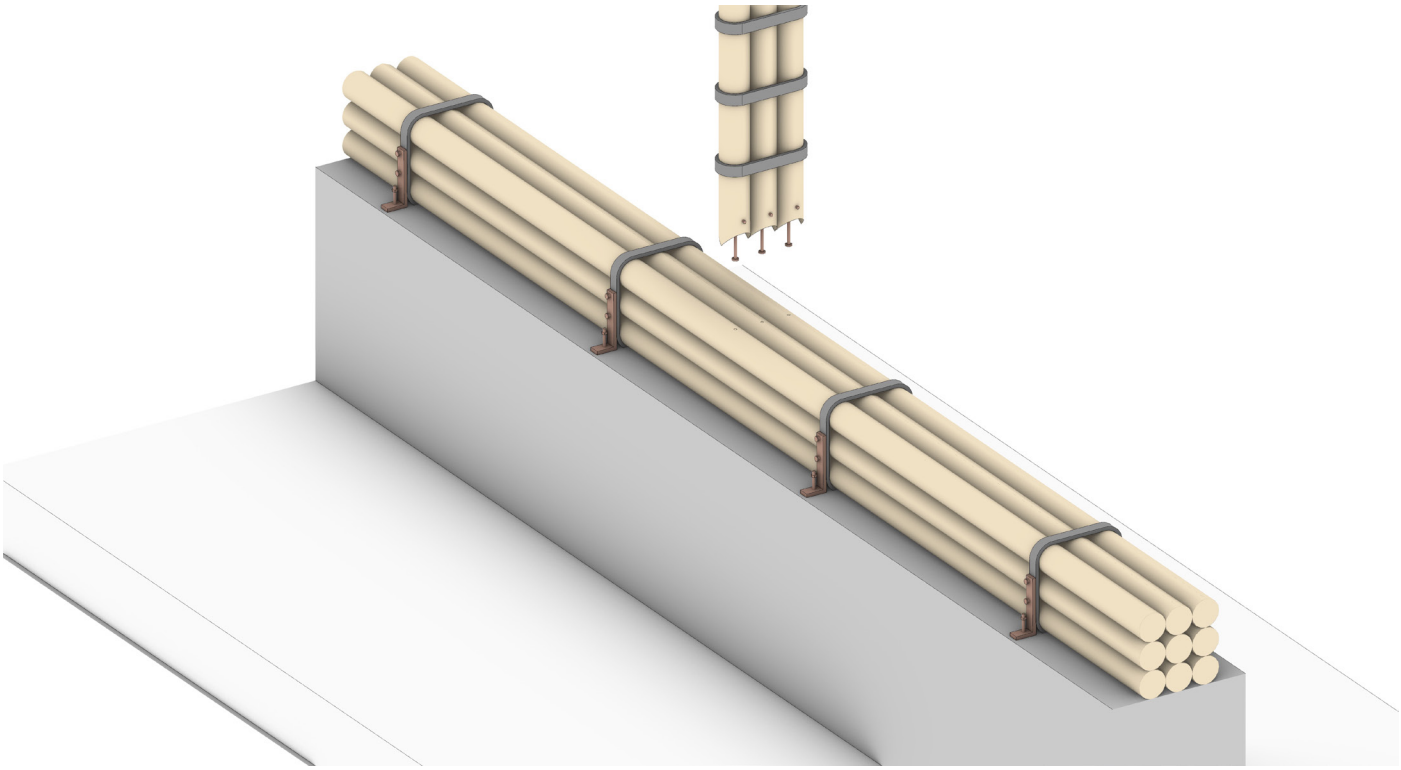


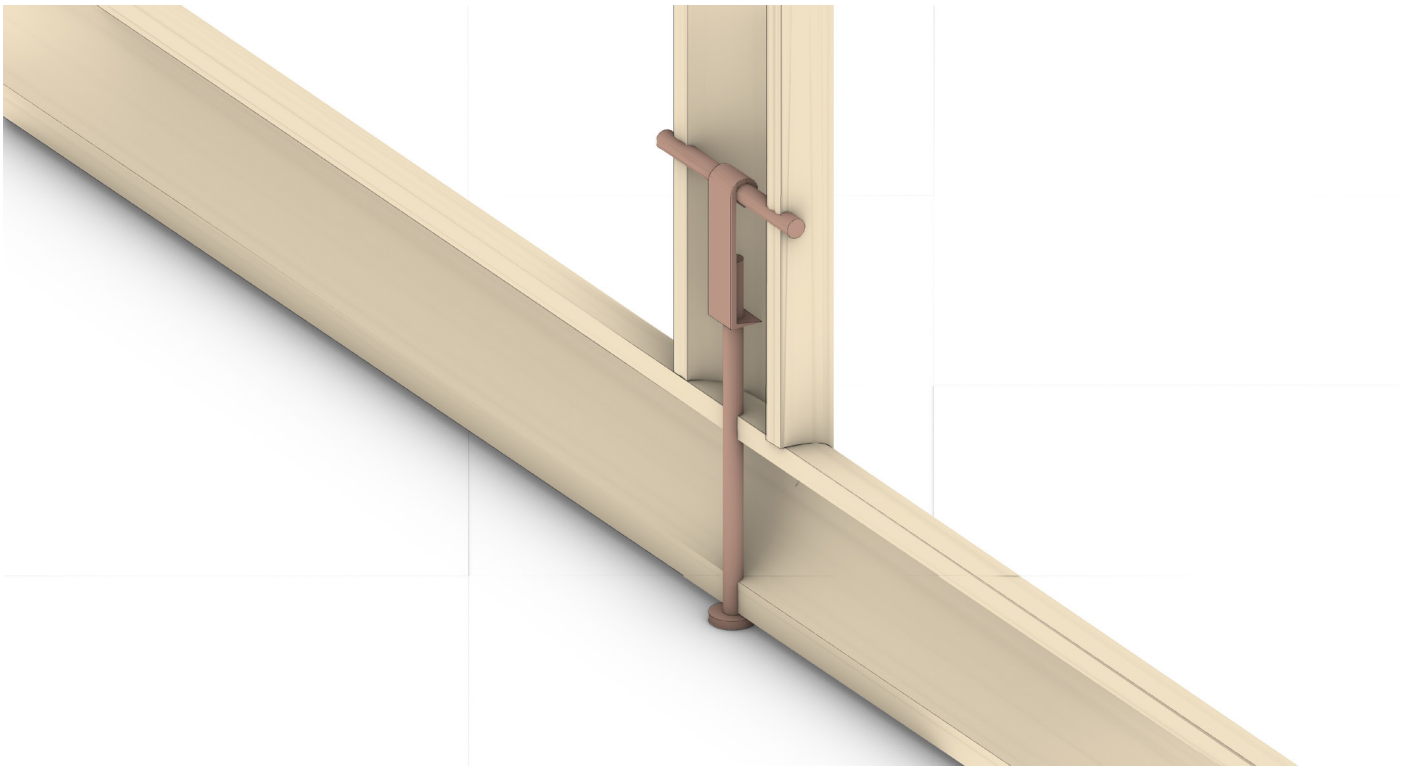


# Detail 03 1:10



## Detail 03-3D diagram





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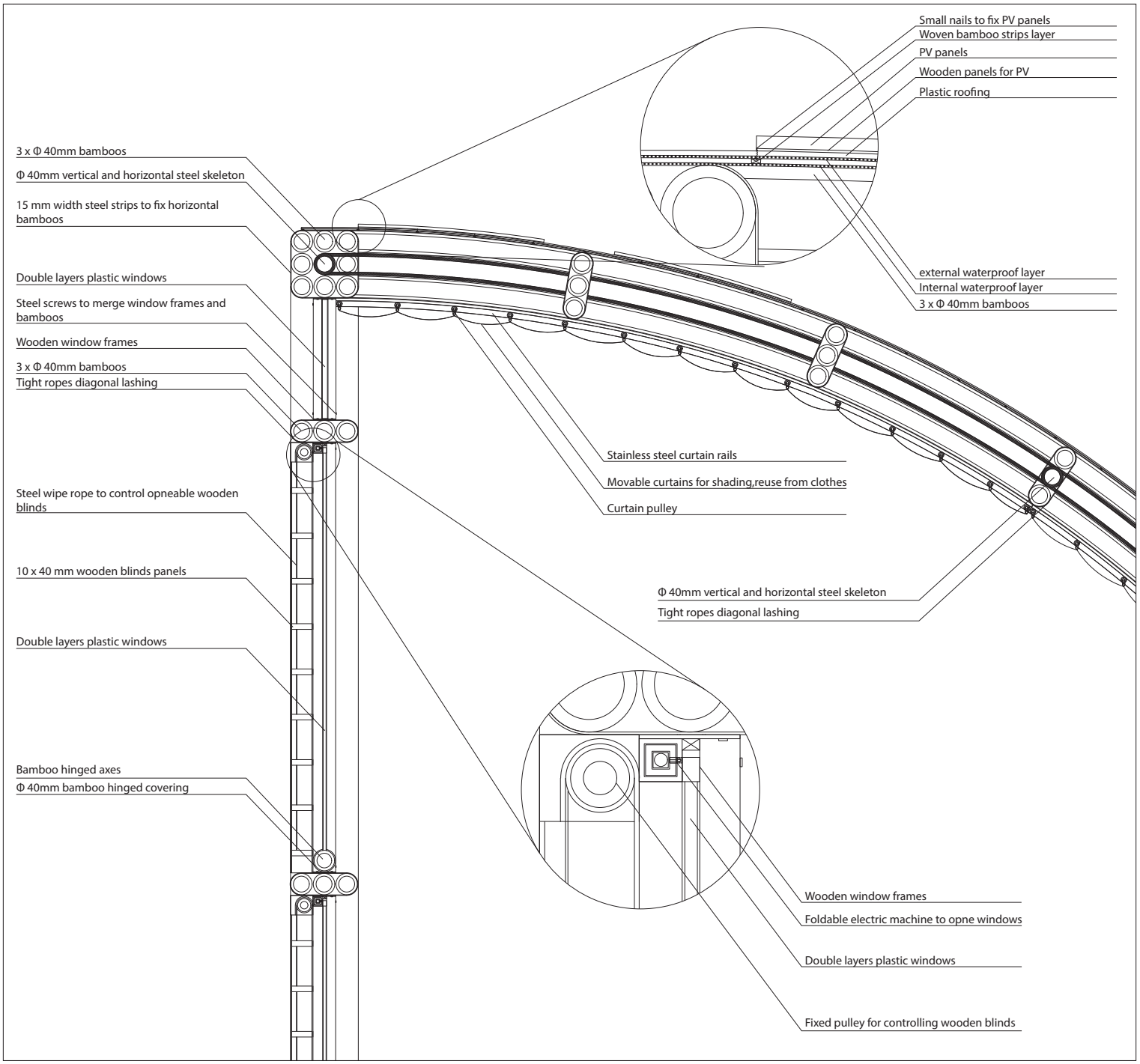

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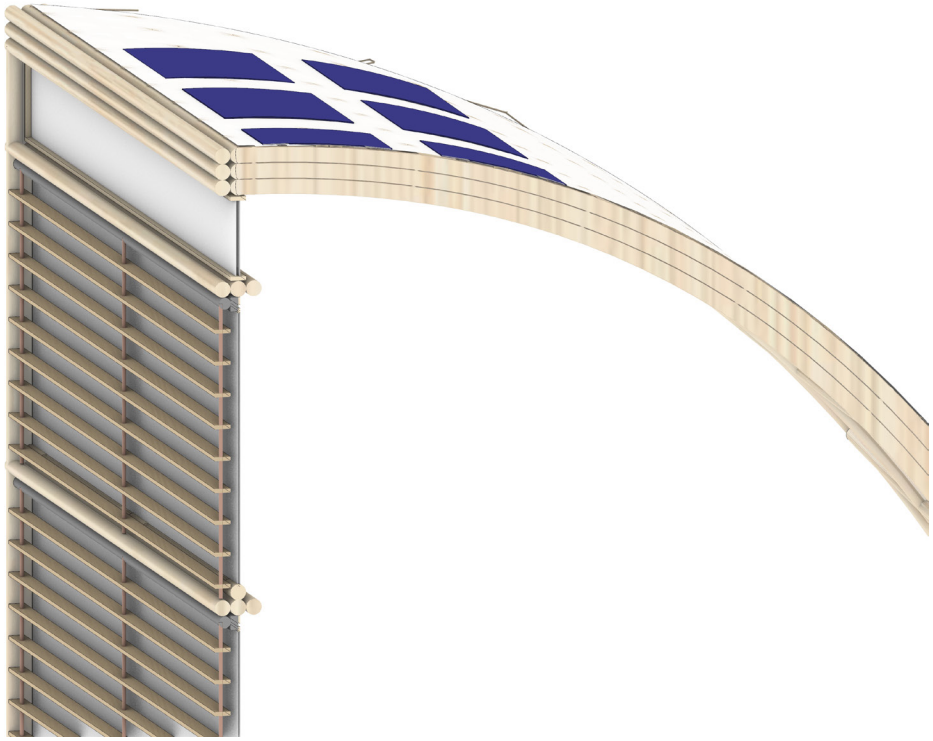

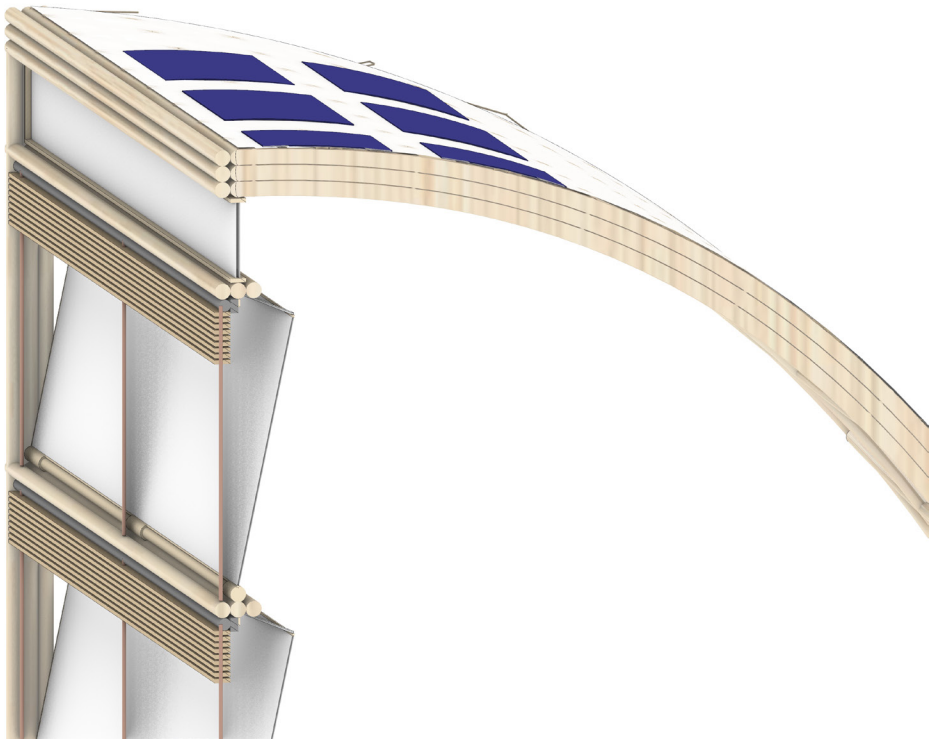

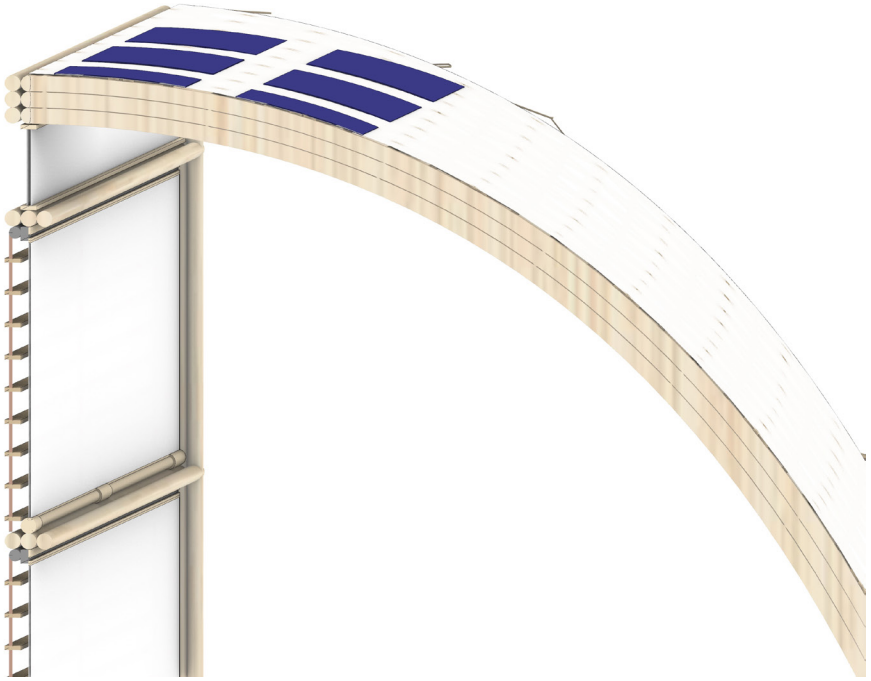

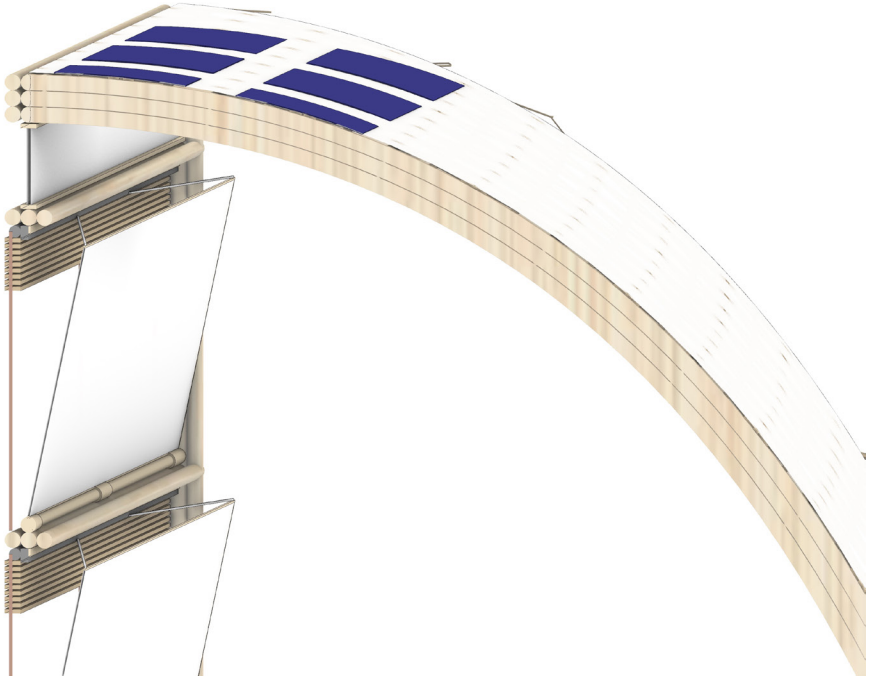

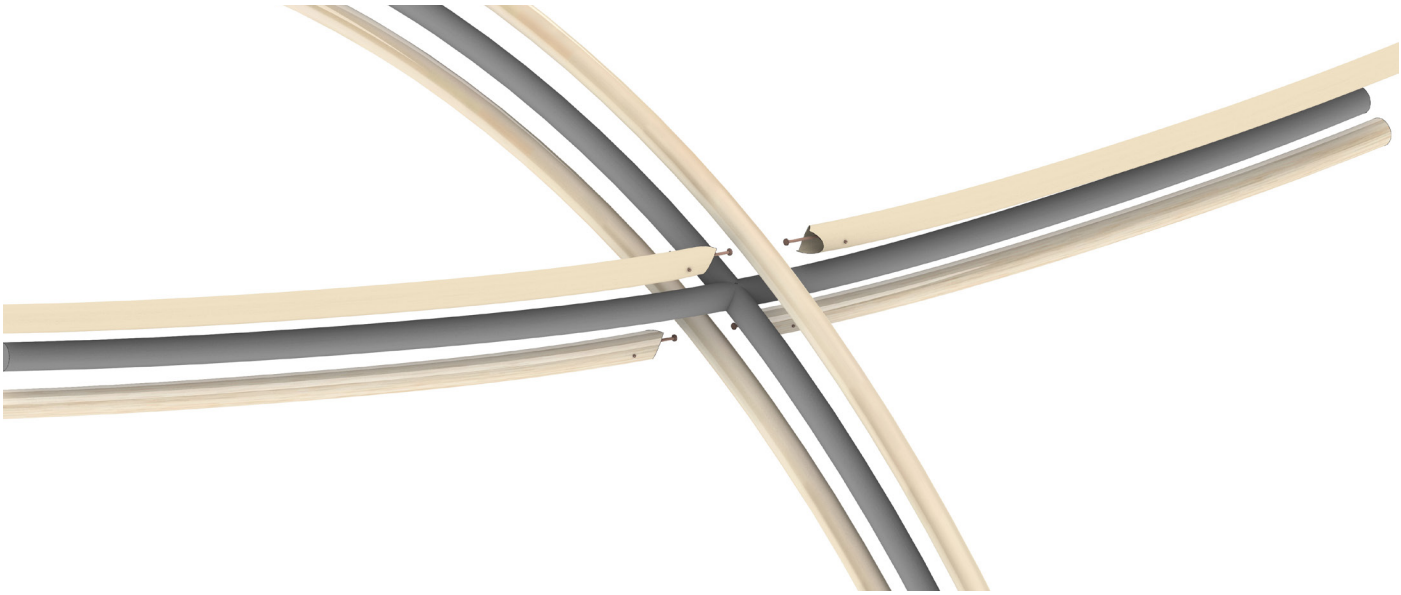

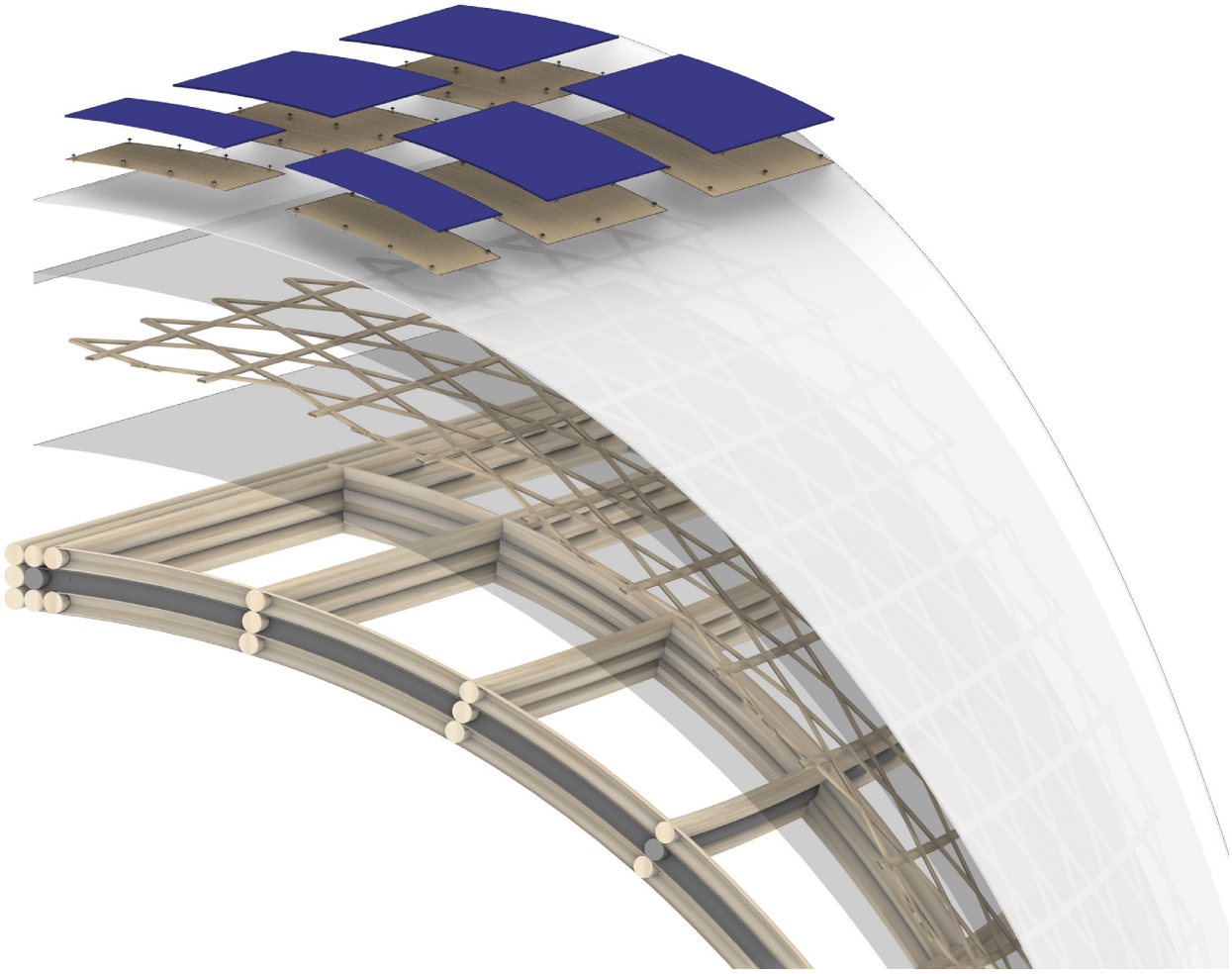

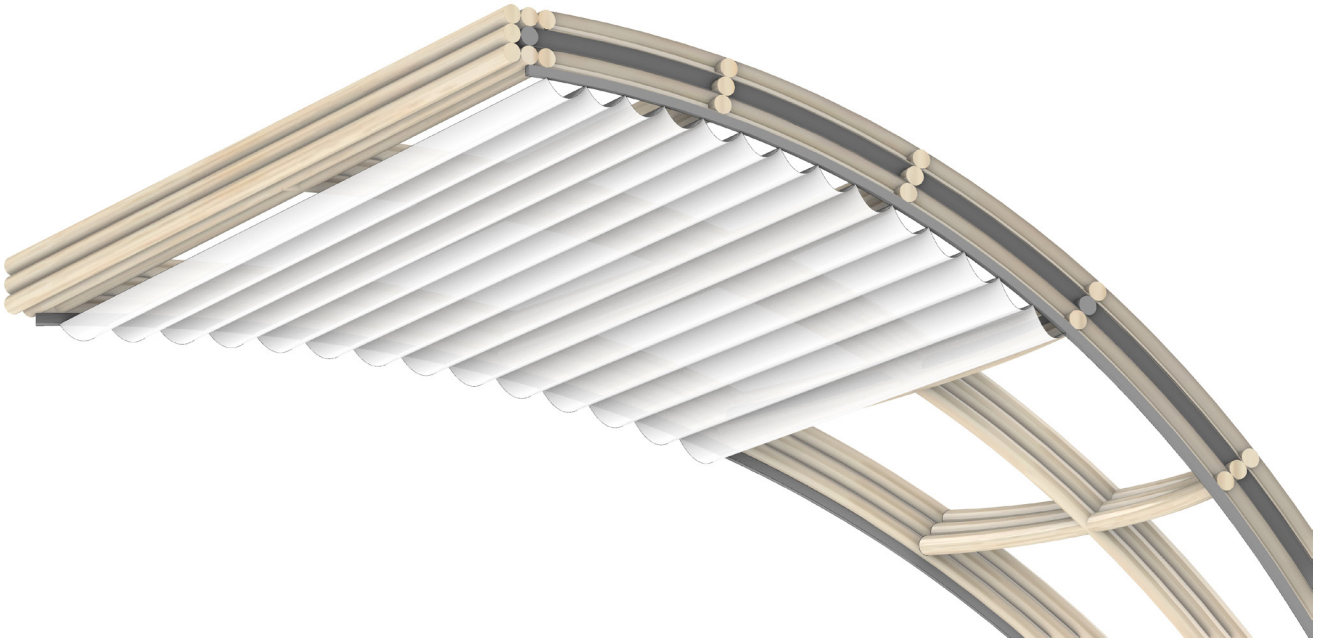

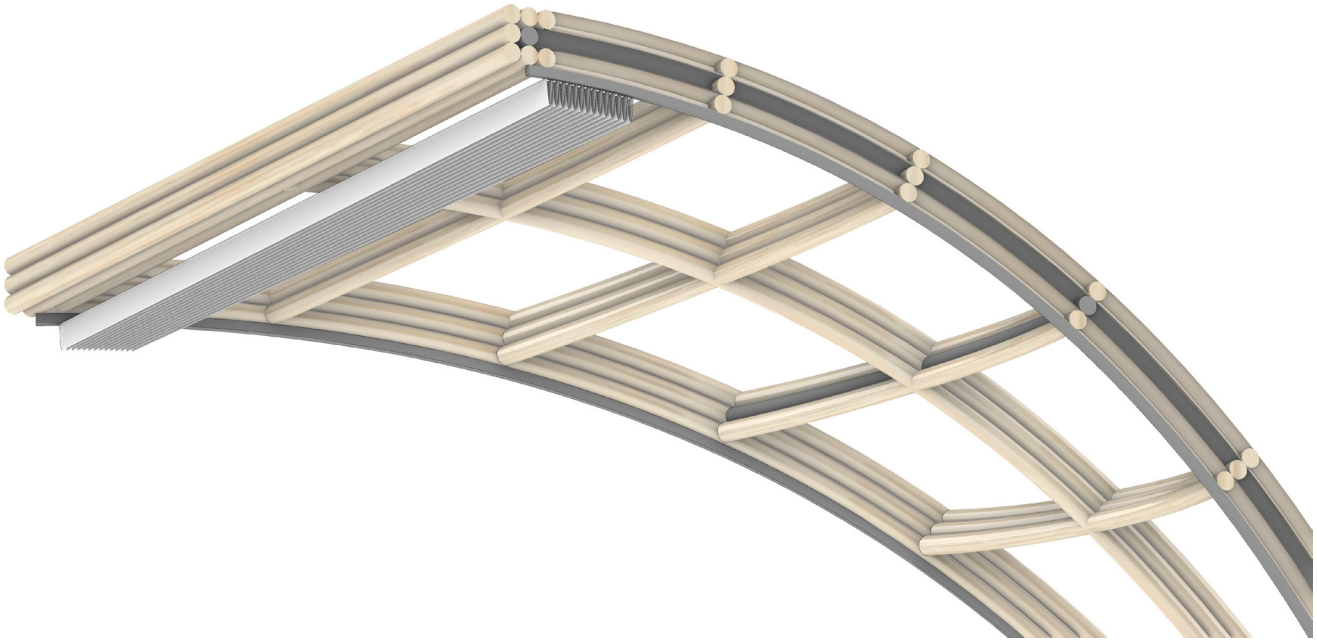

# 7 Conclusion

Bamboo as building materials can help a lot for rural area, where there is not so much money and population. It provides a possibility for local community to plant bamboo and construct building locally by themselves. Also, bamboo property shows that bamboo is an excellent building materials because bamboo grow so fast and has good mechanical property on compression and tension. Castiglione Della Pascaia, located on the area where Forever Bamboo project want to plant bamboo, will be easy to plant bamboo and feed fish locally. Therefore, the idea to integrate sustainable strategies by collecting urban waste and reusing to construct greenhouse, applying aquaponic systems to generate vegetable and fish for community seems to be realistic. The project tried to collect rainfall by modeling shape like umbrellas and saving under the floor decks, and generated electricity from PV panel for lighting planting bed. As a result, I want to provide multiple spaces serving for local community, such as food productions to eat, restaurants and dining area, education spaces for agriculture, playground on the park with shading under pavilion. Local inhabitants could have fun in the park and plant bamboo by themselves.

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