

Review Article

The Potential of Bamboo as an Environmental Friendly Material in Contemporary Buildings Construction

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Abstract

Building materials from their resource extraction through manufacturing, use, and disposal have become the major component of the total human effects on the global ecosystem and earth's climate, particularly in two centuries since the advent of the industrial revolution. So, the main challenge for the construction industry today is sustainability and there is the urge to adopt cost-effective and eco-friendly structures and materials. The research method of this paper is descriptive-comparative, and is based on a literature survey conducted to find the suitability of such locally available material which is known as "green bamboo". Bamboo is a strong, fast-growing and very sustainable material, having been used structurally for thousands of years in many parts of the world. In modern times, it has the potential to be an aesthetically pleasing and low-cost alternative to more conventional materials, such as timber, as demonstrated by some visually impressive recent structures. So, in this paper, the potential of bamboo and the possibilities of usage of bamboo in the construction field have been discussed. Applying bamboo as a material which leaves no harm on the surrounding environment can be a counter-movement to create a world with sustainable products in an ecologically supportive way.

Keywords: Bamboo, Environmental Friendly Material, Sustainable Buildings, Contemporary Buildings Construction.

1. Introduction

In the past half-century, with the rapidly advancing pace of urbanization worldwide, finding the raw materials and energy to produce building material, and absorbing the waste from their production use and disposal have become pressing global problems. For example, the production of Portland cement alone represents 8% of total global greenhouse gas releases deriving from human sources. Another highly visible example is the unprecedented degree of deforestation occurring worldwide to produce wood for building construction. The resulting loss of forest diversity, soil stability, water quality, and other long-term ecological and economic values are well known [1].

In recent years more and more attention is being paid on the environmental impact of building materials. The constantly increasing cost of energy and raw materials force the construction industry to think about alternatives such as renewable energy sources and raw materials and the reduction of waste. The use of bamboo in structural applications is a rapidly developing new field of research which has the potential to change the way that buildings and infrastructure are constructed [2, 3].

In recent years, as the effects of climate change have become more widely understood and documented, there has been a global effort to find new low carbon structural materials to reduce CO₂ emissions from construction. This has led to bamboo being reconsidered as an alternative structural material. Bamboo has many potential advantages as a sustainable material [2, 3].

In the building industry, costs and durability are the main factors determining the selection of building material. However, with sustainability as a key issue in the last decades, especially in Western countries, the environmental performance of building materials has become a more important criterion. Bamboo, as a fast-growing renewable material with a simple production process, is expected to be a sustainable alternative for more traditional materials like concrete, steel, and timber [4].

So, in this paper, the potential of renewable materials and especially bamboo will be investigated.

2. Life Cycle Assessment

The Life Cycle Assessment (LCA) examines the cradle-to-grave (through production, usage, and disposal) environmental impacts of the building materials. CA is an important part of the design phase of a project. It is crucial when choosing building materials [5].

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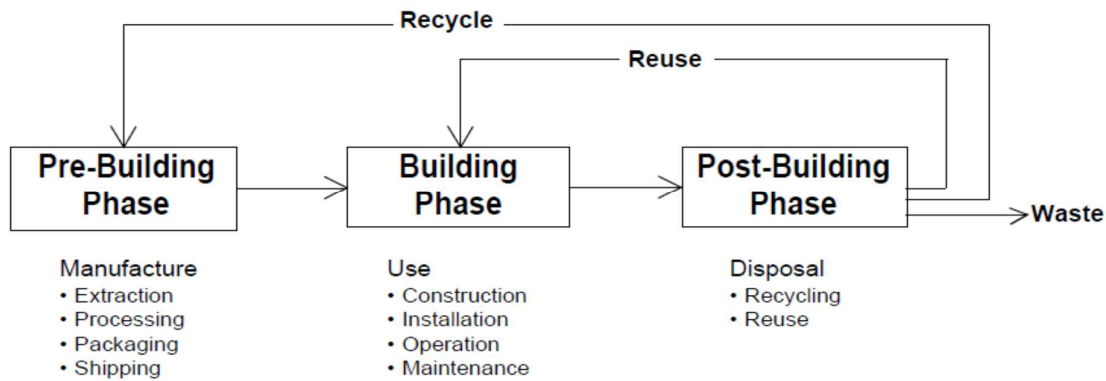


Fig. 2. Three phases of the building material life-cycle [5].

It provides information for the long-term costs of the materials rather than the initial construction cost [5] (Fig. 1.).

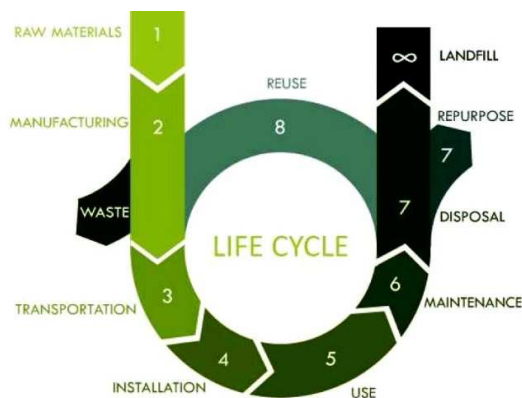


Fig. 1. The Life Cycle Assessment [6].

A material's life cycle can be organized into three phases: Pre-Building; Building; and Post-Building. These stages parallel the life cycle phases of the building itself. Fig. 2. shows the three phases of the building material life cycle.

3. Sustainable Design: Renewable Fibers

Today global trends allow the environment and world economic power to take stock for the benefit of our planet. This extends the interest in natural materials who supply the wood, like bamboo and other plant fibers that regenerate much faster than traditional woods. Companies increasingly bet on the use of natural fibers in an attempt to be "green", which increases their philosophical points of view about "eco." According to the Brundtland report: "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: first, the concept of needs, in particular the

essential needs of the world's poor, to which overriding priority should be given; and second, the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs [7]."

4. Bamboo, Rattan, Wicker and Other Materials with Similar Characteristics

a. Bamboo common name, is a giant grass the group of plants belonging to the family of herbaceous grasses, which are characterized by long stems and woody shrubs that develop stems (culms) of large diameter and size. According to the Colombian architect Simon Velez, "G. *Angustifolia* bamboo is a renewable resource in the areas of construction and infrastructure, which is used structurally in homes and other buildings. With a grade above the normal stress, similar to steel and concrete in compression. It can be used for furniture, carpets, paneling, flooring, partitions, plumbing, roof, structure and forms, among many others [7]."

b. Rattan or Rota (from Malay rotan) is the common name for some species native to tropical regions of Africa, Asia, and Australia. They have slender stems 2-5 cm diameter with long internodes between the leaves. They are superficially similar to bamboo but distinct in that the stems (Malacca) are solid rather than hollow, and they need some support, while bamboo can grow independently often at great heights without breaking [7].

c. Wicker, is a hard vegetal tissue fiber that comes from a family of shrub willows (genus *Salix*, *Salix viminalis* first and *Salix fragilis* and *Salix purpurea*), is knitted to create furniture, baskets and other useful objects. Other renewable fibers are abaca, coir, yute, sisal, and kenaf or cannabis [7].

5. Bamboo the Plant

The use of bamboo as building materials has occurred in a long period.

Most of the traditional houses in Indonesia and Asia use bamboo as building materials, both as structural and non-structural material. The use of bamboo in traditional houses is due to the fact that bamboo grows abundantly in the tropical rain forest. But after the industrial era has begun the use of bamboo as building material become obsolete. Bamboo is considered as cheap and non-permanent materials. It is also considered as low-class material, even called “the poor man timber” by many modern builders [8]. People tend to choose brick, concrete, and steel as structural and construction materials for a modern building, but nowadays, after global warming and sustainability issues have emerged, bamboo as building materials is widely discussed and reviewed. Some architect and builder nowadays tend to choose bamboo for building material. High-quality woods for construction are rarely found nowadays because of deforestation. Wood also takes a long time to regrow and ready to use as construction materials. Fig.3. illustrates world changes in deforestation. The red spots indicate regions that are experiencing a net loss of forests the dark green regions show a net gain of forests and the green regions illustrates the current forest regions. As shown in the map; areas threatened of deforestation are Southeast Asia, Central America, Brazil, Central Africa, and Northwestern Russia.

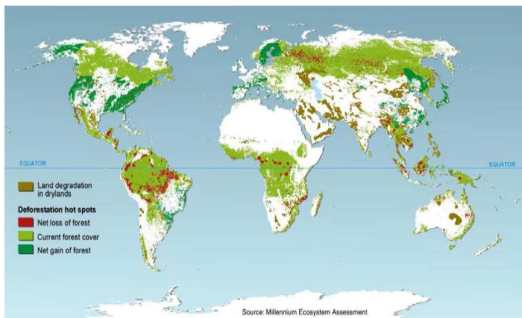


Fig. 3. World map changes in deforestation [9].

Bamboo is primarily a type of giant grass with woody stems. The stems are called “shoots” when the plant is young and “culms” when the plant is mature. Each bamboo plant consists of two parts – the “Culm”/stem that grows above the ground and the underground “rhizome” that bears the roots of the plant. “A single bamboo clump can produce up to 15 kilometers of the usable pole (up to 30 cm in diameter) in its lifetime”. Meanwhile, bamboo can be harvested in a short time, which is between 3-5 years. When planting, bamboo also releases oxygen into the air, the ability that cannot be performed by industrial materials like steel, plastic, and concrete. For the reasons, bamboo has been widely known as sustainable building materials. Bamboo naturally grows in the forest but also can be cultivated in the plantation. While the largest stock of bamboo grows

in the forest, it raises some important questions regarding resource ownership and management[10]. There are over 1500 species of bamboo worldwide, but only about 50 are commercially involved in trade [11]. Fig. 4. shows the contribution of world bamboo resources by continent.

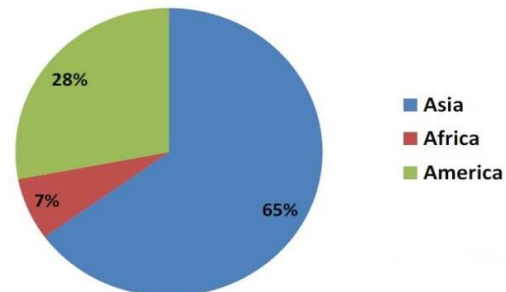


Fig. 4. The Contribution of World Bamboo Resources by continent [12].

6. Ecology and Biodiversity of Bamboo

Bamboo is native to every continent except Antarctica and Europe (where it has been introduced); it endures both rich and poor soils, temperatures varying from -20°C to 47°C , as well as rainfall ranging from 76.2 cm to 635 cm per year [13]. Fig. 4. shows the natural global bamboo distribution.



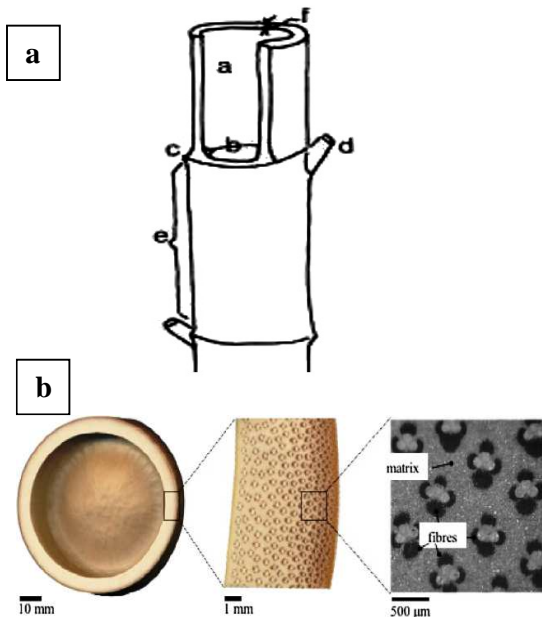
Fig. 4. Distribution of all woody bamboos, Bambuseae [14].

7. Bamboo Properties

Bamboos are tapered cylindrically shaped grasses with mostly hollow forms (though some species are solid cylinders). Bamboos normally have a final height of 20-25 meters and can reach 40 meters. The biomass is produced within a growing season of about 3-5 months. Bamboo is 26-43% cellulose, 21-31% lignin and 15-26% hemicelluloses[15]. Theoretically, the mechanical properties of bamboos mainly depend on the (1) species (2) age (3) moisture content, (4) position along the culm/top or bottom) and (5) positions of the nodes and the internodes [16].

Fig. 5. shows a diagram of the parts of a bamboo culm. The culm is the main axis or stem of the bamboo. The macro-physical structure as seen in Fig. 5. can be divided into the (a) cavity, (b) diaphragm, (c) node, (d) branch, (e) internode and (f) wall.

The nodes provide great resistance to structural failure and part of what has facilitated bamboo's lofty accomplishment. As bamboo is a type of grass, its microstructure is significantly more heterogeneous than that of timber, consisting of small dense fiber bundles in a less dense matrix material [17], as shown in Fig. 5.



**Fig. 5. a) The structure of bamboo culm [16].
b) Bamboo culm showing microstructural detail [17].**

Bamboo naturally grows in groups. Its growth character can be divided into two types: monopodial and sympodial bamboo. Monopodial bamboo roots spread horizontally in a shallow depth of the soil. New shoots are produced in a relatively long distance from the parents' plant. Monopodial bamboo is mostly found in a temperate climate such as Japan, China, and Korea. While sympodial bamboo roots grow very close to parents' plant thus form a clump of many stems or canes. It mostly found in a tropical climate such as Southeast Asia and South America [18, 19]. Bamboo is the popular name for a tribe of grasses, Bambuseae, which are tree-like woody stems. Bamboo is a group of perennial grass and includes the largest members of the grass family. Bamboo is tapered cylindrically shaped grasses with mostly hollow forms (though some species are solid cylinders). It is an extremely fast-growing plant, with some species obtaining growth surges of 100 cm per 24 hour period [11]. Xiaobing Yu (2007) described the components of

bamboo as cellulose, lignin, and hemicellulose. Cellulose is ($C_6H_{10}O_5$) basically a carbohydrate and the most important component of the bamboo for textile purpose. Lignin is another important constituent of bamboo. It is important in conducting water in culms. Hemicellulose is similar to cellulose but is less complex. The hemicellulose in bamboo has its main component Xylan between that of the hardwood and soft wood [20].

8. Bamboo and its Characteristics

Bamboo has certain characteristics which make it suitable for construction. It has been estimated that bamboo has ultimate tensile strength same as that of mild steel and this coupled with other merits can boost the usage of bamboo. Bamboo has a tensile strength of 28,000 lb per square inch, versus 23,000 lb per square inch for mild steel [21]. Bamboo fiber is longer than wood fiber, which gives bamboo some technological advantages due to its rigidity and durability and also makes it superior to wood in some physical and mechanical properties and is highly versatile for application in construction activities. Also, bamboo possesses high strength to weight ratio compared to wood. The strength of the culms, their straightness, smoothness, lightness combined with hardness and greater hollowness; the facility and regularity with which they can be split; make them suitable for numerous end products/purposes. Its strength and flexibility make it a viable material for building shelters that offer protection against hurricanes and earthquakes. Also, its strength-weight ratio supports its use as a highly resilient material against force created by high-velocity wind and earthquakes [22]. Being lightweight and hollow makes it naturally highly resistant to the earthquake (because it has high stiffness in relation to its weight).

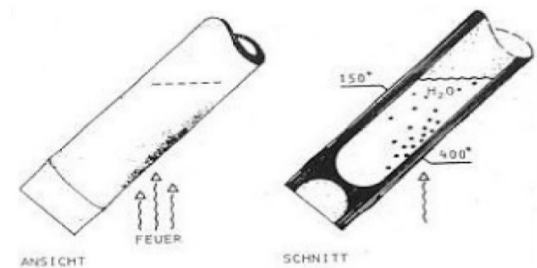


Fig. 6. Fire resistance of bamboo cane when is filled with water [23].

That, it does not shatter at failure means that when the earthquake is over the building can be left standing with relatively minor damage; providing shelter while the damage is being repaired. It can withstand the earthquake of magnitude ranging from 7-9. Bamboo, In a 7.5 magnitude earthquake in April, 1961, in Costa Rica, 20 bamboo houses were left standing near the epicenter [10].

Lightness and flexibility makes the bamboo plant an excellent material for the construction of prefabricated housing and structures. It has been estimated that during processing it consumes even less energy than wood. Bamboo offers sound yet light and easily replaceable form of shelter. The methods, activities and tools are often simple, straightforward, accessible even to the young and unskilled. It also provides protection against UV rays. Also, the fire resistance is very good because of the high content of silicate acid. Filled up with water, it can stand a temperature of 400° C while the water cooks inside (Fig. 6.) [23].

Other then, these characteristics bamboo also possesses characteristics that help in protecting the environment. It has a high leaf surface area that makes it very efficient at removing carbon dioxide from the atmosphere and generating oxygen in its

place. It generates almost 35% more oxygen than equivalent stands of trees and acts as a sequestration agent. Certain Bamboo species have been known to sequester as much as 12 T of CO₂ per hectare [21].

9. Mechanical and Structural Properties

Bamboo, being a circular, hollow structure has certain mechanical and structural advantages and disadvantages as compared to a rectangular solid timber of the same cross-section.

These advantages/disadvantages are, in other instances, complemented or accentuated by the cellulose fiber make-up of the bamboo. These comparative analyses are tabulated in Table. 1. Some rules of thumb for the relationship between the mass per volume of bamboo and some mechanical properties are given in Table. 2.

Table. 1. Comparative Mechanical Properties of Bamboo and Rectangular Lumber [10].

Property	Bamboo	Rectangular Lumber	Assumptions
Moment of Inertia, I	$I = 0.40A^2$	$I = 0.16A^2$	-For most bamboos, $d =$ internal diameter $= 0.82D$ -For timber, mostly $h = 2 \times b$
Optimum Material Use, EI	4900A ²	2240A ²	E cellulose = 70,000N/mm ² E fiber = 35,000N/mm ² • 50% of cross- section of fiber is cellulose. • E≈350x% of fibers. In bamboos, fiber is 60% on outside and 10% on inside, hence E outside = 350x60 = 21,000N/mm ² and E inside = 350x10 = 3500N/mm ² E dahoma =14,000N/mm ²
Bending	-Compression stress during bending may result in transverse strain in fibers of the top face of the culm. Lignin in fibers is weak in strain. Coherence in cross section is lost and EI drops dramatically. -If load removed culm returns to original straight form	-Timber will not regain original length when the load is removed.	-Poisson coefficient for bamboo = 0.3.
Shear	-Shear in neutral layer = 1.3x shear for timber • Smaller thickness to resist shear. -Larger forces on bolt fastness at joints. -Advantage of not having a rayed structure is nullified by hollow nature.	-Larger thickness to resist shear. -Has rays. Rays are mechanically weak. Hence, timber material is weaker in shear than bamboo material.	
Torsion	-Better torsional resistance due to circular shape.	-Poorer torsional resistance because of sharp corners.	
Wind Resistance	-Bending stress due to wind is constant over height of culm -At top (near skin) vessels decrease and cellulose replaces resistance to bending stress.		
Compression	-Because of hallow nature and thus greater distance of the solid mass from center, longitudinal shortening is greater and thus greater the like hood of lateral strain in lignin. -Friction due to clamping at top and bottom of culm reduces lateral strain in lignin.	-Solid nature makes for better compression resistance and reduced lateral strain.	
Density	700-800 kg/m ³	850 kg/m ³	

10. Use of Bamboo in Construction

In the construction sector, bamboo is used to make all the components of building both for structural and non-structural. Traditionally bamboo culms were used for constructing housing in the rural community, scaffolding and for constructing

footbridges. It was used in different ways for the roof structure, for doors and windows, walling, ceiling, manhole covers, etc. Bamboo is an excellent material when confronted with the vibrations of an earthquake: light, strong, rigid and elastic at the same time, making it ideal in construction (Fig. 7., Fig. 8.).

Table 2. Rules of Thumb Factors for Mechanical Properties of Bamboo [24].

Type	Bending	Compression	Shear	E
Air-dry bamboo	0.14	0.094	0.021	24
Green bamboo	0.11	0.075	-	-

Ultimate stress (N/mm²)=Factor×mass/volume (in kg/m³)
 Allowable stress $\approx \frac{1}{7} \times$ Ultimate stress



Fig. 7. Use of Bamboo in Building Construction [25].



Fig. 8. Bamboo as a construction material [25].

10.1. Construction and Structure Application

Traditionally, bamboo culms were used as primary building materials for constructing houses or bamboo frame was plastered with cement or clay which has now shifted to the construction of prefabricated bamboo housing. In modern times, engineered bamboo is used to make prefabricated bamboo houses with the help of bamboo-based panels, veneers, and laminated boards. The technology evolved can be effectively adopted for the construction of low-cost (single storied) depending upon the design of the house and nature of the interior finish, and also upon the local conditions. Lot of development has taken place to improve the technology and techniques that can be used to make bamboo suitable for construction. There has been an improvement in the preservation and protection technology of bamboo as well as in jointing techniques so that the use of bamboo can be proliferated as a construction material. These technologies are helping in increasing the durability of bamboo as a construction material. Advances in structural engineering and the development of bamboo composites have opened new vistas for lightweight, durable and aesthetic construction for a variety of applications with proper treatment. With this patient and natural expansion, the project describes a truly ecological approach to growth, which leaves no harm on the surrounding the environment, nor on the building material itself and is, therefore, a counter-movement to a conventional way of the present construction process. Architecture cannot be detached from form and architecture also requires structure to create the form, without structure, the form cannot be achieved and only become mere concepts. Structural system can be divided into form active, semi-form active and non-form active structure systems.

Form active structure is a structured system that only can withstand the axial forces, tension or compression. While the non-form active structure is a structured system that can withstand both, tension, compression, and also bending moment [26]. Organic shapes are implemented to the roof, and the roof form can be created and developed from spatial or surface structure. Surface structure can be divided into non-rigid shape, such as cables and membranes, and rigid shape, such as grid shell, shell, folded plate, hybrid and freeform. Building masses in Green School are using form active structure to achieve organic shape for the buildings form.

The main hall has used wide span arches that are stabilized by roof rafters, to form the curved shape roof. Long roof eaves provide good protection from sun and rain. The main building, functioned as office, which has nautilus shell shape is resolved using surface structure.

The surface structure of the main building, called as the heart of Green School, uses battens, rafters and purlins supported by bamboo pillars.

The system resemble to the tent-like structure system. The circular purlins play a role in giving the nautilus shell shape to the roof. Meanwhile other smaller buildings are using combination of arches and surface structure (Fig. 9.) [27]. OBI Great Hall which needs a wide span structure for the multipurpose hall is using a semi form active structure system. Trusses frame are arranged in a radially reinforced by braced frame to resist lateral forces. A comparative research of Green School main hall and OBI Great Hall conducted found that OBI Great Hall radial configuration of the trusses are needed compression purlins placed at the outer ring and tension purlins at the inner ring to stabilize the configuration (Fig. 10.) [28].



Fig. 9. Green School structure system; (a) Arches in the main hall “Mepantigan”; (b) Surface structure in main building “The heart of Green School”; (c) Bamboo arches in the class room [27].



Fig. 10. OBI Great Hall structure system; (a) Skylight; (b) Trusses; (c) Details of braced frame [27].

The “Bamboo Structure Project” was the result of a scope of a novel model of construction for the development of a resort town near Katalom in northern Iran Designed by architect Pouya Khazaeli Parsa (Fig. 11., Fig. 12.). The Bamboo Structure Project is a pioneering example of the construction made from natural materials. It is a unique example of a building that used seventy bamboos in their realized model, with two bamboos completing a curve from one side to the other side of the project. The building is a very significant sustainable building. They used gas pipes to make a base for the bamboo but did not fix the base to the ground. The total cost for a structure covering approximately 40m² was €700 which provides built by three non-professionals in merely two days. This distinctive structure provides highly cost-effective shelter and emergency housing [29].

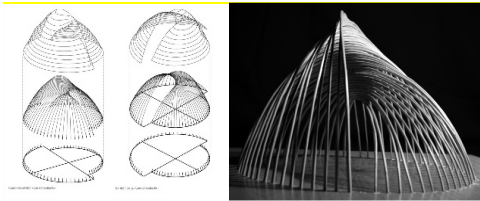


Fig. 11. Bamboo structured project (layers of construction) [29].



Fig. 12. Bamboo structured project [29].

Another highlight of the bamboo project is panda's installation for Beijing Design Week (BJDW) 2015–Rising Canes, a structural system made entirely of bamboo and ropes (Fig. 13., Fig. 14.). Bamboo was chosen as the main construction material and all materials are 100% recyclable. It is fully modular and easy to expand in every direction. The system can grow to habitat for 20 families within the first 9 months.

As the number of inhabitants keeps growing, the structure is extended to accommodate multiple communal spaces, bridges and even floating structures. By 2023 the bamboo development is extended to an urban configuration, which houses a population of 20,000 people and a surrounding bamboo grove of 250 acres. 2 new trees must be planted for each culm of bamboo taken as a construction material to secure building elements in the long run as well as creates a beautiful bamboo forest surrounding the development [30].



Fig. 13. Speculation of Future Developments. Image Courtesy of Penda [30].

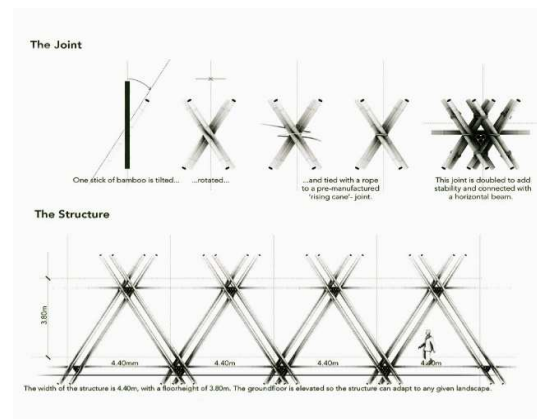


Fig. 14. penda's installation for Beijing Design Week (BJDW) 2015, (detail of structure) [28].

11. Conclusion

Bamboo which is fastest-growing renewable natural building material can be called as one of the oldest traditional building materials used by mankind. Through the limitations of natural forests to satisfy wood needs bamboo is one of the main non-timber alternative resources. One of the most important reasons to build with bamboo is its low cost that will easily shelter millions who could not normally afford a roof over their heads and its enormous elasticity makes it a very useful building material in areas with very high risks of earthquakes. The nature and properties of bamboo are suitable for form active structure system or semi-form active system, although it is also possible to use a non-form active structure system. Different methods are usually employed to curve or bend the bamboo into the desired shape. Curvature shape also can be generated by connected natural curve bamboo. The knowledge about the joinery system is also needed through the use of bamboo as sustainable building material to make different form. It can be easily bent, give desired shape and can provide joints to suit the construction. Finally, bamboo as an independent building material can be a viable alternative for steel, concrete, and masonry.

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