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The new frontier of green architecture: Bamboo as building material

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***Abstract*— The architecture of the 21st century works with unusual and uneven shapes, showing a getting bigger wish to astonish people, but facing the environmental and economic issue and holding out against earthquakes and calamities. So, the point is: which is the right Building Material? All designers know that it's a big challenge finding the perfect building material, that allows creativity being environmentally friendly and cheap. Moreover, versatility would be another good selling point. Let's figure out a building where structure and skin speak the same language: a material that allows that truly exists; naturally grows up in the temperate and subtropical zones of all the existing continents; it is the new muse of architects all over the world: the bamboo.**

Its great mechanical resistance allows us to use it for structural needs, its flexibility is particularly suitable both in seismic zones and in articulated shape design; the low weight makes it a good choice for realizing performant coatings and all kind of furnitures.

Choosing bamboo for architectural designs means using an eco-friendly and infinitely renewable resource, since it grows one meter per day circa and helping the environment, instead of destroying it.

EU strongly believes in this material, since it was, as a matter of facts, included as building material in the project "Switch Asia" by the European Union itself, as reinforcement of concrete instead of iron by Future Cities Laboratory and ETH Zurich. What to say? Two birds with one stone.

This study analyzes the structural functions of bamboo as building material within the project of a civic centre, where it shapes a big gridshell held up by tree-like pillars, realized with twenty centimetres diameter bamboo reeds . The resistance of this material mixed with its huge highness allowed to cover the whole free-space atrium of the civic centre with the bamboo gridshell. As a matter of fact, it turns out to be the key-element of the civic centre itself, meant to be the place devoted to education, sport and culture of Fuorigrotta neighbourhood in Naples.

Keywords—*bamboo, bamboo buildings, eco-friendly, natural materials*

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I. Introduction

This article deals with all the possible applications of bamboo in constructions and examines the main characteristics of this plant, some of the existing architectures that has already been built, and finally presents the project of a civic center in Fuorigrotta, in which the use of bamboo is developed according to the different technologies that this material offers .

II. Biological and mechanical properties

> For its particular structure this plant has a great compressive and tensile strength and, for that reason, is called "the vegetable steel".

Bamboos are perennial evergreen plants and some of the fastest growing; some species can reach almost ninety centimetres per day. Its life cycle is 3-5 years and the environmental impact due to the cut is low, thanks to the rapid growth. The bamboo also has the exceptional ability to tackle air pollution: a plantation is capable of absorbing up to 17 tons of carbon per hectare per year, 40 times higher than that absorbed by a wood of the same extension. That's why it is considered one of the key elements for the sustainable development of building production in developing countries .

Its biological structure is made of fibers scattered throughout the stem that give to the plant the mechanical resistance. By the mechanical point of view, they are similar to tubular rods measuring 0,03 millimetres in diameter. Every fiber is composed by little lamellas and each of them are made of thinner layers oriented both in the same and in the opposite direction. The irregular disposition of the fibers, denser outside than inside, add to the flexural strength almost the 10%. For its particular structure this plant has a great compressive and tensile strength and, for this reason, is named "the vegetable steel". The material between fibers is like concrete for steel and fills the 50% of the reed.

The main characteristics that determine the resistance of the bamboo are: age of the culm, density, moisture content and the position along the culm.

The best age to get the maximum mechanical performance is between 3 and 5 years since the birth of the plant. Bamboo cropped before can be used to make baskets, rods and placemats, while for age greater than 5-6 years its use is very common in furniture and fences constructions.

The resistance, as for wood, is directly proportional to the value of the density. Several empirical formulas define resistance values in relation to the density of the culms.

The water in the culm increases its resistance. In the case of dry bamboo (MC<5%) the resistance can reach values substantially higher than in the case of moderately humid culms (MC> 30%).

Finally, along the height of the stem the variation of fiber density involves high variations in the mechanical strength, because the fiber density increases from the bottom upwards. Then, in the lower areas of the stem the breakdown tension is lower than the higher areas where the fiber density is bigger.

III. Current applications in architecture

The use of bamboo as a structural material has ancient origins and was often used in his natural shape as beam and column in both East, for simple suspension bridges and scaffolding, and South America even for public buildings, with low-cost traditional technologies.

Nowadays, the use of bamboo is very common in the West too, thanks to the laminated technology: it is spliced along its longitudinal axis, cut in a lot of strips and shaped with a mechanical process to obtain rectangular slats. Then, lamellas are glued together to obtain beams or pillars in any requested form. Another innovation in the technological research is the Bamboo Fiber Composite (BFC): there are many industrial products realized by adding bamboo fibers to polypropylene, glass, epoxy resin that reach 350 MPa for the tensile strength.

In the building industry bamboo is not only used as structural element like column or beam, but is also employed in the production of: BMB panels (bamboo-mat boards) for the construction of doors, partitions, boxes, etc.; Laminated LBL (laminated bamboo lumber) with high bending strength; prefabricated panels of bamboo and cement; panels for floors. In order to realize these products the plant of bamboo has to be exactly five years old and dried in special ovens. The strips of bamboo are assembled or pressed together thanks to the use of special formaldehyde-free glues, then they are painted to increase durability and fire resistance.

IV. State of facts

A. *International Network of Bamboo and Rattan (INBAR)*

With its partners in many countries, INBAR is at the forefront of international efforts to promote greater use of sustainable bamboo buildings and other constructions. Bamboo, which supplies millions of households across the world with employment and building materials, has the potential to play a major role in addressing the growing global shortage for conventional building materials. INBAR aims are to formalize and increase local capacity to build with bamboo materials, thereby enhancing the safety, durability, and comfort of bamboo buildings, while also maximizing the environmental and poverty alleviating benefits that bamboo construction can offer.[1]

V. Projects and programmes

A. *Switch Asia - Eco friendly bamboo*

The SWITCH-Asia project-Eco-friendly Bamboo Production for Reconstruction promoted the use of bamboo in place of timber or concrete and steel. It operated in the Chinese region of Sichuan and has become a model for adopting sustainable reconstruction efforts with bamboo in post-disaster areas. The project also demonstrated how such building methods can not only contribute to sustainable development but also help to make houses more resilient in the face of possible natural disasters in the future.

B. *Future Cities Laboratory*

Bamboo has been used as reinforcement for concrete in those areas where it is plentiful, though dispute exists over its effectiveness in the various studies done on the subject. Bamboo does have the necessary strength to fulfil this function, but untreated bamboo will swell with water absorbed from the concrete, causing its break . Several procedures must be followed to overcome this shortcoming. The research conducted at the Future Cities Laboratory in Singapore entails investigating its potential to replace steel reinforcements in structural concrete applications, facing to water absorption, swelling and shrinking behaviour, durability, fungi attacks as well as chemical decomposition of bamboo in order to transform bamboo from a locally applied organic material into an industrialized product.[2]

VI. Examples

A. *Bamboo reinforced pillars and facades: Bamboo house, China*

The use of bamboo as main material of this architecture comes powerfully symbolic because it belongs to both the Chinese and the Japanese culture. The choice of bamboo as both structural and not-structural element had the aim to rediscover the essence of Asian architecture. The bamboo culms have been subjected to some treatments based on protection by woodworm and mold. The system used is an ancient Japanese method, still adopted, and consists of a rapid heating in the flame of the side surface of the barrel (270°) in order to cause the emission of a resin that polymerizes fast, forming a self-protective film. After this treatment, the bamboo was covered with an oil as suggested by Chinese local carpenters. The interior of the vertically cut bamboo has been realized through the use of a special drill. After the removal of interior spinal,

[1] www.inbar.int
[2] http://www.fcl.ethz.ch/

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in order to realize a structural column, a steel rod has been inserted inside the barrel for the whole length of the stem. At this point a controlled jet of concrete has been executed to make everything compact. In practice, the bamboo cane has been used as lost formwork. The structural properties of the bamboo get increased during this process, solving the fragility caused by its inherent flexibility without minimally changing the aesthetic characteristics.

Figure 1 Internal bamboo walls

B. *Bamboo Facades: housing for refugee children in Noh Bo, Tyin Tegnestue*

These houses have been built by combining artificial and natural materials. They are born from the collaboration between TYIN, non-profit humanitarian organization that operates in the field of architecture, and local workers, in a mutual exchange of knowledge. The structure in wood and steel, prefabricated and assembled in site, allows to lift off the ground the huts, preventing deterioration due to moisture. It rests on the concrete cast in four old tires reused.The bamboo taken from local reserves close to the site and braided according to local tradition was used as a coating. The roof of shaped tinplate has a geometry similar to the wings of a butterfly , which facilitates natural ventilation and collects rainwater to be stored for long periods of drought .

Figure 2 Picture of the bamboo roof

C. *Structural Bamboo: Housing, St.Val Architect a Port Au Prince, Haiti*

Bamboo poles are connected together with high tech metal "X" joints to create the exoskeleton of the home. Round platforms act as floors, which are accessed by a circular staircase that wraps around a central supporting element. Wooden slats and glass panels bend up the exterior in a double helix to light the rooms and encourage ventilation. Finally the whole structure is wrapped in canvas to seal the inside off.

Figure 3 The node between Bamboo culms

D. *Structural Bamboo: Zocalo Nomadic Museum, Mexico city, 2008*

In the age it was designed, the Zocalo Nomadic Museum was the largest bamboo structure ever built: the innovative approach consisted in the use of bamboo as primary structural element. The building, that was a temporary construction, occupied 5130 square meters and contained two galleries and three theatres.

VII. Technical standards

Nowadays only a few non-European countries , such as India , Ecuador, Peru , Colombia and the US , have legislation that supports technical architects and engineers in the design and verification of bamboo buildings and structural elements. The first technical standards on bamboo buildings date back to 1973, when the Indian government promulgated the IS 6874: "Method of tests for bamboo" providing a series of recommendations on how to proceed in the laboratory for evaluation of the mechanical strength of bamboo culms and to 1979, with the IS 9096: "Preservation of bamboo for structural purpose", both updated in the 2000s. As the Indian government, also Ecuador, Colombia and Peru proclaimed their legislations for bamboo buildings: above all, in Peru was recently promulgated the "Norma Técnica E100 Bambù", a text that collects all the laws on the use of bamboo as a building material. In the USA the International Council of Building Officials has written the AC 162: 2000: "Acceptance criteria for structural bamboo". Now, thanks to INBAR (International Network for Bamboo and Rattan) in 2004 were written:

ISO22156/2004 applies to the use of bamboo structures, i.e. structures made of bamboo (round bamboo, split bamboo, glued laminated bamboo) or bamboo-based panels joined together with adhesives or mechanical fasteners. It is based on limit-state design, and on the performance of the structure. It is only concerned with the requirements for mechanical resistance, serviceability and durability of structures.

ISO22157/2004 specifies test methods for evaluating the following characteristic physical and strength properties for bamboo: moisture content, mass per volume, shrinkage, compression, bending, shear and tension and provides informative guidelines for staff in laboratories on how to perform tests.[3]

VIII. Case Study - Project of a civic centre: different uses of Bamboo

The choice of bamboo for this project is due to different considerations. The first it's about the production process: the use of materials whose manufacturing process is very polluting made the sector of buildings one of the main emitters of carbon dioxide in the atmosphere, so a material whose production process was of low environmental impact was needed. In the second place, a lightweight but resistant material was necessary, to be used for covering huge spaces. Moreover, a dry manifacturing technique has been chosen, to facilitate maintenance and replacement of deteriorated elements without increasing costs, infact bamboo is cheaper than wood and has a higher growth .

This study analyzes the different applications of bamboo as building material within the project of a civic centre, where it shapes a big gridshell held up by tree-like pillars, realized with twenty centimetres diameter bamboo reeds. The resistance of this material, mixed with its huge highness, allowed to cover the whole free-space atrium of the civic centre with the bamboo gridshell. It covers 1500 square meters and two different levels, achieved by ramps. It is made by laminated bamboo strips, bound together by metal rivets.

Figura 4: Bamboo external gridshell

A. The project

The lot is located in Fuorigrotta (Naples). The main purpose of the project was to maximize the hours of classrooms exposure to sunlight, positioning them to southeast¸ in this way the natural light and thermal contributions due to solar radiation were guaranteed .

The inclination of the rows of classrooms has given to the building a first direction within the lot. Orthogonal to this direction are positioned two blocks: the administration and the civic one, that are diametrically opposite. The civic block includes the cafeteria/ bar/ foyer, an Internet point and library. For their particular vocation of meeting and socializing places, these blocks also host connection functions between different levels. This organization, founded precisely on the separation in functional blocks, can be checked also in the structure: for the classrooms block the system is made of X-Lam panels combined with laminated beams; for the civic and administration blocks the technique of bamboo gridshelles and pillars, while the gyms and the auditorium are designed only with laminated elements.

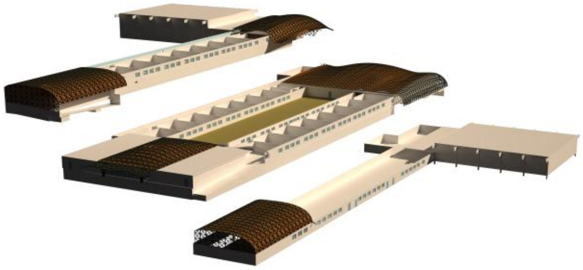

Figure 5: Plan of the civic centre**,** showing the roof made of bamboo

B. Bamboo as roof coating

The roof of classrooms and laboratories, extending beyond the wall, is like brise soleil for windows. The system classroom-corridor has been envisioned to provide soft lighting and natural ventilation: the classroom has openings on both sides; one on the left, in communication with the outside, and the other on the right, in communication with the corridor that becomes a porch in the warmer months, due to its mobile roof made of bamboo panels.

The roof of classrooms consists of a structure composed of laminated beams curves which are connected by purlins and coatings with both external and internal panels of bamboo.

Its stratigraphy allows to effectively moderate external peak temperatures, producing an ample lag of the thermal surge, that reach the value of 13.7 hours (the UNI EN 13786 recommend in fact a value higher than 10 hours. In these conditions the stratigraphy reaches the "excellent performance" category indicated from the mentioned law itself). It is described in Table 1.

Table 1Thermal characteristics of the roof layers

Description	Thickness [m]	Thermal Conducivity [W/mK]	Heat Capacity [J/kgK]	Density [kg/m3]	Thermal Resistance [mqK/W]
Bamboo strips	0.050	0.170	900	700	0.294
Vapour barrier	0.002	0.003	1800	30	0.667
Insulation	0.080	0.035	1030	70	2.286
Wooden plank	0.030	0.034	2700	600	0.882
Breathable layer	-	-	-	-	-
Wooden Slats	0.020	0.150	1600	580	0.133
Wooden finishing	0.030	0.130	2700	600	0.231
Bamboo strips	0.050	0.170	900	700	0.294

C. Bamboo gridshell and pillars

[3] www.iso.org

The civic and administrative blocks have a representative architectural shape. The gridshell is made by bamboo rods having cross section 50x50 millimetres and module 500x500 millimetres and it's linked by metal connectors. It is held up by tree-like pillars, made with twenty centimetres diameter bamboo reeds linked to the gridhell rods arriving to the floor by metal connectors too. The bamboo tube is anchored to the ground by means of an improved adhesion steel screw. To the tube are hooked, by means of metal discs and screws, long strips of bamboo which give the conformation of a tree.

The roof is designed with a layer of interior finishing panelling in wood of about 2.5 cm, a layer of vapour barrier, a layer of 8 cm as insulation, a waterproofing breathable layer, battens for ventilation, raw plank and sheet as finishing.

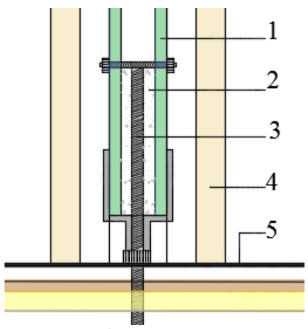

Figura 6 Detail of the Bamboo tree-like pillar

1-Bamboo culm
2-Filling morter
3- improved adhesion steel screw
4-Bamboo slat

IX. Conclusions

With this project it was possible to see the immediate applicability of bamboo as a building material in various ways. It allowed the realization of a very huge and light roof, entirely made of natural materials; at the same time, in the hall and in the cafeteria, it was possible to create a plastic and sinuous space, thanks to its strength and flexibility, congenial to develop children's imagination during breaks from lessons. The technological research about this building material is still going on and there are still many applications to be investigated and defined: this is good for the construction sector, which will soon make the necessary adjustments on modern issues such as environmental sustainability and cheapness.

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