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Constructive systematization of structural bamboo culms: architectural conceptualization and modulation

Sistematización constructiva de los tallos de bambú estructurales: conceptualización y modulación arquitectónica

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ABSTRACT

Bamboo is an essential potential ally for humans in the current situation of climate emergency and systemic crisis. Its transformation to obtain technical products generates emissions and energy consumption that do not exist when bamboo is used in its natural form. Through the analysis of cases (all developed by the architecture and urban planning studio Bambusa Espinosa, based in Madrid, Spain) categorised according to the dimensions of the basic structural modules in each case (one-dimensional, two-dimensional and three-dimensional), the methods of fabrication and installation are studied. As these are non-conventional construction systems based on a little-known material, the manufacturing processes, the necessary training of professional personnel, as well as the graphic expression materials required, are as relevant as the final built result.

Keywords: Bamboo; architectural structures; structural modulus; structural bamboo culms.

RESUMEN

El bambú es un aliado potencial fundamental para los seres humanos en la situación actual de emergencia climática y crisis sistémica. Su transformación para la obtención productos técnicos genera emisiones y consumos energéticos que no existen cuando el bambú es empleado en su forma natural. A través del análisis de casos (todos desarrollados desde el madrileño estudio de arquitectura y urbanismo Bambusa Espinosa) categorizados según las dimensiones que los módulos estructurales básicos tienen en cada caso (unidimensionales, bidimensionales y tridimensionales), se estudian los métodos constructivos utilizados para la prefabricación o la puesta en obra de este material, dependiendo del caso. Como se trata de sistemas constructivos no convencionales y basados en un material poco conocido, los procesos de fabricación, la necesaria formación de personal profesional, así como los materiales de expresión gráfica que se requieren, son tan relevantes como el resultado construido.

Palabras clave: *Bambú; estructuras arquitectónicas; módulos estructurales; tallos de bambú estructurales.*

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1. INTRODUCTION

Bamboo is a natural and heterogeneous material [1], even more so than sawn timber, because bamboo culms have diameters and wall thicknesses that cannot be chosen or modified, unless they are used as raw material for the production of technical bamboo products, such as glued laminated bamboo, cross-laminated bamboo or densified bamboo. However, processing into technical products involves the use of machinery and adhesive products, with consequent emissions and energy costs, which bamboo in its natural state of culms lacks [2].

This article raises the question of whether bamboo culms can be used in their natural form as a structural material and be put on site using conventional graphic expression tools, such as dimensioned plans, perspectives, models and computer graphics. The approach to this question is based on the analysis of the professional practice of an architecture and urban planning studio called Bambusa Espinosa, located in the city of Madrid, which, without limiting itself exclusively to bamboo as a construction material, has used it (in its natural form) in a large proportion of the projects it has developed.

2. METHODS

According to Campo [3], the creator, any creator, investigates when he works tirelessly on his creation; convinced that this creation transcends him, as Stefan Zweig already pointed out. Alberto Campo Baeza alludes to the complete design process in architecture, while this article focuses particularly on the most tangible aspect of this process: the structural conception according to the basic constructive module operating in each case and the graphic representation prior to its manufacture. The common thread running through this process is the constructive systematisation in architectural projects in which the structural material is bamboo, mainly in its full-section stem form and, in one of the cases presented, using laths that can be extracted from the stems themselves without further processing other than cutting and sanding, thus avoiding the energy expenditure and emissions related to densification or the use of adhesives, as is the case with laminated products, for example [4]. The cases considered have all been developed by the Madrid based architecture and urban planning studio Bambusa Espinosa, and have been catalogued according to the dimensions of the basic structural modules in each case: one-dimensional, two-dimensional and three-dimensional. Beginning with the two-dimensional ones, as they are the simplest to execute and serialise (as the traces of what, when erected, will be the basic flat module can be followed by horizontal flat templates), continuing with the three-dimensional ones, and ending with the one-dimensional ones, as they are the most complex to build (even though the starting point is a basic linear module), the cases presented also show the synergies that arise when combining a natural and heterogeneous material such as bamboo, especially in its natural form of culms, with materials such as steel cables, tensioned canvas, typical of so-called textile architecture, the term "tensile architecture" being more appropriate [5], or cellular polycarbonate panels.

3. RESULTS

3.1. Flat / Two-Dimensional Modules

3.1.1. Self-sufficient Hotel in Arusha, Tanzania

The requirements of the programme evolved from a second home first, to a guesthouse and finally to a hotel. The site is a plot of land in the foothills of Mount Meru, facing Kilimanjaro and with a panoramic view of the Maasai steppe. The entire development was to be self-sufficient in each phase due to the lack of services in the area. The project is based on three strategies, concerning energy, water and materials. Regarding materials, bamboo and compacted soil blocks were used instead of the more common materials in the region, which are timber and cement blocks. Bamboo was used for the main structure of the buildings open to the public: the bungalows and a common area (Figure 1).

Figura 1. Longitudinal sections of the compound

These main structures support the roof of the aforementioned buildings and consist of six flat triangulated modules composed of beams, columns and struts. The six modules are arranged radially, generating a dome with a hexagonal base, articulated at the apex as a reciprocal structure (Figure 2). As there was no bamboo for construction in the Tanzanian market at the time, the whole industrial process related to its harvest and treatment to obtain a high quality building material was put into practice on site. Training sessions were held for local craftsmen and workers to learn how to build with bamboo.

Figure 2. Interior of a bungalow

Figure 3. Gallery of the extension

3.1.2 Hotel Extension in Palenque, Mexico

The client requested the extension of the main building of a hotel complex located next to the road leading to the Mayan site of Palenque, in the state of Chiapas, Mexico. In this case, the area already had treated material ready to be used in construction, as well as craftsmen experienced in bamboo construction. The result is a gallery parallel to the existing building (Figure 3), created by seven flat modules. Each one of the modules is conceived as a truss whose beam extends beyond the support furthest from the façade of the existing building, generating a cantilever which free span is shortened by means of an inclined strut. This generates a three-dimensional structural framework which, in addition to optimising its operation and resistant sections, generates an organic lay out that turns the supports into tree-like structures (Figure 4).

Figure 4. Cantilever of the extension

These are types of support widely used in the history of architecture with different materials, not only to shorten the span of cantilever elements but also to group and channel the resulting loads, as in the case of Gaudí's Sagrada Familia [6] , the famous Palazzeto in Rome by Pier Luigi Nervi [7], Terminal 4 at Madrid airport by Richard Rogers and Antonio Lamela [8], or Stansted Airport by Norman Foster [9].

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3.2 Spatial / Three-Dimensional Modules

3.2.1. Structure with Tensional Integrity, 'Tensegrity', in Mallorca, Spain

In 2017, a 'tensegrity' structure [10] was designed, calculated and built for a circus company planning to perform a show on it. Its final height was 8 metres, achieved by using nine bamboo culms compressed by steel cables (Figure 5). The bamboo culms were joined in groups of three, each group generating two tetrahedrons linked by a vertex. These groups were connected horizontally, on the ground, using the steel cables. Once all the cables had been tensioned, the assembly, being a rigid structural unit in itself, was lifted with the help of a crane and placed vertically in its final location (Figure 6).

Figure 5. Finished structure

Figure 6. Left, photograph of the installed structure. Right, night photograph of the structure in use as a circus device

3.2.2. Experimental greenhouse, in Madrid, Spain

In October 2019, a three-day intensive course on bamboo construction took place at the Universidad Politécnica de Madrid, aimed at students and professionals. The theoretical part of the course was held at the Escuela Técnica Superior de Arquitectura, while the practical part aimed at the execution of a greenhouse to remain in the experimental agronomic fields of the Ciudad Universitaria – Moncloa campus (Figure 7).

Figure 7. The greenhouse from the outside

The design concept behind the experimental greenhouse is based on three-dimensional, self-supporting structural modules (Figure 8). A sequence of three of these modules was arranged one after the other and covered with polycarbonate panels previously fixed to flat bamboo modules as gables (Figure 9).

Figure 8. Self-supporting three-dimensional module

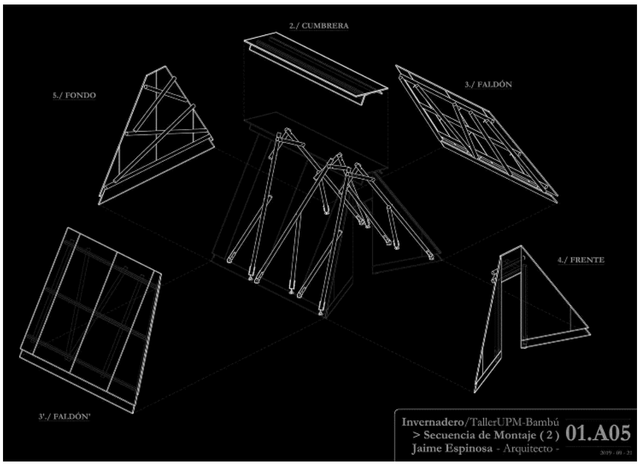

Figure 9. Axonometric perspective of the main greenhouse elements

3.2.3. Structure with Tensional Integrity, 'Tensegrity', in Madrid, Spain

Greenpeace Spain, inspired by and activism action developed in the UK and knowing the previous experience of the studio in Mallorca, requested in autumn 2020 a similar vertical structure for one of its actions. However, due to the requirements of this case, the modular system is radically different: it must be transported in a small vehicle such as a van, and it must be able to be assembled without auxiliary means (such as scaffolding or cranes) in a maximum time of 15 minutes (Figure 10).

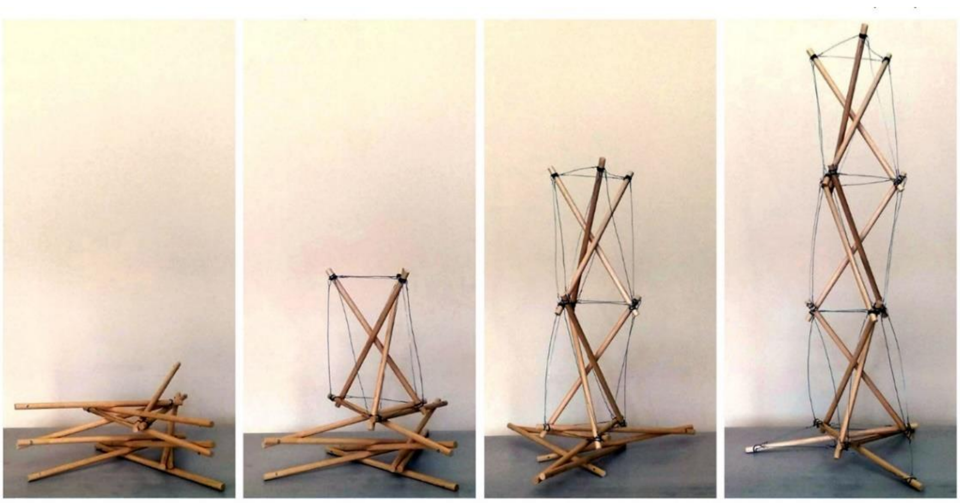

Figure 10. Model of the deployable structure

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The system consists of three equal elements, made up of culms hinged together at their ends [11]. Each of these elements can be extended lengthwise or folded in the shape of a W or M. When these three elements, which in isolation could be considered flat (or even linear, if they are extended lengthwise), are linked together, they manage to remain in equilibrium, the whole being a three dimensional element (Figure 11). This assembly is deployed vertically in sections, up to a total of three, each of these sections being fixed by means of the triangulation carried out with steel cables, exceeding 6 meters in height when the device is fully deployed (Figure 12).

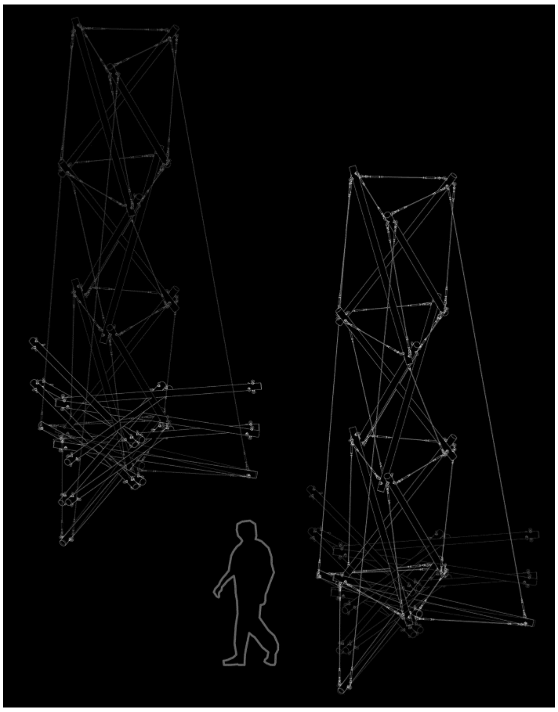

Figure 11. Axonometric perspectives of the 'tensegrity', folded and unfolded

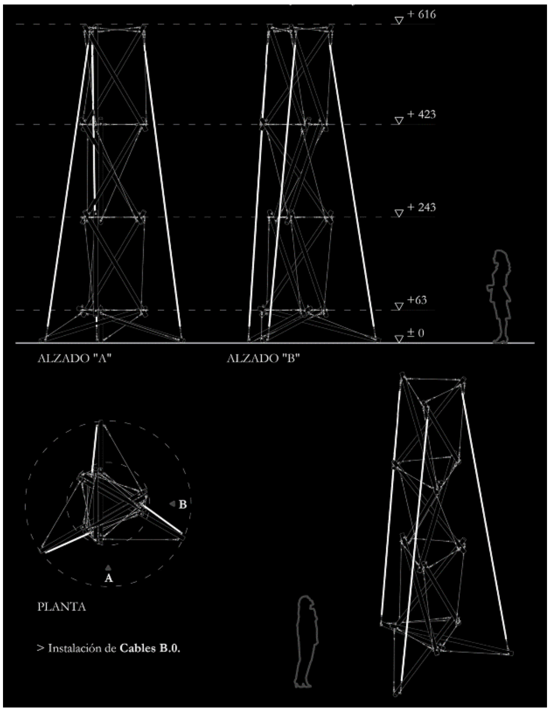

Figure 12. Plan, elevation and perspectives of the device deployed

3.3 Linear / One-Dimensional Modules

3.3.1. Prefabricated bamboo and tensile canvas pavilions (various locations)

In order to achieve a design that could be easily assembled and disassembled, 'bamboopod' was conceived, a system that has been fully developed and patented by the studio. The main reasons for the application of this design concept are to reduce the impact of logistics on the selling costs of bamboo structures, to optimize resources (due to the controlled working environment in the production plant) and to increase accuracy, which is reflected in the quality of the final products (Figure 13).

Figure 13. 'bamboopod' prototype

The aim of this technology is to turn bamboo into a common, even mainstream, building material. The strategy for this is to develop products in which bamboo plays a key role, combining it selectively with other materials and adapting it to work together with commercially available building systems. Used as culms, not as boards or laths, bamboo is a material that can even have a positive environmental impact, given its carbon dioxide sequestration performance and the low energy consumption required for processing [12]. The design is driven by the concepts of added

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value, prefabrication, mass-serial production, zero-waste manufacturing, and a quality working environment. These are all existing concepts. However, bringing them all together in a harmonious way in relation to bamboo construction is an unprecedented approach. The main material of the system is bamboo in its natural form [13], but it is combined with iron fittings, PET and PVC fabric, and eventually an aluminium frame cladding system such as windbreaks or curtain walls. In this way, all materials used in the system are biodegradable (bamboo), reusable (iron) or recyclable (fabric, and aluminium), and therefore zero-waste manufacturing can be achieved (Figure 14).

Only what is to be built arrives at the construction site, where no more than two people with spanners and ladders are needed to erect a given structure. Once dismantled, it is packed in a compact form, i.e., a 7 by 7 metre module, which reaches 4 meters at the highest point, and its roof, takes only 3 by 3 by 1 meter room. This reduces transport costs, both in economic and environmental terms. The system is designed to be easily assembled and disassembled by following the instructions manual, making it suitable for both permanent and temporary uses. The heaviest component of the system weighs 20kg, thus any of them can be handled by one person. All components are packed in boxes of less than 50kg, to be carried by two people. Power tools are only used on the production plant, which increases safety.

Figure 14. Infographic of a proposal for an events tent

3.3.2. Hexagonal dome, in Granada, Spain

The commission received was a room for practices and group therapies, with a drop-shaped appearance from the outside, based on the concept of a rhombohedral dome and with bamboo laths as the structural material of choice. The roof is made of reused ship's sail fabric (Figure 15).

Figure 15. Interior of the dome

The required surface area made it evident that structural ribs were necessary for the structure to be safe and sound. Therefore, the building is a drop-shaped tent with a hexagonal plan whose structure is based on polygonal arches. Each segment of the arches is made of bamboo laths arranged in parallel and tied with cable ties, inspired by the traditional Japanese weapon called 'shinai'. The project is conceived as a set of pieces that users shall assemble following a manual, which is organized in three parts (Figure 16).

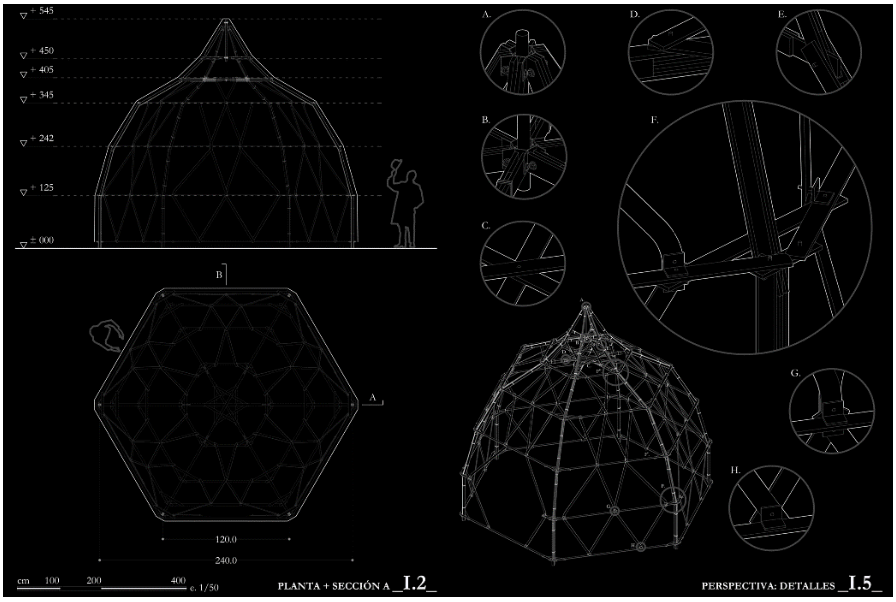

Figure 16. Drawings from Part I of the dome assembly instructions manual

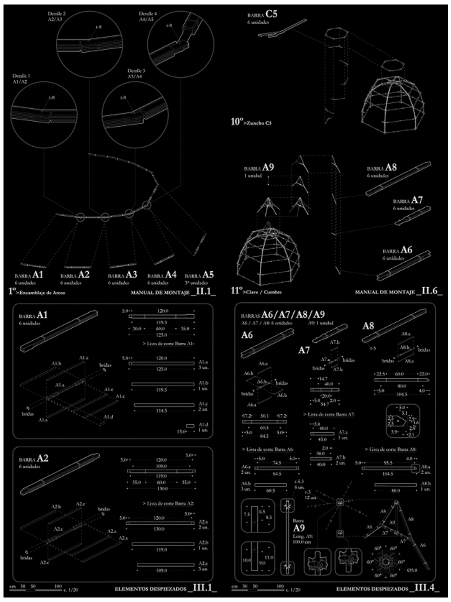

Figure 17. Excerpts from Part II and III of the assembly instructions manual

The first part is the drawings of the finished construction. The second part is the steps to follow for the assembly and erection of the prefabricated parts. And the third part contains the instructions and drawings for the fabrication of these parts, which have limited dimensions to minimize transport costs. Therefore, when the construction is disassembled, it also needs very little room to be stored. Due to the hexagonal plan, six half-arches rise from each corner of the room and join at the top, first creating a six-pointed star and also forming the base for a cupuline, in order to achieve the intended drop shape of the structure (Figure 17).

To stabilize and give structural unity, a series of horizontal rings are installed to link the vertices of the polygonal arches that are at equal heights. The structure is finished with the incorporation of shorter elements, in the form of triangulation between the rings, to prevent them from buckling (Figure 18).

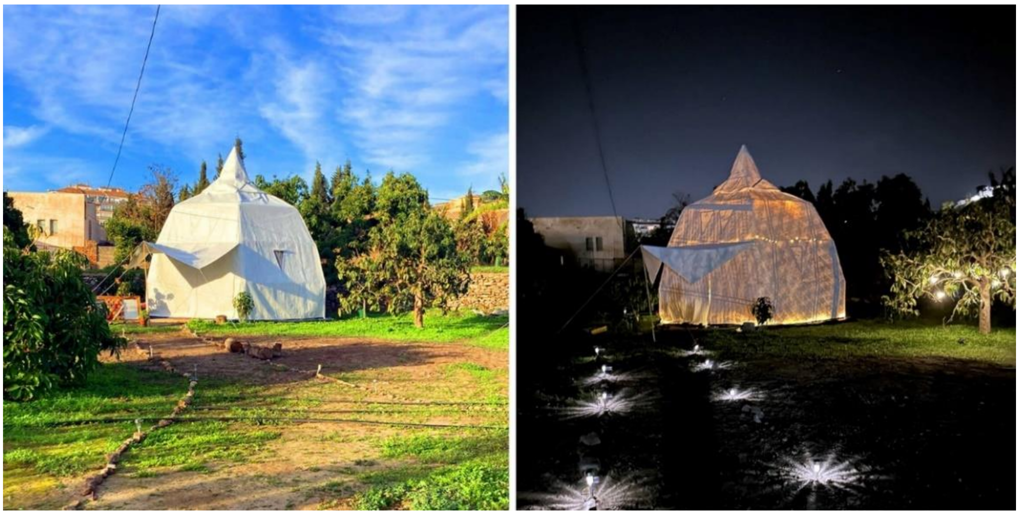

Figure 18. Left, daytime photograph of the dome. Right, night-time photograph of the dome

4. DISCUSSION

Use of bamboo in its natural form of culms as a structural material contributes to reversing the current ecological impact of the construction industry, even in non-producing countries. Bamboos are potential carbon dioxide sinks, like trees, but much more renewable [14]. They are fast-growing plants that embed carbon remarkably while alive, especially before the fifth year after sprouting: during the growth and maturation stages, they absorb carbon dioxide at higher rates than the rest of their lives.

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Managing bamboo forests and plantations for use as a building material means storing carbon dioxide from the atmosphere (until that bamboo burns or decomposes) while at the same time providing a potentially high-quality building material that could be comparable in mechanical performance to steel and reinforced concrete [15]. Global warming is therefore addressed in two ways simultaneously: by stopping carbon dioxide emissions related to steel and concrete construction because there is a reliable alternative, and by reducing carbon dioxide in the atmosphere by capturing and storing it. When treated with environmentally friendly methods, bamboo does not withstand prolonged exposure to direct rain and sun. For this reason, all the structures analysed are self-protected by design [16], except those with tensile integrity in Mallorca and Madrid, because they had to remain functional for only 3 months and the time for the activist action, respectively.

In the case of unconventional construction systems based on the use of alternative material that is little known outside the places where it is produced (it is common that it is not known how to work it properly even in those places), the manufacturing process, regardless of whether it is in a factory or on site, and the training of professional staff involved, as well as the graphic expression materials required, are as important as the final resultant construction.

DECLARATION OF COMPETING INTEREST

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

AUTHORSHIP CONTRIBUTION STATEMENT

Jaime E. Espinosa: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft.
María J. Cassinello: Project administration, Writing – review & editing.

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