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# Design protocol for bamboo structures based on the principles of Building Information Modeling

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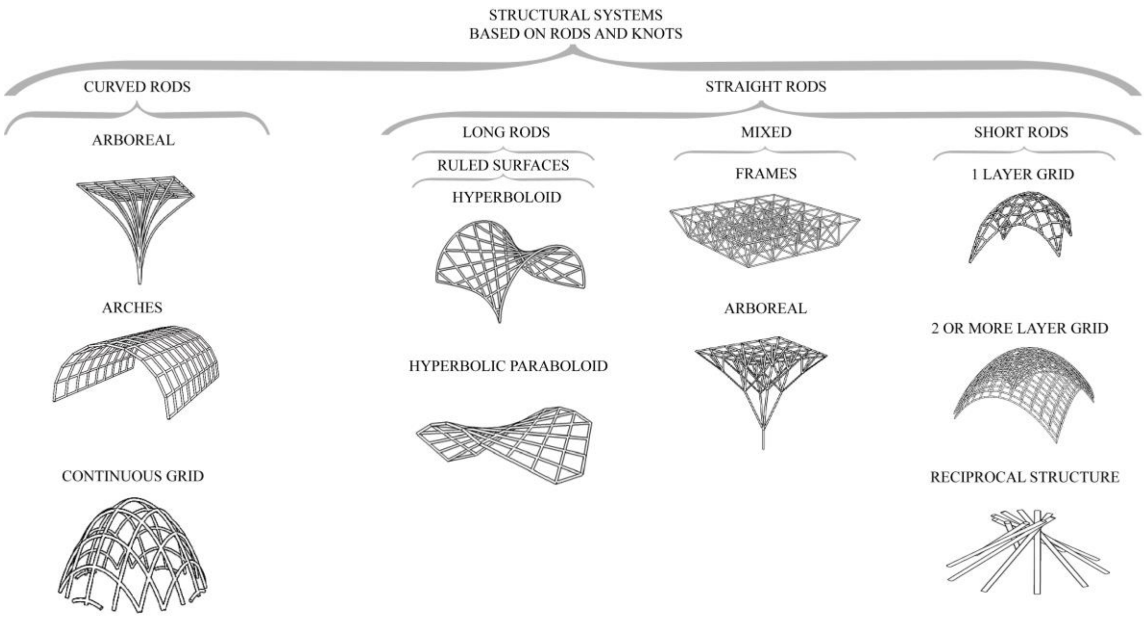
## Abstract
Bamboo has been used worldwide long before the discovery of modern construction techniques and materials. Nevertheless, its use has remained as a handcrafted practice, with regionalized methodologies and construction techniques. The research group at the *Universidad Nacional Autónoma de México-UNAM* has successfully characterized the mechanical properties of three different species of Mexican-grown bamboo: *Oldhami*, *Guadua Angustifolia* and *Phyllostachys bambusoides*, as well as started the development of research projects for the analysis and design of lightweight structures with bamboo [1, 2]. Translating the results into practice, UNAM and University College London-UCL are working on a joint research project with the goal of developing an international design protocol for bamboo (whole culms) structures based on the principles of Building Information Modeling-BIM; expecting to develop the relevant scripts for geometric 3D modeling, structural analysis and robotic fabrication. The project's preliminary results are presented in this paper.

**Keywords**: Building Information Modeling (BIM), design methods & aids, bamboo.

## 1. Introduction
In the world of shell and spatial structures, there is a great variety of classifiable systems both from theirs constructive process as for the use they are going to behold. The research group has tested advantages and disadvantages of each system with the aim of choosing the one that more opportunities presents for the implementation of the BIM system, considering variables such as: knot complexity, rod uniformity, geometrical efficiency, module fabrication, etc. A conceptual map of structural systems based on bamboo rods was developed and is presented in the Table 1:

Table 1: Conceptual map of bamboo´s structural systems based on rods and knots.




## 2. Bamboo rod connections

Due to the fact that bamboo is an anisotropic material, composed of longitudinal fibers held together by weaker parenchyma cells, the shear resistance of this material parallel to the fibers is less than in any other direction. Besides, it has been observed that bamboo´s behavior under stresses indicates that it possesses great deformability; therefore permanent displacements are generated at applied loads lower than bamboo´s ultimate resistance or under the action of loads over time.

In structural systems where compression predominates, the fracture is produced slowly starting from the connections. Therefore the premise “the whole system behavior depends on the nature of the connections” is born. In the research project PAPIIT IG 401014, the group has worked on connections based on knotting, bolts, bidirectional carbon fiber, unidirectional carbon fiber, fiberglass and assemblages, observing a better structural behavior when assemblages are present, meaning “the bigger the contact area is, the more rigidity the system will have. (Figure 1).

Figure 1: Laboratory testing photographic register.

This process requires certain geometrical expertise; nevertheless, it opens a new field of esthetic solutions that combine the connections with structural resins. (Figure 2).

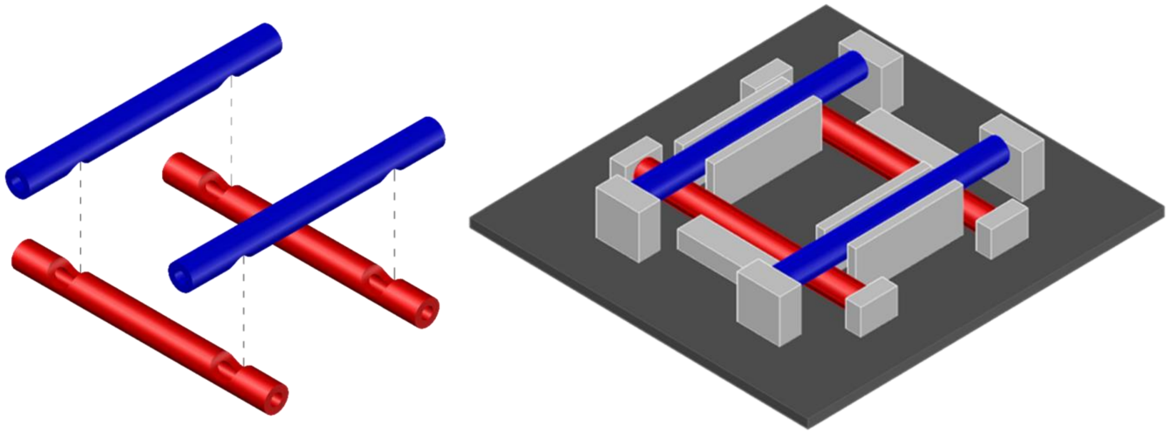


Figure 2: Guiding system to control the form and connections.

The main focus of the exploration process was to increase the rigidity of the structure through the management of knot interactions. During this process it was possible to reduce and even remove the necessity of traditional bolt and nut connections. In the cases where bolts were kept, it was possible to reduce its diameter and use it only for added rigidity at the connection.

The acknowledgement about the state of the art, gave the guideline for the design of a portable positioner that lacks in nowadays practice, with the aim to achieve a better geometric control during the constructive process, since many discrepancies between the original project and the constructed form were identified.

During the research process, three prototypes of positioners where designed. The first positioner is a basic model that only controls 90º connections; the second model guarantees perpendicular connections and allows horizontal displacement in both directions. The third positioner offers angular freedom between the rods, allowing the connections to be made at angles other than 90º.

The research process has required the fabrication of physical prototypes for recreating the building management of the connections, with the aim of conducting properly and gradually the improvements required by each component of the models. (Figure 3).

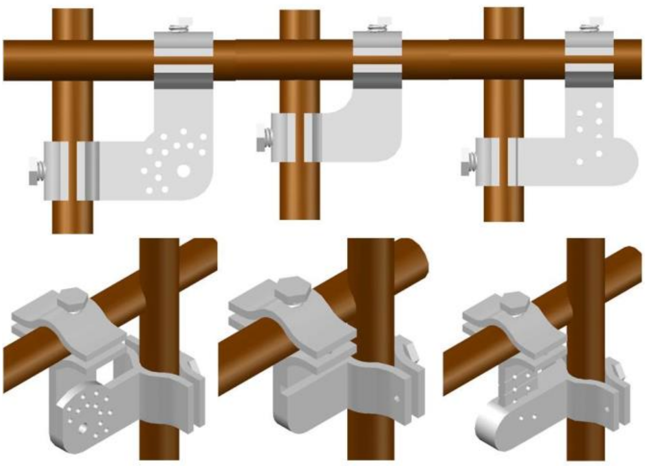


Figure 3: 3D portable positioners.

## 3. BIM Bamboo: UNAM-UCL Collaborative Research

**BIM Bamboo** is a research project funded by the UK's Engineering and Physical Sciences Research Council (Grant Ref EP/M017702/1: BIM BAMBOO, PI Lorenzo) which has provided a collaborative platform for the Structures Laboratory at the UNAM and the Department of Civil, Environmental and Geomatic Engineering at UCL. This research re-examines the structural use of natural bamboo culms against the backdrop of the Digital Age and postulates a new design and fabrication framework to support the construction of high-quality, sustainable and resilient bamboo structures suitable for the 21st century.

The work plan between both universities is based on an information exchange between both parties. It is designed to integrate research results and practical experience generated at the UNAM during previous research projects [3] with the resources and expertise in technological development of UCL. All of this in order to define new application schemes, avoiding formal typologies or procedures; looking for a renovated approach towards bamboo as a serious construction material with the technological possibilities of information management, design methodologies and manufacturing processes that BIM systems provide.

A prototype called BIM-Bam 1 will be designed and built in order to achieve these goals. This case study aims to comply with the fourth stage of The Royal Institute of British Architects - RIBA protocol (Technical Design). The following 3 stages are established, where the first two define the design and the third one defines the manufacturing process:

1 DESIGN COMPONENTS
- 1.1 Main components of the system (Bamboo culms).
  - 1.1.1 Geometrical digitalization of different bamboo species.
  - 1.1.2 Parametric definition of bamboo.
  - 1.1.3 Production control and material quality.
- 1.2 Secondary components of system (knots, ties and connections).
  - 1.2.1 Definition of connection and construction elements.
  - 1.2.2 Mechanical and geometrical modeling of secondary components.

2 STRUCTURAL AND CONSTRUCTION SYSTEMS
- 2.1 Cataloging in terms of geometrical parameters and structural behavior the constructive and structural systems where bamboo is typically used.
- 2.2 Contrast analysis between the structural systems where bamboo is used and the mechanical properties of the material.

3 CASE STUDY
- 3.1 Definition of the structural system for the prototype.
- 3.2 Design and development of prototype through BIM methodology.
- 3.3 Industrialized manufacture of prototype.
- 3.4 Monitoring of prototype behavior.

## 4. Case Study BIM-Bam 1

In order to prove the viability of the research project, a translation grid shell–TGS [2, 3, 4, 5], constructed with knots and rods with straight bamboo culms was proposed as case study – Project BIM-Bam 1. (Figure 4).

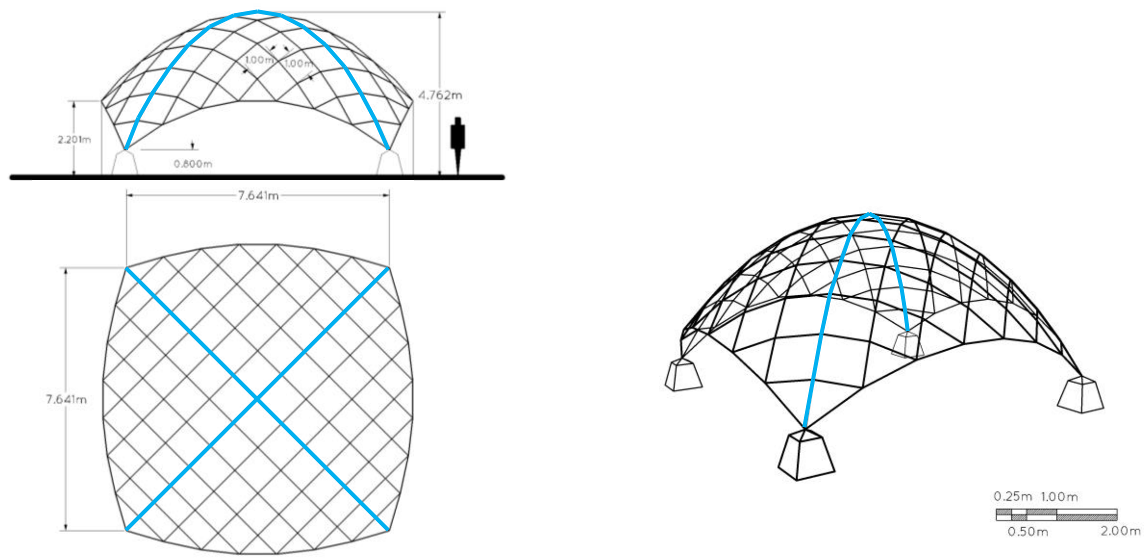
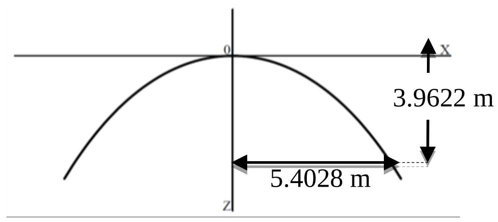



Figure 4: Case study BIM-Bam 1

The computer program GEOG (**Geo**metry-**G**rid shell) developed by Professor Oliva Salinas in 1982 during his Doctor studies at the Universität Stuttgart, was used during the form finding process of the prototype. In 1990 GEOG was improved by Reinhard Kürtten at the Universität – Gesamthochschule - Essen.

GEOG calculates and delivers the whole geometry of a TGS with positive Gaussian curvature. The form finding procedure is based on the translation of two catenaries and it obeys exactly to the form of a grid shell, which form is determined by inverting the form of a flexible hanging net. All arches in the prototype obey to the geometry of the following catenary (Figure 5):




$$\mathbf{Z = c\,[\cosh \frac{x}{c} - 1]} \quad \text{where} \quad \mathbf{c = 4.215887}$$

Figure 5: Catenary used as directrix and generatrix for BIM-Bam 1

The four edges of the grid are designed as rigid structural elements, and this equilibrium condition must be guaranteed during its construction. The geometry of the TGS offers the following advantages during the design and construction process of BIM-Ban 1:

1. “The form of a grid shell is determined by inverting the form of a flexible hanging net. To invert the catenary so that it becomes the thrust line of an arch free of moments is an idealization. Analogously, inverting the form of the hanging net yields the support surface of a grid shell free of moments.” [7, 8].
2. The rods form a planar grid with rectangular meshes and constant spacing between the knots. Straight bamboo culms with constant length will be used for all inner rods of the shell. Later on, it will be possible to dismantle the prototype and to use the same rods in other TGS with different wide span and curvature.

3. A universal knot (Figure 6) was designed, considering the original ideas of Professor Oliva Salinas. As described in point 2, it is possible to dismantle the prototype and to use the same knots in other TGS with different wide span and curvature.

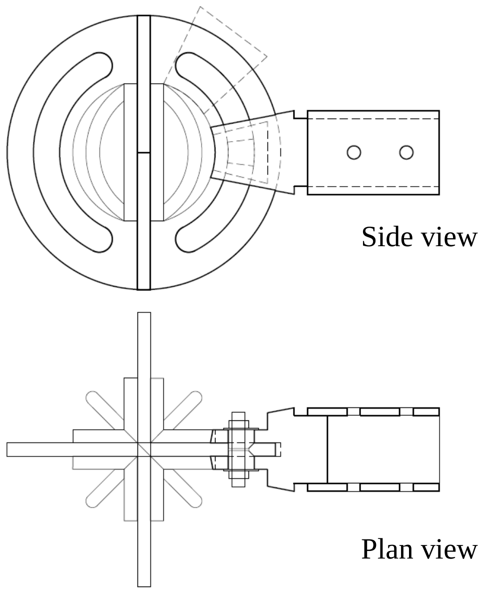



Figure 6: Universal knot fabricated with biopolymers for BIM-Bam 1

4. Four knots at any mesh lay always on a plane surface, therefore it is possible to cover each mesh of the grid shell with plane elements, such as timber, glass, reinforced concrete, flexible membranes, bio composites, ETFE, sisal or jute, among many other possibilities.

## 5. Complementary approaches

The main objective of this collaborative project is to develop a design and manufacturing protocol based on BIM principles. The work that has been carried out integrates the information concerning the geometrical and mechanical properties of bamboo previously stated in this article. The focus will be in a typical rod element that can be used to build any structure within Autodesk´s Revit software. In order to study the application of the prototype with a BIM approach, the information needs to be classified in two levels: integral system and components. Firstly, the integral system is the whole structure in its totality and secondly, the components are all the elements that make up the system (rods, knots and supports). The research group in the Structures Laboratory has studied a defined geometry and a universal knot that allows both the accurate geometrical dimensioning of the system and a proper stress distribution. The bamboo rods that have been analyzed at this first stage of research are straight 1.0 m elements with a 10 cm diameter and 1 cm wall thickness. (Figure 7)

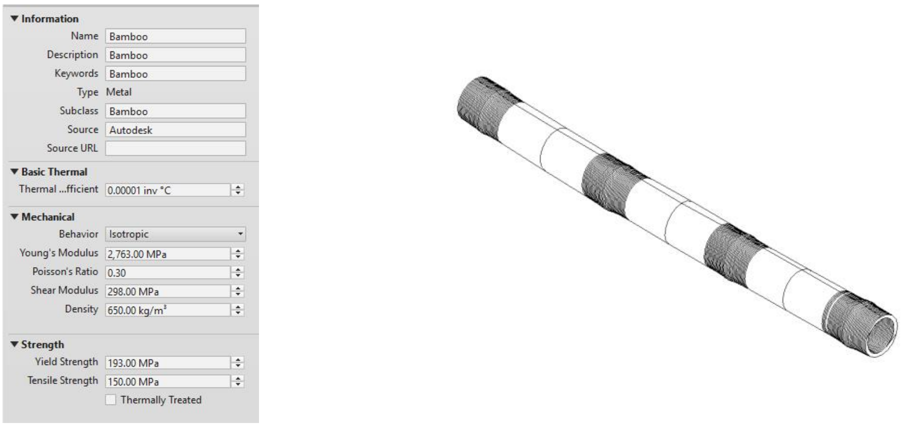



Figure 7: Input information to the BIM model for a rod element (bamboo culms)

Besides the geometrical analysis, a virtual model of the final geometry has been structurally analyzed with the specialized software "SAP2000", in order to fully understand the system and to obtain information to complement the BIM inputs in Revit.

## 6. Conclusions

Every day new materials are presented to the market that allow architects, builders and engineers to increase their conception, design and construction possibilities. Most of the times, these materials are of synthetic or man-made origin as the focus tends to orient itself to lighter and stronger. Nevertheless, there are various natural materials, which without being new or innovative, require attention and focus from designers as their potential has not yet been truly recognized. This cannot be done if the mechanical behavior of these materials is simplified to isotropic properties, as it is done nowadays. The results obtained in this research project allow a degree of optimism towards the possibilities of defining new approaches towards bamboo as a trustworthy material.

In the specific case of bamboo, the popular idea of it being "green steel" has generated a problem in the pursuit of its own identity. The differences between bamboo and steel are abysmal and the fact that it has been compared to steel has provoked, in many cases, a wrongful application in the design process. This wrongful application tends to overlook other properties and capacities, mistakes that can be critical as for example "bamboo dos not resist bending whereas steel does". A partial conclusion that has been made through the case study is that the proper design process for bamboo structures needs to be based on light structure theory, especially in geometrical configurations. This focus is to have bamboo work axially and for it not to bend.

Finally, the research team cannot conclude with respect to the use of digital tools of simulation, analysis and design needed for the BIM model, nevertheless, the research team is optimistic and believes that changing the design paradigm is worth the effort. Traditional design methods tend to overlook natural materials because of the previously known limitations, then again new technological tools can help overcome those limits and reinstate these materials in the prestige they deserve.

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