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Research Article

Deployable Dome Form Finding Using Physical and Virtual Models

Natalia Torres[1], Diana Peña[2] and Eliana Cortes[3]*

[1]UPC Polytechnic University of Catalonia. Barcelona Tech., Vallès School of Architecture

[2]Structural Morphology in Architecture SMIA, LITA. Laboratory of Innovation and Technology in Architecture - UPC

[3]Department of Architecture and Civil Engineering, University of Bath Claverton Down, Bath, BA2 7AY, United Kingdom

***Corresponding author:** Eliana Cortes, Department of Architecture and Civil Engineering, University of Bath Claverton Down, Bath, BA2 7AY, United Kingdom.

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Abstract

This article describes the process of design, analysis, and manufacture of a modular, adaptable, and lightweight folding Bamboo dome. The study developed a new form-finding method with rigid scissors to simulated complex geometric forms to show rigid-bar deformation and using more uniform bars. The structure is composed of six flat semi-arches that fold through the scissor-type system reducing the size of the dome to facilitate is transport. Bamboo bars with a circular section are used as a main material for the structural arches. This research has been contextualized in the development and the form-finding process of curved surfaces with articulated bars. Félix Escrig's projects have been utilized as the main reference, in particular, his method based on the regular polyhedron's geometry, which allows obtaining the largest number of similar pieces. For this case study, a new approach to the regular polygon method is applied in the design process. The new methodology allows easy definition of the main characteristics of the bars: length and position of the joints; as well as achieving equal and modular pieces. The case study incorporates analysis and simulation graphics in two dimensions of the semi-arch type elements on its final stage of deployment. This graphical method of analysis allows finding the adequate deformation based on the self-weight of the structure and in this way to define the ideal position for the opening of the semi-arch that matches the initial geometry established to form a stable arc. The fabrication process explains the design strategies employed to select the connection mechanisms between the bamboo bars that will ensure correct structural behavior and functionality of the dome. The resulting prototype aims to demonstrate the potential of bamboo bars within deployable structures to generate innovative and sustainable solutions for temporary buildings.

Keywords: Deployable structure; Scissors system; Bamboo; Form finding; Domes; Lightweight construction; Bamboo connections; 3D printing

Introduction

The construction industry is one of the economic sectors which carry out the most high-impact activities against the natural environment. Over the last decade, proposals to decrease this problem have been tackled in most of the ongoing research within the faculties of architecture and civil engineering. For academics and researches, this challenge has been understood as an opportunity to put in the mainstream alternative structural systems and non-conventional methods of construction that could offer more sustainable architectural solutions. The present research is part of this academic field, aiming to demonstrate through the construction of a deployable bamboo dome structure that temporary architecture can be made sustainable by using low-impact materials. Bamboo is a natural renewable material with a low-carbon production footprint for building construction. For centuries its potential was hidden within the vernacular constructions of different cultures around the world [1]. Nonetheless, the ongoing search of sustainable materials has unveiled the amazing mechanical behaviour of most of the species belonging to this subfamily of grasses. On their work on bamboo, Dunkelberq, et al. [2] state that with 'regard to its mechanical/ technological properties bamboo is superior to constructional timber (softwood) and to constructional steel in terms of the ratio live load /deadweight'. This ratio is a relevant advantage when selecting a material for lightweight structures such as a deployable scissor system. Additionally, despite misconceptions, it is a durable material when treated under an appropriated method of preservation and proper maintenance to extend its lifespan. Aesthetically, bamboo bars have unique features compared with other timber species, making the use of entire rods, the preferred profile for architectural solutions where the structure will be visually exposed. Most of the challenges imposed by using bamboo bars stem from the connections and joints between elements which still represent a labour- intensive work of craftsmanship. However, recent research applying new technologies of fabrication such as 3D printing has allowed to improve the elaboration methods, bringing bamboo construction into a more industrialized process of manufacture with high-quality standards.

Previous research has studied bamboo as a material for temporary deployable structures [3], concluding that the implementation of functional connections represents a challenge of structural behaviour and requiring of further study. With the construction of this prototype of a deployable bamboo dome using a scissor-type system within arches, the aim is to study three types of joints proposed which can facilitate the loadbearing behaviour of the structure on its final deployable stage. Also, the performance of the structure accomplishing a function as a temporary exhibition pavilion will be analysed.

Form Finding

Geometry definition

The method used to define the deployable-arch geometry is based on geometric patterns. Taking the circle as the geometric regular-polygon base; similar to the technique used in traditional Islamic mosaics applied to decorative elements in walls, ceilings, and doors where their designs are based on geometric patterns. This technique allows segments based on scissor groups inscribed inside a circle to be visualized and, in this specific case, arches formed by articulated bars to be designed. By setting the diameter, bar length, and hole position, the desired curvature can be obtained.

Some basic values for the different arch configurations are set:

1. Six-meter-diameter circles serve as the polygon geometric base.

2. Dome height is three meters, which equals the radius of the base.

Steps

The geometry begins with a circle divided into four or more sections. From there, lines are drawn that join the vertices with every other vertex to form two polygons. An example of the step-by-step construction of a polygon, in this case a hexagon:

1. Draw a circle and divide it into the number of desired polygon sides multiplied by two. For our example, a hexagon has six sides: N = 6. The circle is then divided into 2*N (12) sections (Figure 1).

2. Connect every second vertex to create the first hexagon (Figure 2).

3. Connect the remaining vertices to construct the second hexagon. The result is a polygon star formed by two overlapping and rotated hexagons (Figure 3).

4. Take half the circumference and mark the intersecting points between the sides of the polygons and the radial angles. These points mark the estimated bar length and hole positions (Figures 1-5).

5. Polygons with a large number of sides, two arch types can be obtained: semicircular and horseshoe, where the curve can be larger than a half circle (Figure 6).

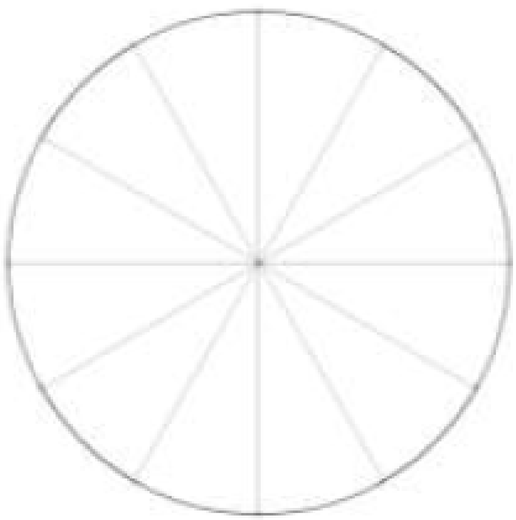

Figure 1: Circle divided into 12 sections.

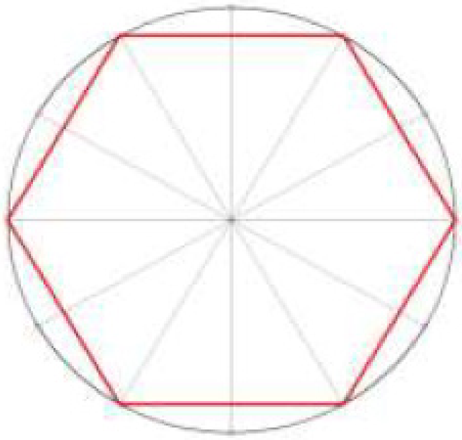

Figure 2: First hexagon formed.

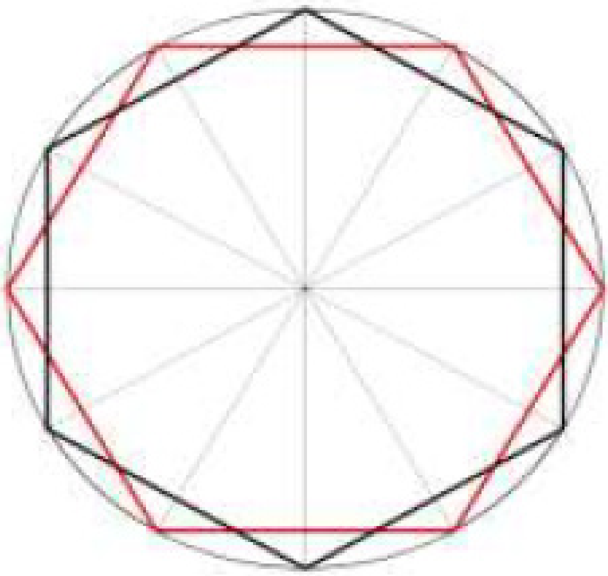

Figure 3: Two overlapping hexagons.

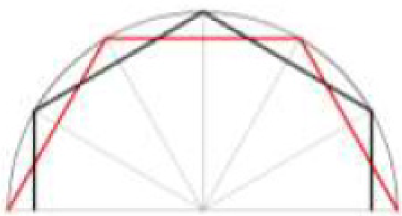

Figure 4: Deployable-arch projection.

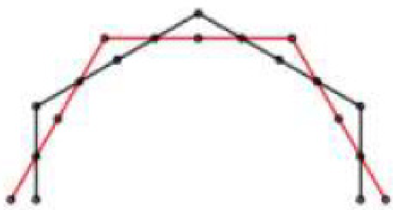

Figure 5: Articulation points.

Parametric definition

Using the parametric-design software Grasshopper, this information can be synthesized in a single parametric definition. This allows one to vary the radius parameters, circumference subdivision, bar sections, hole diameters, and final dome configuration. Describing the dome parametrically allows both design and, ultimately, the structure's manufacturing process to be optimized (Figure 7).

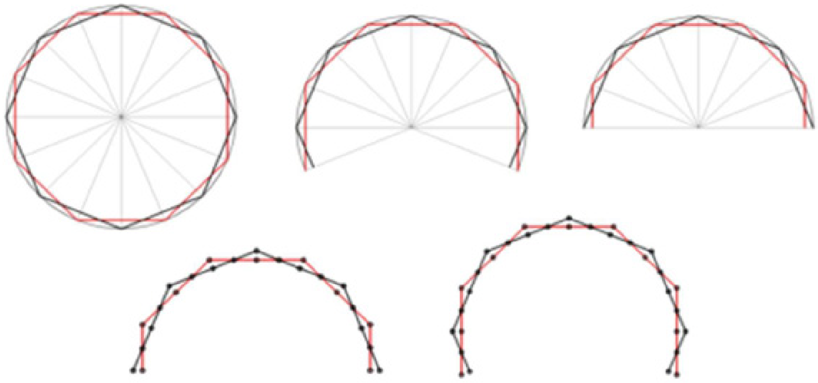

Figure 6: Semicircular and horseshoe arches derived from an octagon.

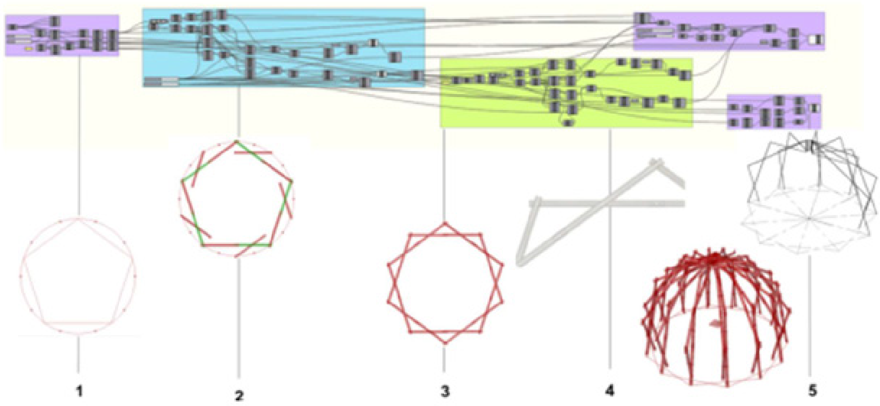

Figure 7: Deployable-arch parametric definition.

Diagram

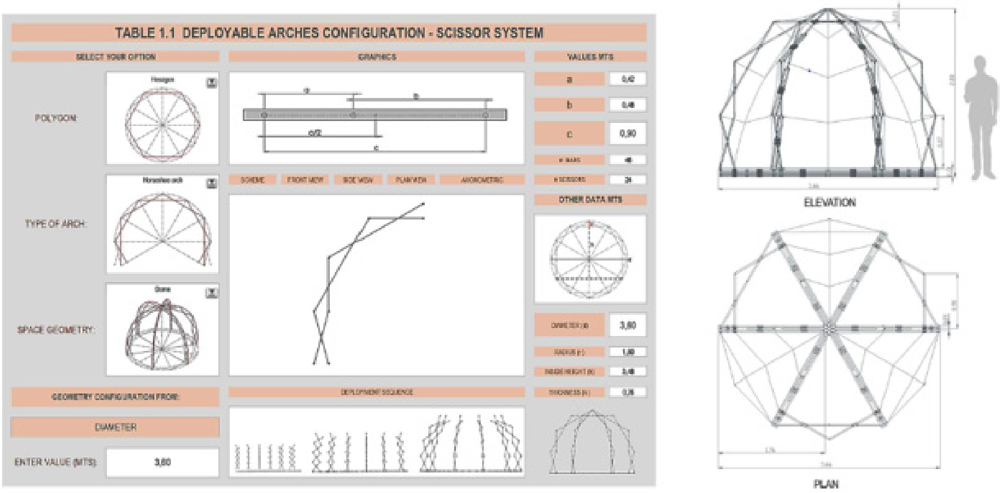

Figure 8: Diagram of the software proposed by Torres & Peña [4] to form-finding the geometry for the deployable dome structure using scissor type components.

The form-finding approach applied in the design of this deployable double-curved structure using articulated bars -commonly denominated scissor- has been the geometry of regular star polygons. This geometrical method proposed by one of the authors allows an easy definition of the most important construction features of the scissor-type elements: length of the bars and precise position of the articulations. As seen in Figure 8, by introducing the diameter or the length of the bar as a parameter, modular bars of the same length can be obtained, facilitating fabrication of the dome structure. The method also offers different geometrical alternatives of arches and its correspondingly volumetric configurations between domes and vaults. The dimensional parameters to design this structure were the 4 x 4 x 4 meter set up for the exhibition pavilion contest in the IASS-Expo 2019. Therefore, it was selected as geometrical plant for the dome, one based on a regular hexagonal geometry with a combination of three horseshoe arches in the section. It gives as a result, a dome with 3.60 m diameter as shown in Figure 9 (Figure 9).

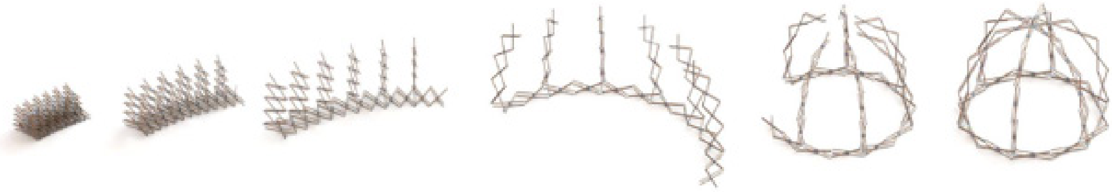

Figure 9: Axonometric, plan and section views showing its correspondent process of deployment of the bamboo dome.

The deployable system consists of six semi-arches assembled over the hexagonal ring, which functions as a guide mechanism to unfold these six elements simultaneously. The stability of the half-arches is attained by increasing the cross-sectional area of them. Therefore, it was added a bar parallel to one of its lineal elements (Figure 10 a-b). The same action is repeated in all the lineal elements on the ring basement structure. Once it has reached its final deployed position according to with the geometry, the half-arched elements are connected into a central node, aligning them into three structural axes. The central articulation accomplishes the same function as a keystone within an arch, helping to gain the structural stability required by the entire system (Figure 10).

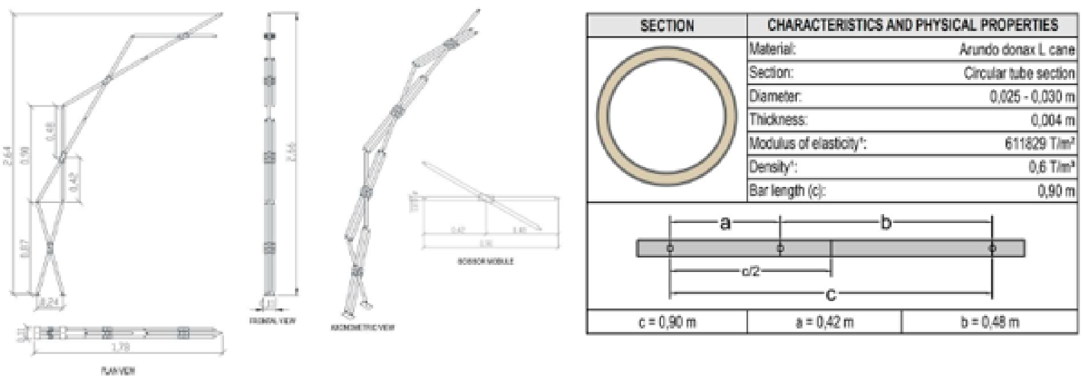

Figure 10: a-b. semi-arch details in section and isometric view. c. Chart of mechanical properties bamboo bars.

Analysis

Structurally, the deployable dome has been designed with a half horseshoe arch as the main module, composed of four scissor-type elements as illustrated in Figure 10. Perez Valcarcel [5] presents a wide and complex methodology of analysis for this type of deployable structures by applying matrix calculus. After this mathematical analysis, he summarizes that:

'Basically, the bars work under tension-compression stresses, although the central articulation produces non-symmetric bending stress of relevant affectation within the overall behaviour of the structure. Moreover, this behaviour is generated on the weaker segment of the bar, which coincides with the position of the security bolt. For that reason, the profiles with the best performance are those of circular, tubular (hollow-circular) or rectangular geometry'

By understanding the mechanical behaviour expected from the scissor-type arch, the focus of the structural analysis will be on verifying that the deformations and displacements are the minimal allowed when the structure reaches the final position of stability. An analysis of elastic deformations and stresses resultant on the bamboo bars when the arch is deployed to its final stage was carried out by using WinEve v8. It is necessary to input within the software the physical and mechanical properties of the bamboo bars to obtain accurate results from the loadbearing simulation (Figure 10). The material selection was done based on ongoing research carried out by Cortes-Paez at the University of Bath. On her work, she has studied the mechanical behaviour of bamboo Phyllostachys aurea and a giant reed known as Arundo donax L as construction materials for active-bending structures. One of the advantages of Around donax L. or wild cane is being a local resource and free of cost, commonly used on vernacular Spanish architecture. The cane grows in massive extensions along the Llobregat bank river in Barcelona and is considered an invasive species. Mechanical and physical analysis of specimens taken from the area [6] shown that wild cane bars had an adequate resistance and modulus elasticity for this deployable dome structure.

Semi-arch discretisation. WinEva (v.8)

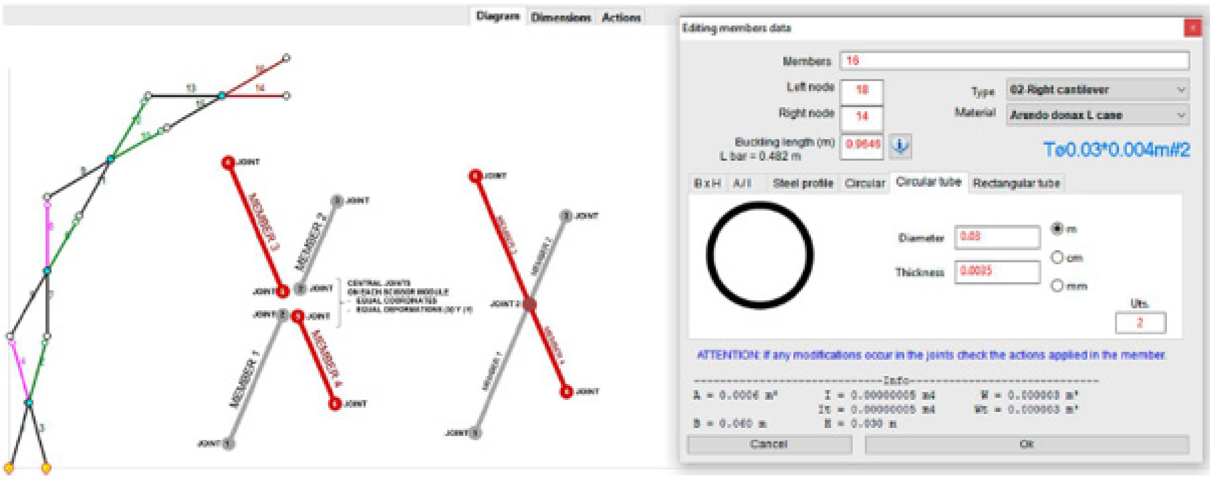

Figure 11: Visual sequence explaining the definition and position of the central nodes.

Discretising this semi-arch structure on WinEva [7] requires deconstructing the scissor-type element into its two main components:

1. The bars, where two collinear bars configure a single lineal element.
2. Nodes, which correspond to the two ends of each bar and to the central articulation that attach two overlapping bars.

Fundamentally, the structural model of the deployable semi-arch consists of a line drawing of the geometry in any CAD software. This file is imported to WinEva, where the lower node of the external bar is positioned on the 0.0 coordinates. Finally, the physical and mechanical properties of the bamboo material and diameter of the cross-section are input on the software as illustrated in Figure 11. To analyse a scissor deployable arch structure on WinEva we need to specify that each module is configured by four bars interacting by the central node. This specification helps the software to identify those two linear elements integrate each scissor module, as shown in Figure 11. Obtaining an accurate simulation of the mechanical behaviour of the scissor module in its final stage of deployment on WinEva, requires an additional step: a central node with equal deformations within the axis (x) and (y) must be inserted. Both nodes must coincide with the same position where the central node is located on each scissor module. To assure a precise location we need to input the same coordinates for each node as exemplified in Figure 11. The ending nodes on each bar are defined, verifying a correct collinear relationship of the two bars that compose the scissor module. This process is repeated within each scissor module that configures the deployable semi-arch (Figure 12).

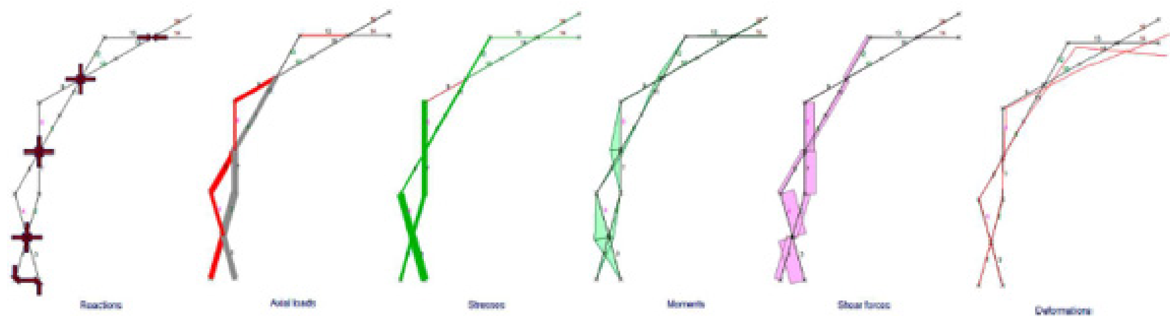

Figure 12: Sequence of diagrams plotted from Win Eva simulation analysis of the semi-arch in its final stage of deployment.

Having defined the physical features and design parameters of the semi-arc, the next step is to carry out the structural analysis. For this analysis, the primary load supported by the dome is its own weight, which acts as a uniformly distributed load along the bamboo bars. Once the simulation is done, the software plots different diagrams correspondingly with the reactions, axials and tensional stresses, ultimate moments, shear, and deformations (Figure 12). The deformations diagram is crucial in finding the ideal position before the final deployable stage, on which the semi-arch will coincide with the geometry selected. The own weight of the structure attains this position while the semi-arch scissor is in movement.

Analysis of deformation within the dome structure

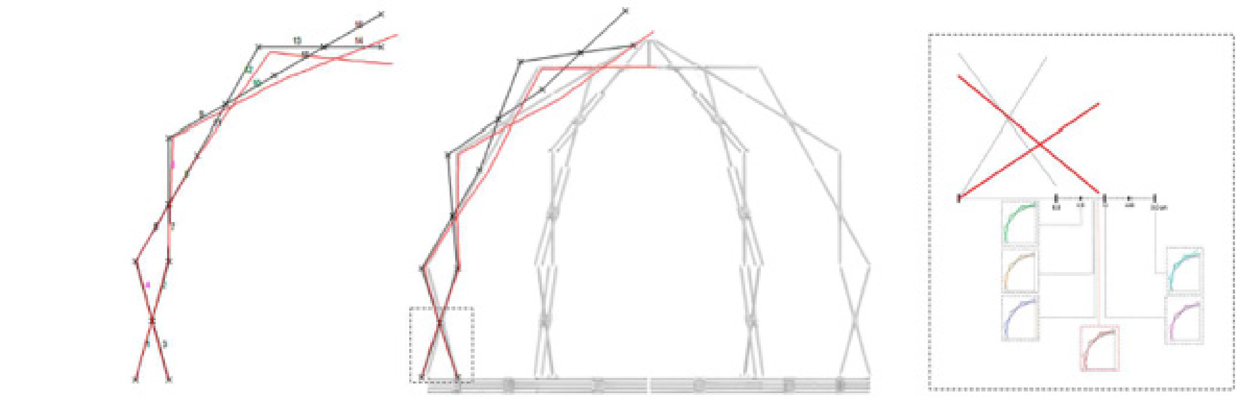

Figure 13: Method to find the ideal position of deployment to assure correct assembly of the central joint.

One of the most significant challenges designing this type of deployable dome is assuring that when each of the six semi-arches is deployed to its final stage, they will be in the right place to be assembled with the central joint and simultaneously correspond to the final design geometry. The methodology proposed by Torres & Peña [4] uses the deformation's diagram and outcoming data from the simulation done with WinEva to calculate this position. In her research, she uses a combination of two parameters, such as the own weight of the arch and the deployment position of the scissors to sit all the semi-arches in place by means only of displacement forces. As illustrated in Figure 13, on the top-ending scissor, the distance of nodes 1 and 2 must correspond with the height of the central joint piece but also reach the geometry of design of the semi-arch. It will facilitate the assembly of both components when the entire structure reaches the final stage of deployment. On this scissor-type semi-ach, the movement of the top- ending scissor element is controlled by the displacement of the bottom-ending scissor. If we run a series of pondered simulations where @ is a numerical value assigned to the distant between axis of deployment (Figure 13), it is possible to find the ideal position for the nodes 1 and 2 that simultaneously agrees with the geometry of the design proposed for the half-arch.

Fabrication and assembly of the dome

As has been demonstrated previously, the utilization of computational models to determine the structural behaviour in deployable scissor-type structures has facilitated their design and calculation. However, physical models are fundamental to a realistic perspective on the challenges involved in its construction, due to the complexity involved within the deployment and functionality of the hinged connections. As this type of structures is less conventional than other systems, there is a limited supply in the construction industry of suitable hinged joints to build a medium or large span structure. In the case of this deployable dome, before the elaboration of a full-scale prototype a 1:2 scale model was built with two objectives. First, to verify the geometrical and mechanical simulations obtained from WinEva to identify possible structural failures. Working with a physical model enables the improvement of the computational model, providing a more accurate structural analysis (Figure 14 & 15) (Figure 14).

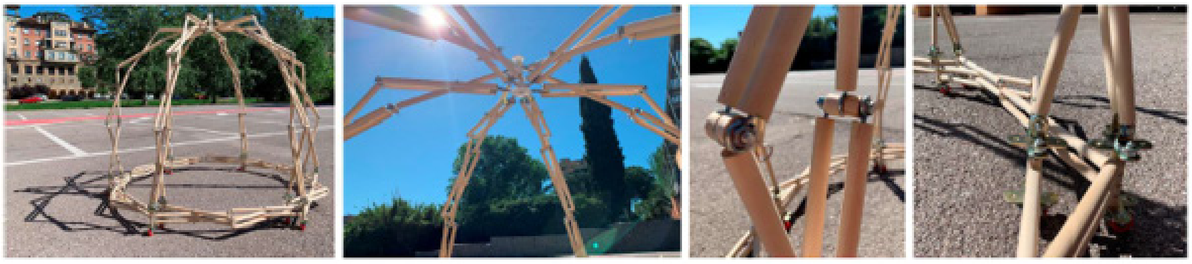

Figure 14: Diagram of the deployable dome and its corresponding scissor modules.

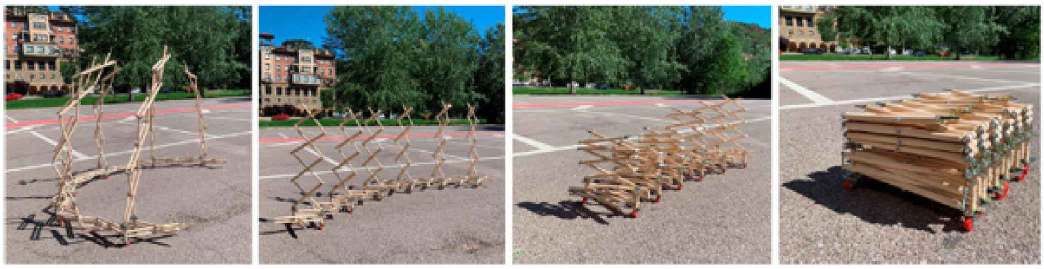

Figure 15: a. Physical model 1:2 deployed showing a single horseshoe arch and the hexagonal support ring.

The second objective was to explore different hinged connections using a variety of mechanical pieces available in the industrial market. The major challenge was finding pieces compatible with the dimensions of the bamboo bars selected. Bamboo is a material that is not as precise and homogeneous in dimensions as man-made materials such as steel or aluminium, so it adds more complexity to the construction process. Nonetheless, the availability of new technologies such as 3D printing makes it possible to fabricate bespoke pieces at a low cost. In this section is detailed the design and functionality of the mechanical joints created for this deployable dome structure (Figure 15).

Single-hinged and pinned connection on the support ring

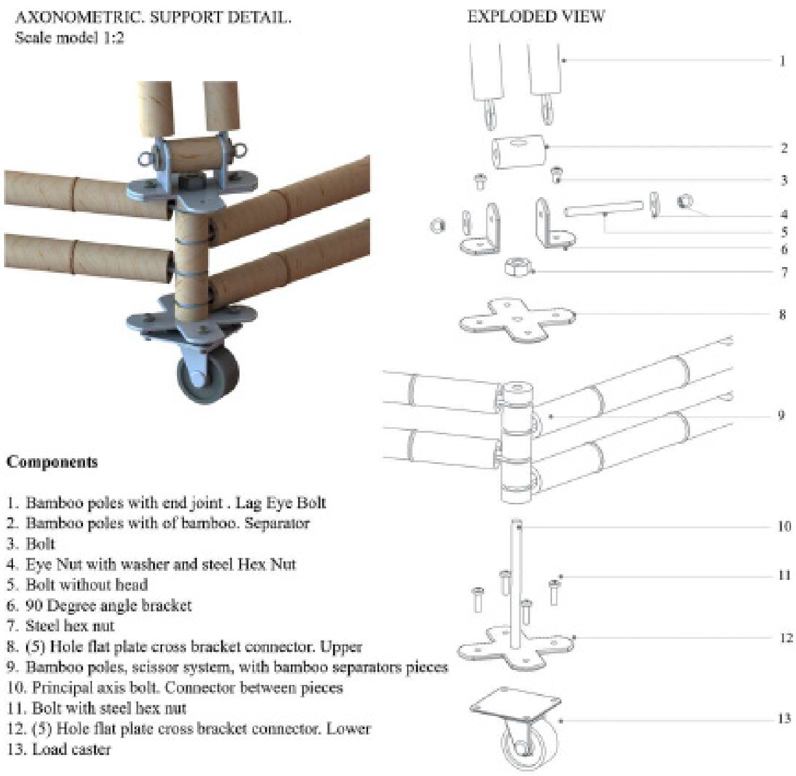

Figure 16: Photo of the single-hinged and pinned connection on the support ring in the scale model. b. Detail of the 3D design of the piece in Solid works.

This piece plays the role of transmitting the loads from the semi-arches to the ground as illustrated on Figure 17. Due to it, the joint has restricted movement in the (y) axis while it allows rotation in the (x) axis. Overall, the hexagonal ring has 12 of this type of hinged joints, two per each semi-arch. This connection allows the simultaneous deployment of the support ring and the six semi-arches. Against the ground has been installed a roller system to facilitate the radial movement of deployment and folding carried out by the hexagonal ring as seen in Figure 16 & 17. This joint was designed using fittings available from the timber furniture sector, however, an alternative connection using 3D printing technology has been proposed to reduce the number of components (Figure 16).

Double-hinged axial joint

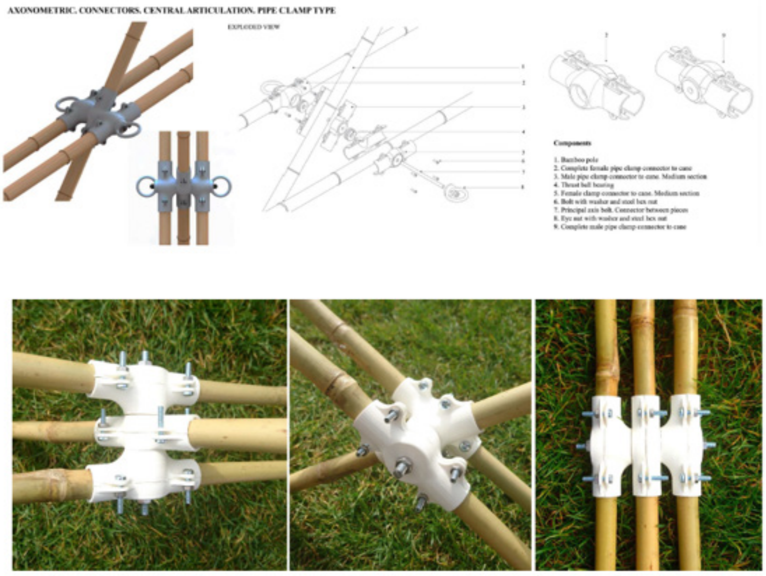

Figure 17: a. Detail of the components of the type 1 double-hinged axial joint designed in solidworks. b. Photos of the 3D printed joint using wild cane bars on real scale.

This connection is essential to allow the axial movement of the bamboo bar elements that integrated the deployable scissor modules within the semi-arch. The connection must enable a rotational movement with a minimal friction resistance in the vertical axis of the scissors. For this prototype has been developed two types of hinged axial joints. One illustrated in Figure 17. which would be located in the central node of the scissor module. This joint has been designed to allow the insertion of an entire bar assuring continuity of the load transfer within the arch. The mechanism of this piece joints simultaneously three hinged bars by a system of male-female connectors (Figure 18).

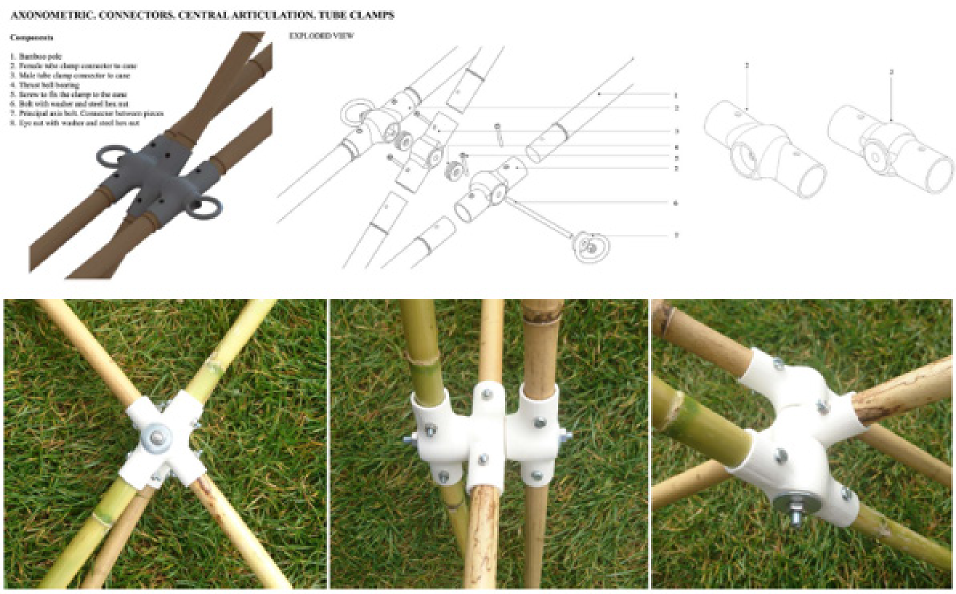

Figure 18: Detail of the components of the type 2 double-hinged axial joint designed in solidworks. b. Photos of the 3D printed joint using wild cane bars on real scale.

The second type of double-hinged joint is shown in Figure 18. This connection has been designed to interconnect deployable scissor modules. Consisting of a hollow tubular section were the endings of the parallel bars are fitted by pressure and secured with a bolt. This joint has been designed to assuring continuity and alignment of the collinear bars in the same plane. The mechanism of this piece joints simultaneously three hinged bars by a system of male-female connectors.

Central top fixed joint

This joint is crucial on giving the stability and stiffness required as it functions similarly as the keystone within a traditional dome structure. The design of this joint includes two components. One is a conical nucleus with six jointing plates which are aligned configuring the three geometrical axes of the structure. These joining plates will be connected to a tapered hollow fitting inserted at the ends of the two bamboo bars of the top-ending scissor. When all the semi-arches reach the position of deployment calculated, both joining plates are assembly using a bolt to create a rigid pinned joint as seen in Figure 19. The height of the central piece has been defined based on the geometry assigned to the deployable arch as it was explained in 3.1. The diameter and size of the fitting at the end of the bamboo bars has been set up based on an average dimension from the bamboo bars selected (Figure 19).

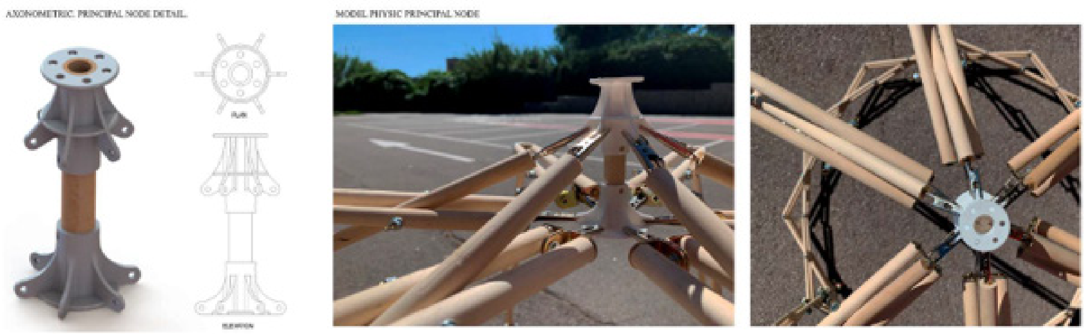

Figure 19: a. Detail of the central top fixed joint designed in Solidworks. b. Photo of the 3D printed joint installed in the 1:2 scale model.

Results

In one hand, the results obtained from the process of design and manufacture of this pavilion contributes to extend the knowledge regarding the potential of bamboo and cane bars within the construction of deployable scissor structures. This first approach to the material through the building of a physical scale model enables the visualization of the challenges faced concerning the functionality and constructability. However, the fabrication of the real prototype has been postponed while are carry out additional mechanical testing an improvement on the three types of joints proposed. New possibilities of using other species of bamboo bars have emerged linked to funding granted by a local sponsor. Bambusa Estudio, which is a bamboo supplier in the city of Valencia, Spain, has offered to sponsor the construction of this pavilion using part of their products. Results obtained from building the scale 1:1 bamboo dome will be published in upcoming papers.

Conclusions

This prototype validates the methodology proposed by Torres based on the use of regular polygons to design and calculate deployable scissor-type domes assisted by WinEva software. The novel contribution of this paper has been the implementation of bamboo bars as the primary material for the construction of the scissor modules. Bamboo is a natural material with a low-carbon footprint when compared with aluminium, PVC or GFRP bars commonly used in the construction of this typology of lightweight structures. By using bamboo as the main material for this deployable dome, we are not only considering the advantageous mechanical properties inherent to it. The use of bamboo on this proposal includes an implicit consideration about the life cycle of this temporary structure, aiming to reduce the waste produced during manufacture and the possibilities of being recycled after accomplishing its purpose, a feature that must be a requirement for most of the temporary and ephemeral structures. Overall, bamboo is a low-cost material which is available around the world in different diameters and thickness. It does not require complicated methods to produce it. However, the heterogeneity of the bars involves additional complexity on the construction process of the dome structure regarding the type of hinged joints and fixings required to assure the proper functionality of the system. Therefore, the development of these pieces has centred most of the design proposal created for this semi-arched deployable dome. Designing the fittings and connections for a scissor-type structure implies a deep understanding of the stress and deformations on each joint, seeking to reduce the friction produced by the rotational movement of the bars. Also, it is important to continue expanding the different alternatives available to fabricate this type of mechanism. This paper demonstrated that by using a new method of fabrication such as 3D printing, which produces affordable bespoke solutions enabling the construction of this scissor semi-arched deployable dome.

Acknowledgment

None.

Conflict of Interest

No conflict of interest.

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