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# Design and analysis of a self-supporting bamboo roof structure applying flexible connections

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## Abstract

The present study investigates a mobile textile bamboo roof structure applying flexible connections. The developed ultralight structural system built with modular space frames, tensile pantographic grids, lashed joints in polyester ropes and biocomposites, presents a self-supporting behavior. Prefabricated hinged lashed connections (HLC) designed for the structure allow a deployable mechanism, free of torsion stresses in the bamboo bars. Nonlinear analysis using the finite element method (FEM) presents forces applied in the structure. Static loading patterns for wind loads were investigated and showed that forces can be safety absorbable by the structural members. A numerical model, physical models and full-scale prototypes, simultaneously, investigated the complex mechanical behavior of the bamboo structure, drafting its overall operation and introducing design guidelines.

**Keywords:** Bamboo, roof structure, self-supporting space frame (SSF), hinged lashed connection (HLC), structural analysis, design, ultralight, deployable, textile, pantographic

## 1. Introduction

Bamboo plant grows faster than any other vegetal in the world. Bamboo culms reach its final size in approximately 6 months and reach its maximum mechanical performance after 3 years old. Bamboo culms cylindrical geometry, reinforced by transversal nodes are suitable for construction even in its raw state. In the last decades, bamboo properties started to receive attention of universities, laboratories and companies as an industrial material with potential to substitute steel and timber in engineering design and also to be used in innovative technical applications. In 1980, the 1st International Workshop on Bamboo was realized at Singapore, organized by the International Development Research Centre IDRC from Canada. This event was the historic mark as the beginning of systematic international efforts on researching bamboo in a scientific and technical approach. In the field of structural design, bamboo joints have been the main problem in the draft of bamboo structures. The technical application of bamboo requests joint solutions able to preserve the original physical and mechanical properties of the material. Bamboo joint systems can also contribute for the durability of the material, besides the fact that joints should be cost-effective and suitable to be reproduced. Bamboo scaffoldings, bridges, houses and furniture have been applied in Asia and South America for many centuries. Vernacular cultures developed flexible joint techniques in vegetal fibers as bamboo, liana, rattan, coconut, sisal and cotton, to name a few. India, China, Indonesia, Colombia and Brazil presents several ancient traditions in the use of bamboo and bio-based materials in structural applications. Bamboo as a structural material can be observed in the Balinese artistic buildings, the scaffoldings from Honk Kong and in the indigenous houses at the Andes Amazon Region in Brazil. Vernacular bamboo buildings connected by elastic joints in Asia were previously investigated by Dunkelberg and Frei Otto in the 80’s [1]. *Guadua* bamboo arched structures and hyperbolic paraboloid designs were studied by Oscar Hidalgo-López in Colombia

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[2]. More recently, Vélez and Villegas designed large-span roof pavilions with a novel bolted connection system for bamboo structures, which was applied in the Hannover Expo Pavilion built in Germany in 2000 [3,4]. In the year of 1991, the first bamboo space structure applying nodal steel joints was developed in PUC-Rio [5]. Shear and torsion forces in bamboo bars and its buckling behavior were studied [6,7]. The bamboo geodesic dome with nodal steel joints [8] were developed in PUC-Rio in 1995. The high level of stresses around the perforations of the structural members determined the limit load, especially in the case of special loadings such as assembly and disassembly loadings, requiring labor-intensive techniques in the production and maintenance of these structures.

## 1.1. Design of bamboo joints

The Laboratory of Investigation in Living Design - LILD, old LOTDP, from the Arts & Design Department of PUC-Rio developed a research program focused in the design of bamboo structures and its connections since 1985 [9]. Since 2004, the research program is conducted in collaboration with the Laboratory of Structural Systems - LASE from the Structural Engineering Department of UFMG and the Bambutec Design company. Materials such as PVC, canvas, timber, steel, aluminum and composites were studied and applied in experimental joints [9]. Bamboo structures were investigated applying nodal joints and eccentric joints in rigid and flexible materials. Several prototypes developed tensile structural principles applied in the design of bamboo structures as can be seen in the nodal steel joint for space structures [10], in the bamboo bike with biocomposite joints [11], in the bamboo frame wheelchair [12] and in bamboo deployable structures [13]. Bio-based materials such as earth, cotton fabrics and vegetal polymer composites were investigated. Bamboo joint technologies were developed for pantographic structures, tensegrity structures and space structures, such as tetrahedrons, icosahedrons and geodesic domes with geometries described by Buckminster Fuller [14]. Form-finding methods using physical scale models were developed in the design of ultralight bamboo structures [15].

## 2. Methodology

The present research studied the structural behavior of a textile bamboo roof structure applying flexible connections. Our investigation focused in the design, analysis and construction of roof structures for the tropical climate applying portable structural members. The methodology can be summarized as:

(i) Form-finding physical scale models
(ii) Investigation of the physical and mechanical properties of bamboo and the applied materials
(iii) Engineering tests in scale and full-scale models
(iv) Form-finding computer models
(v) Structural design and analysis
(vi) Detailing and fabrication of full-scale prototypes
(vii) Building of full-scale structures
(viii) Monitoring of the structures in the physical and social environment

### 2.1 Objective

This paper aims to describe the mechanical behavior of a self-supporting textile bamboo roof structure with flexible connections and to propose draft guidelines for this architectural design typology. Physical scale models, full-scale models and a numerical model investigated simultaneously the self-supporting bamboo structure, drafting its overall operation and the load-bearing capacity of the structure. Section 3 presents the structural system and the developed modules which constitute the bamboo structure: flexible connections, tensile pantographic grids and the self-supporting space frames (SSF). Section 4 presents the structural analysis and the mechanical behavior of the structure under wind loads. Finally, section 5 presents the design guidelines and project recommendations.

## 3. Form-finding of a Self-supporting Textile Bamboo Roof Structure

Textile bamboo roof structures are built with modular self-supporting space frames (SSF). The structural system presented in figure 1 is a prefabricated ultralight structure. The first self-supporting textile bamboo roof structure was built in 2013 in Rio de Janeiro [16]. The structure applied bars using *Phyllostackys pubescens* (moso) and *Phyllostackys aurea* bamboo species. The connections were designed applying a novel joint system so-called the hinged lashed connection (HLC). The HLC uses textile polyester ropes and locking biocomposite bandages in cotton fabrics and castor-oil polymer [17]. HLC is a connection system for deployable structures that allows the articulation of the structural members during the assembly steps, free of torsion stresses in the members. After deployment, the structural modules are locked using additional constraint polyester rope lashings. The SSF was designed through form-finding small scale and full-scale experimental models for load carrying capacity tests. The briefing used in the design of the SSF can be described as:

. Application of mobile ultralight structural modules (7.5 kgf/m² in average)

. Use of the bamboo in its natural cylindrical shape, considering the greater length of the bars;

. Use of single bars between 2 nodes;

. Bamboo connections applying textile flexible materials;

. Simplicity in manufacturing, assembly and maintenance processes


(a) (b) (c)

Figure 1: Textile bamboo roof structure. (a) (b) Assembly procedure of the self-supporting bamboo structure. (c) As-built structure mounted in Rio de Janeiro, 2018

### 3.1. Hinged Lashed Connection (HLC)

Hinged lashed connection (HLC) is a deployable joint for bamboo structures developed by the authors. HLC is designed with polyester plastic ropes and biocomposite bandages glued in the bamboo culms, avoiding sliding of the joints. HLC deployable mechanism allows the articulation of the structural members during assembly and disassembly steps, free of torsion stresses in the bars, distributing local stresses around the diameter of the bamboo bars. HLC presents a rotational degree of freedom in the center of the joint (Fig. 2). The bandages use cotton fabrics and castor-oil polymer biocomposite, biodegradable in correct conditions of disposal. HLC allows the mobility of the members during the assembly procedure in free-form geometries [16]. In this process, the structure is assembled until reach its final form and after the erection process the joints are braced by additional constraint lashings, locking HLC.


(a) (b)

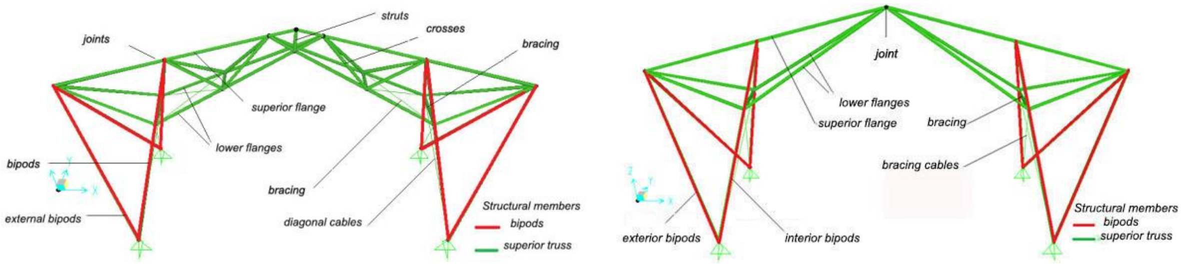
Figure 2: Hinged lashed connection (HLC). (a) HLC articulated mechanism. (b) Detail of HLC

### 3.2. Tensile Pantographic Grids

Tensile pantographic grids are modular planar structures used for roofing the self-supporting structure. The structural system consists of a deployable bamboo grid tensioned by textile membranes, resulting in a self-stressed structure. The bamboo grid presents an articulated behavior allowing mobility of the grid length and width. The applied HLC allows a pantographic motion without mechanical damage in the operation of the bamboo bars. The grid is prefabricated and transported to the assembly site in its stowed state and deployed until reach its final form. After deployment, the grid is compressed by prefabricated textile membranes in acrylic or other textile materials. Bamboo and textile pantographic grids are lifted and connected on the self-supporting structure and then, are capable to resist mechanical actions of nature, mainly wind forces.

### 3.3. Self-supporting Bamboo Space Frames (SSF)

The self-supporting bamboo space frames (SSF) are prefabricated in 2 architectural designs: SSF1 spanning 4 x 15m, rising 7.50m and a free span of 10m, and SSF2 spanning 3.5 x 12m, rising 5.50m and a free span of 8m, see figures 3a and 3b, respectively. Both space frame models are modular and can be subdivided in 2 parts: the superior truss (in green) and the inferior supporting bipod columns (in red). The structural members of the SSF are presented in figure 3. Both SSF1 and SSF2 have been applied in permanent and temporary structures in Rio de Janeiro. In order to develop an ultralight SSF using even less material, optimization processes were conducted in the design of a space frame model variant SSF2. Both frames present a space truss behavior, erected by a tilting system were the half part of the module is lifted and cantilevered. Then, the other half part of the space frame is assembled and lifted until reached the connection point in the ridge of the structure (Fig. 3). The SSF1 model presents a rigid behavior on the top of the ridge, as presented in figure 3a. The SSF2 model presents a hinged behavior on the top of the ridge and a property of disengaging the bending moments near the ridge of the 2 symmetrical parts of the frame, as presented in figure 3b.



(a) (b)

Figure 3: Modular Self-supporting Bamboo Space Frames (SSF). (a) SSF1 model – rigid on the top of the ridge. (b) SSF2 model – hinged on the top of the ridge

## 4. Structural analysis

The present study investigates aspects of the structural analysis regarding the distribution of forces in the bars and connections and verification of limit states. The structure for analysis applied the SSF2, considering a hinged ridge on the top of the structure. The computational model is built with bamboo bars with a diameter of 90mm and a wall thickness of 9mm, dimensions for *Phyllostachys pubescens* bamboo species. The structure sized $14 \times 28 \times 5{,}5m$ (width, length and height), respectively, and was analyzed under static loadings for live and wind loads. A FE model were modeled in the SAP2000 program [18]. The bamboo bars were modeled as tubular elements with modulus of elasticity E = 12500 MPa; nodal loading; frame structure; geometric nonlinearity parameters P-delta. Considering the isopleths mapped in the Brazilian map ABNT (NBR 6123) [19] the basic wind speed adopted for Belo Horizonte, Minas Gerais, Brazil, where the structure is planned to be built, is v0=32m/s. The characteristic speed of the wind is given by Eq. (1):

$$vk = v0 \times S_1 \times S_2 \times S_3(1) \tag{1}$$

The topographic factor $S_1 = 1$ was used for a flat ground distant from hills and slopes. $S_2$ is the roughness factor, function of the height ¨z¨ of the building, of the maximum dimensions of the frontal façades exposed to the wind load and also because of the obstacles that are located in the vicinity of the building. Interpolating in Table 2 of ABNT (NBR 6123), it is obtained $S_2 = 0{,}77$. $S_3 = 1$ for buildings with high occupation factor.

Then, the characteristic wind speed will be:

$$v_k = 32 \times 1 \times 0{,}77 \times 1 = 24{,}6\ \frac{m}{s} \tag{2}$$

And the characteristic wind pressure in *kN/m²* is given by:

$$q_k = 6{,}13 \times 10^{-4} v_k^2 = \ 6{,}13 \times 10^{-4} \times 24{,}6^2 = 0{,}37\frac{kN}{m^2} \tag{3}$$

The loading patterns were combined according to the recommendations of the ABNT standard (NBR8681) [20]. The study investigated normal loadings i.e. those loadings resulting from normal use, permanent actions, overload and wind loads on the structure in the enduring situation of design and use. The studied loading patterns does not contain any forces or special loading, nor any loading corresponding to the assembly (considered special loads), nor any actions of exceptional magnitude. The following combinations of loadings were considered for the Ultimate Limit States, which by hypothesis would lead to the higher forces in the structure. The loading hypothesis according the Turkstra Criterion were:

Wind loads at 0º angle with the axis of the structure:

. *COMB1:* $F_d = 1{,}4G + 1{,}4Q + 1{,}4Wc \times 0{,}6$ (live load as the main load)

. *COMB2:* $F_d = 1{,}4G + 1{,}4\ Wc + 1{,}4 \times Q \times 0{,}6$ (wind internal suction as the main load)

. *COMB3:* $F_d = 1{,}4Wa - 0{,}9G$ (wind external suction as the main load)

Wind loads at 90º angle with the axis of the structure:

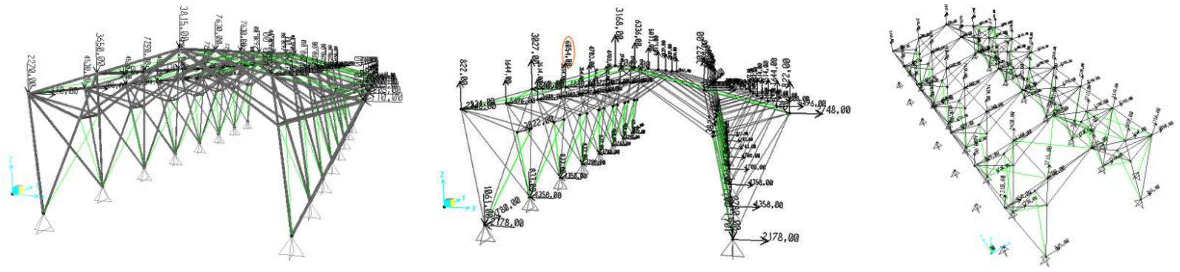
. *COMB4:* $F_d = 1{,}4Wa – 0{,}9G$ (wind external suction as the main load)

These expressions present *G* for permanent actions, *Q* for overload, considered equal 0,15 kN/m$^2$; *Wc*= $-0{,}3q_k$ for wind internal succion and *Wa* = $[(0{,}7 + 0{,}2)q_k]$for wind external suction + internal pressure, respectively. Considering an equal permeability on all façades, the norm recommends *cpi* = $-0{,}3$, considering the overlapping with the external forces given by the coefficients *ce*. However, since the internal coefficients *cpi* can reach $-0{,}9$, depending on whether there are dominant openings during high wind loads; it is recommended in practice to consider a *cpi* = $-0{,}3$ as the minimum result because of security.

So, the unfavorable wind, considered as that wind which pull the roof downwards together with gravity loadings was considered as a resulting internal suction, an internal suction coefficient *cpi* = $-0{,}3$; neglecting the coefficients of external suction – this is a practical loading for evaluation of the SSF. The probabilistic weighting coefficients of the different actions are given by ABNT (NBR8681), for normal, special and exceptional loads. The coefficient of combination of the secondary variable action is obtained from the same standard, $\psi_0$= 0,6 for accidental loads in buildings with a high factor of occupation. Similarly, we have $\psi_0$ = 0,6 for the dynamic wind pressure.

Structural engineers can combine all the actions before applying the nodal loading of the structure in the software or applying each isolated forces, obtaining the applied loads in the bars separately, by combining the actions in the software. When designing, the second option is more interesting because it allows to make changes of one or other action very easily, only applying reduction coefficients or increasing to the actions already given.

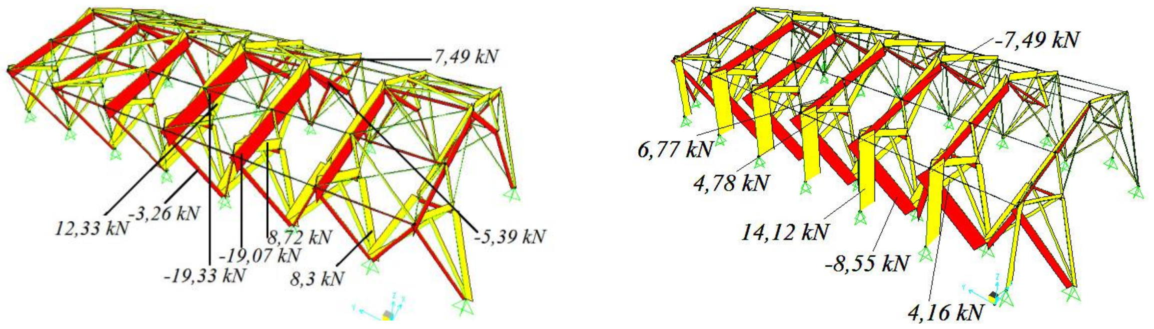
It was not applied eccentricities between bars in the FE model. The nodal forces for wind load combinations are presented in figure 4 for COMB1, COMB3 and COMB4, respectively.



(a) (b) (c)

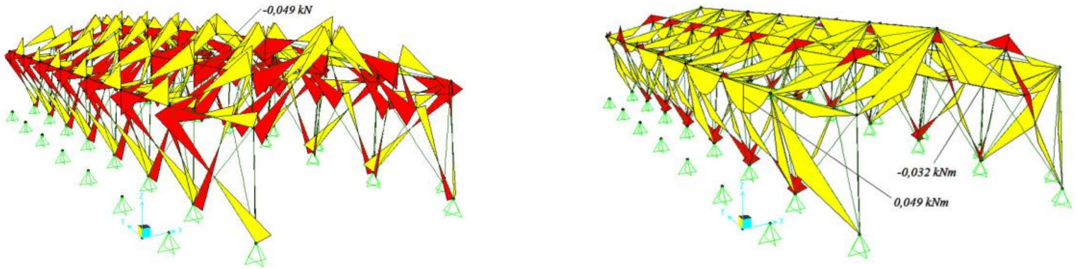
Figure 4: (a) Nodal forces for COMB1. (b) Nodal forces for COMB3. (c) Nodal forces for COMB4

The critical loading was for lateral wind forces applied in the structure at 90º with the axis of the shed. The structure was considered fully closed and with equal permeability in all façades, superimposing the external forces of the wind pressure on the roof membrane with an internal coefficient $cpi = +0, 2$. The axial forces are shown in figure 5 for COMB4. Shear forces and bending moments for COMB4 are presented in figure 6. This combination resulted in the relatively high forces on the upper flanges of the SSF, where there is only one single bar, weighing -7.1 and -3.87 *kN*, which could require diagonals bars as bracings connected with the bottom flanges, avoiding buckling of compressed elements. In the example, the upper flange has 2 free-span lengths, measuring 3,2m and 3,6m, respectively. The subdivision of these free-span lengths would already be sufficient for the safe absorption of the estimated compression force. It is so recommended to specify the upper flange with larger diameters and larger wall thickness.



(a) (b)

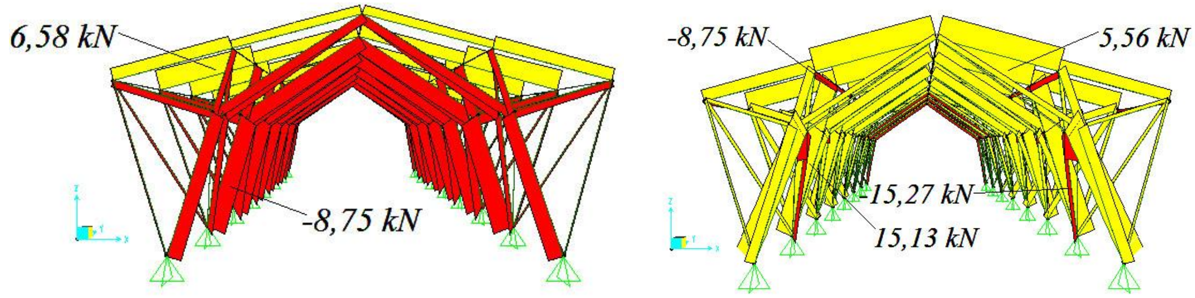
Figure 5: (a) Axial forces for COMB4 without anchorages. (b) Axial forces for COMB4 applying lateral anchorages



(a) (b)

Figure 6: (a) Shear forces for COMB4. (b) Bending moments for COMB4

The axial forces for COMB1 and COMB3 are presented in figure 7. Compression forces are showed in red and tension forces are showed in yellow (Fig. 7).



(a) (b)

Figure 7: (a) Axial forces for COMB1. (b) Axial forces for COMB3

## 5. Design Guidelines

The authors recommend local fillings inside the bamboo hollow chambers in the critical load points analyzed, avoinding crushing of the bamboo bars. The local fillings can be made applying expansive castor-oil PU polymer. The applied polymer is expandable in 10 or 5 times of its initial volume and presents different densities. The authors also recommend to anchor the vertices of the space frames with cables fixed on the ground to reinforce the structure under high lateral winds. Adopting this design guideline, the maximum compression force on the upper flange decreased from -7.1kN to -3.62 kN, and the compression force on the external bipod columns was about the same in boh cases, i.e., -1.0 kN. The bipod column bar of the SSF2 has a free-span length of 5,09m. Assuming that this bamboo bar presents a 90mm diameter with a 9mm wall thickness, we have $A = 250\ mm^2; I = 2040\ mm^4$.Considering an accidental imperfection of the bar axis equal to $e_a = \frac{l_0}{300} = \frac{5090}{300} = 17mm$ and $e_i = 45\ mm$ (eccentricity of the load on the top of the bamboo bar), since the flexible HLC transfer loads to the outside part of the bipod columns with 90mm diameter. This bar has a slenderness $\lambda = \frac{509}{\sqrt{\frac{204}{25}}} = 178$ which is not a problem for bamboo structures. Despite the high slenderness of bamboo bars, the eccentricity due to creep by bending in this case doen't need to be considered, since the wind load was responsible for higher forces and the wind load is considered as an instantaneous load.

The Euler loading of the column:

$$F_E = \frac{\pi^2 1250 \times 204}{509^2} = 9{,}71kN \tag{4}$$

Since Euler's load is so small, it is necessary to reduce the buckling length of the bipod columns. Reducing this length of buckling to 3,6m, which is the maximum free-span length of the upper flange, we have:

$$F_E = \frac{\pi^2 1250 \times 204}{360^2} = 19{,}4kN \tag{5}$$

And the maximum instantaneous lateral displacement would be a second order effect given by:

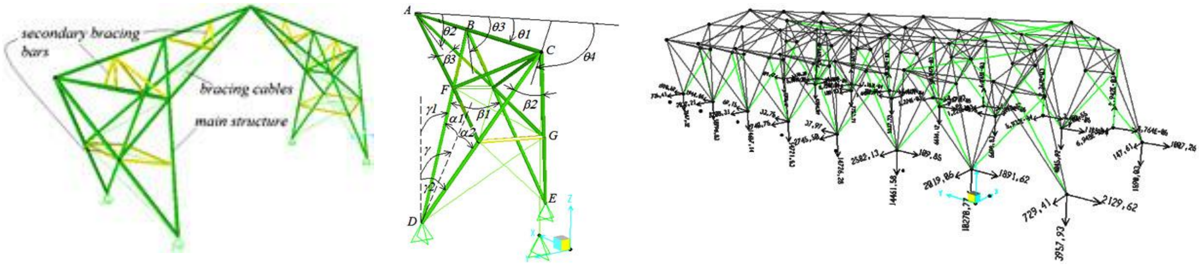
$$\delta = \frac{\delta_0}{1-\frac{P_d}{F_E}} = \frac{45+17}{1-\frac{1{,}0}{9{,}71}} = 1{,}11 \times 62 = 69mm \tag{6}$$

This is a superestimated value for lateral displacements because for Serviceability Limit States design the loadings are many times smaller than for Ultimate Limit States.

Analyzing the maximum compression stresses applied in the bamboo bars, we would have:

$$\sigma_c = \frac{1{,}0}{25} + \frac{1{,}0 \times 6{,}9}{204} \times 4{,}5 = 0{,}04 + 0{,}15 = 0{,}19\frac{kN}{cm^2} = 1{,}9MPa \tag{7}$$

This is a negligible value in terms of the strength of the bamboos *Phyllostachys* under compression forces, which can reach at failure 80 *MPa*. Bamboo culms, in general, are a highly resistant and flexible material. However, although it was not mechanically necessary, it is interesting to adopt braces in the structural design as presented in figure 8a, to decrease the buckling lengths of the external bipod columns, thus, increasing the stiffness of the SSF2. The definition of the geometry of the angles between bamboo bars in the SSF2 is presented in figure 8b. The anchors present horizontal and vertical reaction forces for wind loads. The maximum force analyzed was -14.72kN for wind suction and occurred for COMB4. The anchors reaction forces are presented in figure 8c.



(a) (b) (c)

Figure 8: (a) SSF braces in the superior truss and in the supporting bipod columns (b) Definition of the geometric angles between bars in the SSF2. (c) Anchors reaction forces for COMB4

## 6. Concluding remarks

The study presents design aspects and the structural analysis of a self-supporting textile bamboo roof structure applying flexible connections. Physical scale models, full-scale models and numerical models investigated the self-supporting structural system applying bamboo space frames, tensile pantographic grids and textile flexible joints. Hinged lashed connection (HLC) in polyester ropes and biocomposite bandages developed and presented an articulated mechanism allowing design mobile ultralight bamboo structures. HLC distributes the local stresses around the circunference of the bamboo bars and kept the operation of the bars in the structure free of torsion stresses, also avoiding the sliding of the connections in the structural members. After deployment of the structural modules in the final geometry, HLC is locked by additional constraint lashed joints. Modular self-supporting bamboo space frames (SSF) were developed in 2 architectural designs. SSF1 presents a rigid behavior on the top of the ridge and SSF2 presents a hinged behavior on the top of the ridge. Both space frames were applied for roofing open spaces in the tropical climate of Rio de Janeiro, Brazil. A FE model applying the SSF2 in the SAP2000 program was analyzed mathematically, drafting the mechanical behavior of the structure, establishing its Ultimate Limit States for static loading patterns. The authors investigated wind forces at 0º and 90º with the axis of the roof structure. The study presents forces applied in the structure and showed that forces can be safety absorbable by the structural members. The authors propose design guidelines for the developed structure. Project recommendations include local filling reinforcements using expansive castor-oil PU polymer applied inside the hollow chambers of the bamboo connections between flanges and beams, and also reinforcements in the extremities of the bamboo structural members, which are considered the critical load points of the structure. The study shows the potential of the developed ultralight bamboo structure and its serviceability in global operation. The study presents bio-based materials applied for a sustainable engineering design.

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