Aerodynamic and structural analysis using computational fluid dynamics and finite element method applied to an arched bamboo greenhouse

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Abstract. The protected cultivation system uses greenhouses to partially control soil and climate conditions, such as temperature, air humidity, radiation, wind, and atmospheric composition, thus exhibiting quantitative and qualitative advantages compared with field cultivation. Bamboo is considered a sustainable material because it is renewable, absorbs carbon dioxide, uses solar energy, and is easily incorporated into nature at your life cycle end. The aim of this paper was to analyze the aerodynamic and structural behavior of a bamboo greenhouse, aiming at the use of this material as a sustainable and low-cost construction element. For this, computational tools were used to obtain the loads acting on the structure, such as the computational fluid dynamics method to determine the wind loads and the structural analysis by finite element method to obtain the natural frequencies, the nominal stresses and the maximum displacements.

Keywords: Finite element method, CFD, modal analysis. greenhouse, bamboo

1 Introduction

Currently, the construction of greenhouses in the system of protected cultivation is another alternative to circumvent the climatic adversities and create a favorable environment for agriculture, even in regions where the climate or soil are unfavorable. Today there are in the market several materials used for the manufacture of these structures, but they demand high cost and non-renewable raw materials such as synthetic polymers (PVC) and metallic materials. Aiming at the use of renewable materials many farmers opt for timber, especially eucalyptus, which requires chemical treatment to withstand the conditions of use. As a result, the cost rises and treatment residues can contaminate the environment. [1].

Rethinking the use of materials in construction to make it more sustainable from the environmental point of view, bamboo appears as an effective proposal. This is because it is a material with excellent mechanical properties at the same time that is not polluting, does not require large energy consumption in its production process, its source is renewable and low cost [2].

Computational fluid dynamics (CFD) is a method of analysis involving fluid flow, heat transfer or related phenomena. Thus, through a numerical approach it is possible to simulate in a computational environment effect of diffusion and convection, aerodynamic behavior, turbulence, chemical reactions, among a multitude of actions that help from the conceptual phase of a project to the production and application stage of a product or system [3].

The finite element method is a numerical methodology where a continuous system is discretized into a finite number of elements and nodes. After this process, stiffness matrices are generated for each element and an interpolation function between the nodes, considering the properties of the material and geometry. The stiffness matrices defined for a linear analysis are singular and symmetric, making it impossible to solve them through a linear system. In order to get around this problem restrictions in degrees of freedom and external loads are applied to the structure, thus making it possible to obtain the nodal displacements present. Thus, from the nodal displacements it is possible to find an approximate global solution of the structure's behavior. [4]

Currently, in the market there are several finite element software programs, but all work with the same numerical basis of the method, changing only the specific functionalities for each area. The finite element program adopted in this study was the *RFEM* software, because it is a powerful software for quick and easy modeling, structural analysis and design of 2D and 3D models consisting of member, plate, wall, folded plate, shell, solid, and contact elements. [5]

2 Materials and Methods

For the development of this study, an arched greenhouse of 224 m² was used. That structure is composed of nine frames spaced at 3.5 m apart. Each of these frames consists of a main column 4.0 m high, two side columns 2.5 m high, and two intermediate columns 3.6 m high, all spaced at a distance of 2.0 m. A 200-micron plastic film covering is applied over the structure, supported by arches with a spacing of 1.75 m, which are embedded in connecting beams that connect all the frames. Between those beams are added lateral braces in 3/8" Gerdau CA-50 steel rebar connecting one arch to the other, in order to reduce the effective lengths of these elements. The graphical representation of the structure is shown in Figure 1.

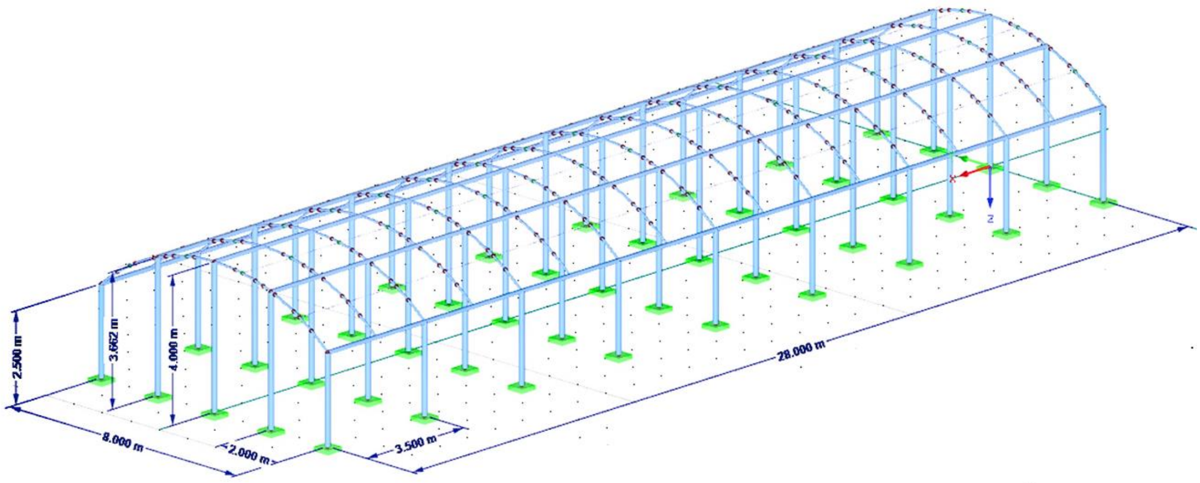

Figure 1 - Three-dimensional representation of the greenhouse. Source: The Author (2021)

According to information from Ghavami [6] bamboo is a natural material with a multiple factor that influence its mechanical properties. These properties are defined by the age of the plant, climatic conditions, harvest time, moisture content, location in relation the length of the thatch, the presence or absence of knots in the sample, and the type of test performed. To conduct the analysis procedures of this work two species of bamboo were used, *Bambusa tuldoides* as material for the arches and *Dendrocalamus Asper* for the construction of the columns and beams. The mechanical properties of both species according to Gonçalves et al. [7] are presented in Table 1.

Table 1 - Mechanical resistance of the bamboo species used.

Property	*Dendrocalamus Asper*	*Bambusa tuldoides*
Density [Kg/m³]	744	712
Elastic Modulus [GPa]	21,9	22,5
Poisson's Ratio	0,26	0,26
Tensile Strength [MPa]	103,9	85,5
Compressive strength [MPa]	30,8	26,2
Flexural Strength [MPa]	83,2	71,6
Shear strength [MPa]	35,4	41,6

Source: Adapted from Gonçalves et al. [7]

The bamboos used in the finite element analysis model were considered as adult sticks, with diameters of: 150 mm for the columns, 120 mm for the beams, and 60 mm for the arches. Likewise, they have a wall thickness of 25, 20, and 15 mm for the columns, beams, and arches, respectively. This is because in these dimensions the adopted species present a stability in the mechanical properties due to maturation.

2.1 Analysis of aerodynamic behavior using the computational fluid dynamics method (CFD)

Ansys CFX software was used as an analysis tool for the computational fluid dynamics method. This software uses the finite volume method to solve the Navier-Stokes's differential equations. The fluid used in the analysis was considered as Newtonian and incompressible, presenting turbulent flow and a steady state analysis

With the assistance of the *Ansys* software *Space Claim* tool, the greenhouse modeling was prepared and an analysis domain was created following the dimensions recommended by Ansys [8]. This process was developed to avoid the interference of external influences on the wind flow around the structure.

According to Takano [9] a model using tetrahedral elements with the refinement of discretization in the region of interest was elaborated as indicated in Figure 2. The dimension of the elements on the surface of the greenhouse was obtained through Equation (1), where the thickness of the first layer, y, is given in relation to the turbulence model used.

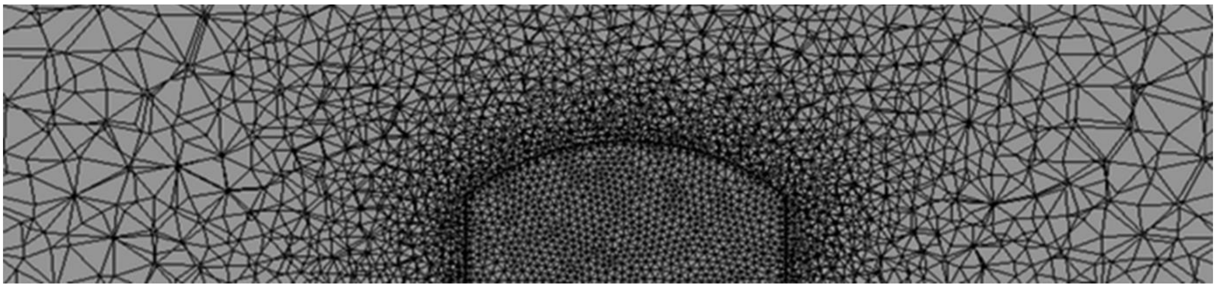

Figure 2 - Mesh used for the analysis with Ansys CFX. Source: The Author (2021)

$$y = \frac{Y^{+}\mu}{\rho u^{*}} \tag{1}$$

Where μ and ρ are the dynamic viscosity and the air density respectively. To determine the fluid friction velocity (u*), parameters provided by ABNT NBR6123:1988 [10] were used, such as the average wind speed and roughness length, besides that the value of 0.41 was used for the Von Kármán constant. As a dimensionless parameter Y+ referring to a turbulence model κ-ε a value of 200 was adopted, respecting the condition that according to Wilcox (1998) should be $30 \leq Y^{+} \leq 300$ so that the Reynolds stress is constant and approximately equal to the stress on the wall.

To evaluate the mesh quality, orthogonality, aspect ratio and Skewness checks were used following the limit values proposed by Ansys [8]. In addition, the dimension of the first layer was evaluated, thus gauging whether the value adopted for Y^{+} satisfies the hypothesis assumed based on the turbulence model adopted.

With the definition of the model to be analyzed and the finite volume discretization, the boundary conditions were then applied. The average wind speed was determined in the potential form following Equation (2).

$$\underline{V_z} = b\, Fr\, \underline{V_{(ref)}} \left(\frac{z}{z_{ref}}\right)^{p} \tag{2}$$

This equation matches the average velocity $\underline{V_z}$ at Z meters over the terrain to an average velocity $\underline{V_{(ref)}}$ at Z_{ref} meters over the ground. the exponent P depends on the terrain roughness and the gust time interval, the parameter b makes the correction for the building class and the parameter Fr corresponds to a gust intensity factor. The adopted values were defined based on ABNT NBR6123:1988 [10].

To define the domain, it was considered on the floor and wall regions as "wall" and in the flow contention as "no slip wall". For the inlet flow the velocity was defined through Equation (2) with an "inlet" condition and for the outlet an "outlet" condition with null relative pressure.

With the application of the boundary conditions in the model, the convergence criterion for the solution of the analysis was then determined. For this, the standard *Root Mean Square* (RMS) obtained through Equation (3) was used. Where R_I is the calculated residual in each mesh element and RMS the value of the average residual adopted for this work as 10^{-4} standard value of the software Ansys CFX.

$$RMS = \sqrt{\sum {R_I}^{2}} \tag{3}$$

After solving the computational model, the external pressure coefficients (Cpe) acting on the structure are obtained through Equation (4). For this, the aerodynamic characteristics of the building are considered, where the regions of overpressure (Cp>0) and suction (Cp<0) are obtained. The overpressure acts on the face of the building where the direct incidence of wind occurs (windward) and the suction on the opposite face (leeward).

$$C_{pe} = \frac{\Delta P_e}{q} \tag{4}$$

Where ΔP_e is the external pressure variation obtained through the analysis with Ansys CFX and q is the dynamic wind pressure defined by NBR6123:1988 [10] which is presented by Equation (5). The characteristic wind speed V_k is calculated by Equation (6).

$$q = 0{,}613.V_k{}^2 \tag{5}$$

$$V_k = V_0 * S_1 * S_2 * S_3 \tag{6}$$

The S_1 coefficient was adopted as 1 because the terrain is flat, the S_3 coefficient is equal to 0.95 because greenhouses are identified as rural buildings with low occupancy factor, the basic wind speed V_0 as 45 m/s by an analysis on the velocity lines map of ABNT NBR6123:1988 for the southwest region of Paraná. The coefficient S_2 was calculated with ABNT NBR6123:1988 according to a meteorological parameter, gust factor, correction parameter of the building class and the height above ground limited to the gradient height.

The internal pressure coefficients (Cpi) are used to consider the openings of the building, which are given through the permeability of each face of the building, the dimensions of the structure, the values of external overpressure and suction acting on the internal part and the location of the openings and wind direction. The values referring to the internal pressure coefficients were obtained through ABNT NBR 16032:2012 [12] for an arched greenhouse with permeable windows.

The wind loads in the greenhouse were obtained using Equation (7) following the criteria defined by ABNT NBR16032:2012 [12] where Cp is the difference between the external and internal pressure coefficients and L is the distance between the frames.

$$F = C_p \cdot q \cdot L \tag{7}$$

2.2 Analysis of structural behavior using the finite element method (FEM)

Because it is a reticulated structure, the model was developed from beam elements with the aid of the software *Dlubal RFEM*, thus aiming to obtain the primary stresses and natural frequencies through dynamic and static linear analysis respectively. To simplify the structural model, the bamboo was considered as a uniform cylindrical element, without diaphragms and conicity effect. As a way of restricting the degrees of freedom, fixed supports were considered at the base of the columns, at the joints between the arches and the beams, and between the beams and the columns.

The wind loads obtained in section 2.1 were applied to the structure. To consider the variable actions it was used according to ABNT NBR16032:2012 [12] an overload of 0.25 kN/m², in addition to the self-weight of the building elements defined by the density of the material and their respective volumes.

With the structural model of the greenhouse in beam elements from the software Dlubal RFEM, a modal analysis was developed with the aid of the external module RF-Dynam PRO, where the natural frequencies and periods for the first 6 vibration modes were obtained through the Lanczos method.

3 Result and Discussion

3.1 Aerodynamic behavior

Table 3 presents the results obtained with the mesh quality check. The values shown in the orthogonal quality are 13% lower than the minimum limit recommended by Ansys [8], but as they are in a small number of elements, outside the region of interest and with a low standard deviation, they were accepted to decrease the computational cost of the analysis. The aspect ratio values have values above the limit proposed by Ansys [8], but they belong to the boundary layer and their average is within the acceptable limit.

Table 2 - Mesh quality parameters used in the model

Model	Orthogonal Quality		Aspect Ratio		Skewness		Y^+
	Minimum	Average	Maximum	Average	Maximum	Average	Maximum
Wind 0°	0,13	0,81	204,30	14,26	0,90	0,20	268
Wind 90°	0,12	0,80	205,18	13,20	0,79	0,19	287

Based on the flow lines presented in Figure 3 it is possible to observe that vortices are generated on the leeward face, places where flow separation occurs. It is also observed that the wind that falls to windward is drained to the sides and top of the structure, thus causing an increase in velocity at these points.

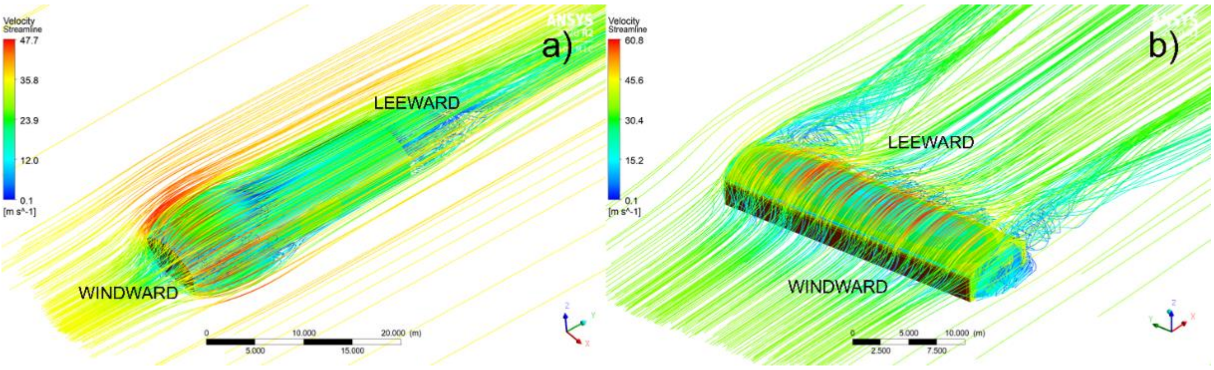

Figure 3 – a) Flow lines for wind 0° b) Flow lines for wind 90°. Source: The Author (2021)

Comparing the distribution of the external pressure coefficients represented in Figure 4 with the ranges specified by ABNT NBR6123:1988, defined in Figure 5, a similarity between the results is verified. It is also possible to analyze in Figure 4 the regions of overpressure (positive) and suction (negative) along the model.

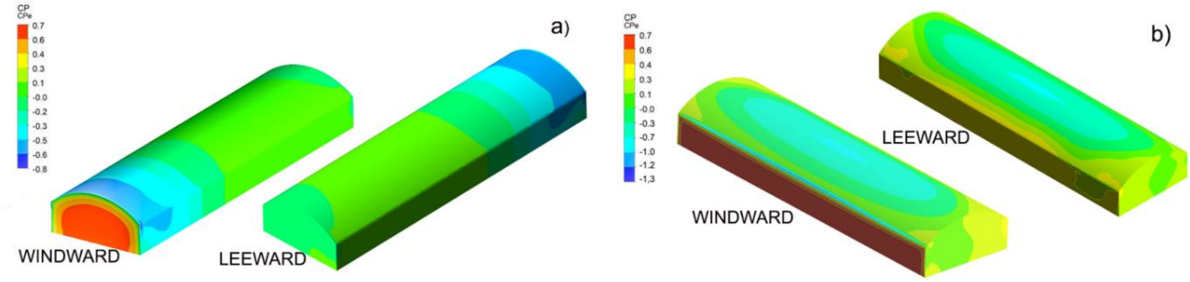

Figure 4 - a) External pressure coefficients for wind 0° b) External pressure coefficient for wind 90°
Source: The author (2021).

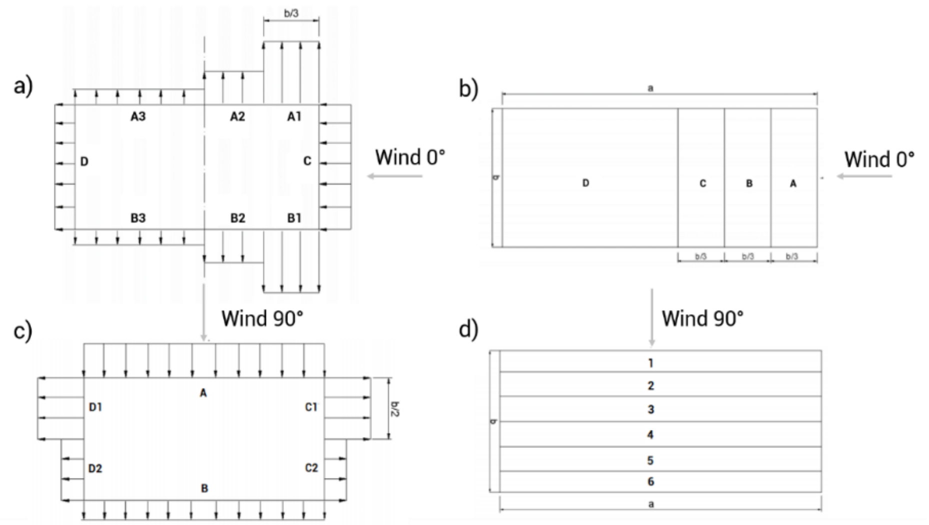

Figure 5 - a) Incidence of wind 0º on the walls b) Incidence of wind at 0º on the roof c) Incidence of wind 90º on the walls d) Incidence of wind 90º on the roof. Source: Adapted from ABNT NBR6123:1988 [10]

Through data processing the maximum and minimum values of the external pressure coefficients for each region indicated in Figure 5 were obtained. The values obtained are presented in Table 3.

Table 3 – Values of external pressure coefficients for wind conditions at 0° and 90° in different regions of the structure

Wind 90°				Wind 0°			
Roof	Cpe	Wall	Cpe	Roof	Cpe	Wall	Cpe
1	-1,3	A	0,7	A	-0,8	C	0,7
2	-0,7	B	-0,5	B	-0,5	D	-0,2
3	-1,2	C1/D1	-1,1	C	-0,4	A1/B1	-0,8
4	-1,2	C2/D2	-0,5	D	-0,2	A2/B2	-0,4
5	-0,4					A3/B3	-0,2
6	-0,3						

Through Equation (7) it was possible to determine the wind loads on the structure. These loads are presented in Table 4 and were left per unit area to easily the application of the software.

Table 4 – Wind load per unit area in different regions of the structure

Wind 90°				Wind 0°			
Roof	Load [kN/m²]	Wall	Load [kN/m²]	Roof	Load [kN/m²]	Wall	Load [kN/m²]
1	-1,37	A	0,46	A	-0,97	C	0,48
2	-0,82	B	-0,64	B	-0,68	D	-0,39
3	-1,23	C1/D1	-1,19	C	-0,58	A1/B1	-0,97
4	-1,23	C2/D2	-0,64	D	-0,39	A2/B2	-0,58
5	-0,55					A3/B3	-0,39
6	-0,46						

3.2 Structural behavior

According to item 9.1 of ABNT NBR6123:1988 [10], in buildings whose fundamental period of a given natural frequency exceeds the value of 1 second the wind loads must be calculated considering the dynamic effects due to atmospheric turbulence. Therefore, to validate this consideration the natural periods of the first 6 vibration modes of the structure were analyzed as presented in Table 5.

Table 5 - Angular Frequency, Natural Frequency e Natural Period for the first 6 vibration modes

Mode [N°]	Angular Frequency [rad/s]	Natural Frequency [Hz]	Natural Period T [s]
1	43,286	6,889	0,145
2	45,297	7,209	0,139
3	45,776	7,286	0,137
4	49,046	7,806	0,128
5	54,656	8,699	0,115
6	60,488	9,627	0,104

As the natural periods of the structure were below 1 second it is consistent to use the static method for calculating the forces due to wind, as discussed in section 2.1.

The Table 6 presents the values of displacements and critical loads obtained from the finite element analysis. It is denoted that due to the crimping the columns suffered the greatest action regarding the bending moment. In relation to the displacements presented in Figure 6, the arches were the most requested due to their slenderness and the action of the suction wind affecting these components with greater modulus.

Table 6 - Critical forces and displacements acting on the structure.

Operating	Columns	Beams	Arches
Maximum deformation [mm]	16,9	7,60	21,9
Maximum bending moment [N.mm]	11450000	4710000	1200000
Maximum shear force [N]	15230	3380	3380
Maximum normal force [N]	9660	11420	8120

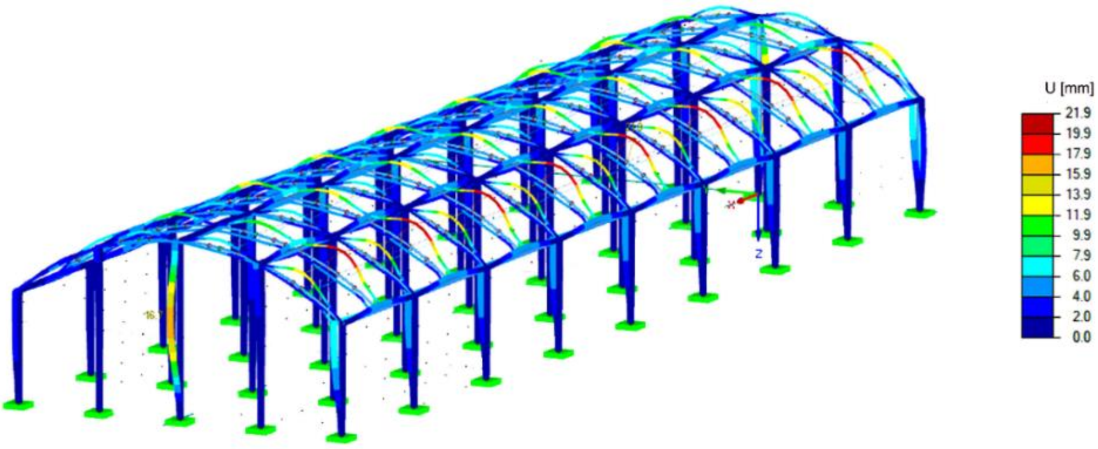

Figure 6 - Displacements acting on the structure. Source: The author (2021).

4 Conclusion

With the adopted methodology it was possible to obtain the aerodynamic and structural actuants of the greenhouse. Through CFD analysis the external pressure coefficients and the flow lines of the flow were determined, demonstrating the expected behavior and the consistency of the results based on ABNT NBR6123:1988 [10]. With a modal analysis it was determined the method of calculation of the wind loads, which applied along with the normalized loads in the structural model resulted in the nominal forces and the acting displacements through a static linear analysis. With this data it is possible to perform a design of the structural elements, the joints and the geometry of the greenhouse through standards for the design of bamboo structures. It is worth emphasizing the importance of a deep study that takes into consideration the nonlinearity of the material, the conicity effect of the bamboo sticks, the presence of diaphragms and the type of connection between the structural elements.

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