STUDY OF THE AERODYNAMIC AND STRUCTURAL BEHAVIOR OF AN ARCHED BAMBOO GREENHOUSE

ESTUDO DO COMPORTAMENTO AERODINÂMICO E ESTRUTURAL DE UMA ESTUFA DE BAMBU EM ARCO

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ABSTRACT

Greenhouses used for agricultural production are structures to partially control soil and climate conditions such as temperature, air humidity, radiation, wind, and atmospheric composition. Thus, according to Cermeño (1990) protected cultivation has quantitative and qualitative advantages compared to field cultivation since productivity in the first system can be 2 to 3 times higher. 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 technical feasibility of bamboo in the construction of a greenhouse for protected cultivation. For this, the aerodynamic and structural behavior was analyzed in order to obtain the safety margins for this construction. With the safety margins it was determined that bamboo is a plausible material for the construction of these structures.

KEY WORDS: Greenhouse; Bamboo; Finite Elements; CFD; Structural Analysis.

RESUMO

As estufas utilizadas para a produção agrícola são estruturas para controlar parcialmente as condições edafoclimáticas, tais como temperatura, umidade do ar, radiação, vento e composição atmosférica. Assim, de acordo com Cermeño (1990), o cultivo protegido tem vantagens quantitativas e qualitativas em relação ao cultivo em campo aberto, uma vez que a produtividade no primeiro sistema pode ser 2 a 3 vezes superior. O bambu é considerado um material sustentável porque é renovável, absorve dióxido de carbono, utiliza energia solar, e é facilmente incorporado na natureza no final do seu ciclo de vida. O objetivo deste trabalho foi analisar a viabilidade técnica do bambu na construção de uma estufa para o cultivo protegido. Para tal, foi analisado o comportamento aerodinâmico e estrutural, a fim de obter as margens de segurança para esta construção. Com as margens de segurança foi determinado que o bambu é um material plausível para a construção destas estruturas.

PALAVRAS-CHAVE: *Estufa; Bambu; Elementos Finitos; CFD; Análise Estrutural.*

1. INTRODUÇÃO

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. (PURQUERIO; TIVELI, 2010).

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 (BERALDO; PEREIRA, 2016).

Even with several positive aspects, bamboo is still a material undervalued in our society. For this reason, there is a deficiency of standards and criteria for tests and trials of its mechanical properties, making the structural application of this material expensive.

The lack of technical knowledge for the application of bamboo as a structural element limits the benefits presented by this material. Hence, this paper aimed to analyze the technical feasibility of bamboo in the construction of a greenhouse for protected cultivation. As a parameter to evaluate the fulfillment of the objective, the safety margins were evaluated based on the sizing of the sections through the limit state equations proposed by Kaminski et al. (2016). For this, it was necessary to obtain the wind loads through a computational fluid dynamics analysis and then evaluate the tensions acting on the structure through a finite element linear static structural analysis.

2. THEORETICAL FRAMEWORK

Due to the lack of Brazilian standards for the use of bamboo as a structural element, Marçal (2018) analyzed in his work the different international standards that govern bamboo constructions, thus defining the most compatible standard with the reality of bamboo use in Brazil. Kaminski *et al*. (2016) proposes a method of limit state design encompassing factors from international standards such as: ISO 22156 (2004) Bamboo — Structural design, ISO 22157-1 (2005) Bamboo — Determination of physical and mechanical properties and NSR-10: Colombian code for seismically resistant construction. With this method, Rosalino (2019) evaluated the possibility of producing a roofing system composed of trusses for small and medium spans using bundles of bamboo species *Bambusa tuldoides*, where the results presented the technical feasibility of using this material.

When it comes to the numerical analysis of wind actions for arch structures, Takano (2019) develops his work aiming to determine and evaluate, through numerical models performed in Ansys CFX software, the pressure coefficients due to wind loads around sheds with arch roofs and exhibiting various amounts of roof spans.

The finite element method is a numerical method for solving typical engineering problems, such as structural, heat transfer, fluid mechanics, and mass transport problems. For its formulation, 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. From the nodal displacements it is then possible to find an approximate global solution of the structure's behavior. (ALVES FILHO, 2013).

According to information from Logan (2007), because it is a numerical method, the finite element method provides an approximate solution that depends on the quality and quantity of the elements used. For the model result to converge to the real result, it is necessary to use elements that correspond to the physical behavior of the analyzed structure, whether it is a beam, plate, shell, solid, or thin-walled beam.

Furthermore, one must choose an adequate discretization so that the elements remain regular, without significant variations in internal angles, because this leads to an increase in the model's singularity and decreases the accuracy of the results. To verify the quality of the mesh, parameters such as aspect ratio, internal angle, orthogonal quality, warping, and skewness, among others, are used.

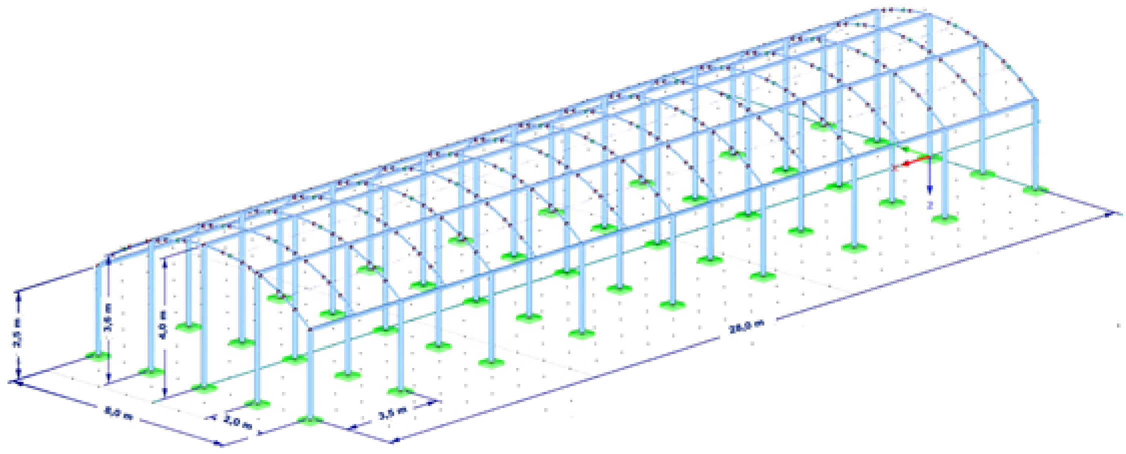

Figure 1 - Three-dimensional representation of the greenhouse.
Source: Authors

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 work 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. (DLUBAL, 2021).

According to Alves Filho (2013), the number of companies adhering to the finite element method in product development is rising. This is due to the increase in quality, agility and performance of projects that adopt this method, thus increasing profitability through predictive engineering, in other words, the behavior of components is simulated computationally preventing failures and developing corrections, considerably reducing spending on prototyping.

3. 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.

According to information from Ghavami (1995) 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.* (2001) are presented in Table 1.

3.1 Computational fluid dynamics

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 (2016). This process was developed to avoid the interference of external influences on the wind flow around the structure.

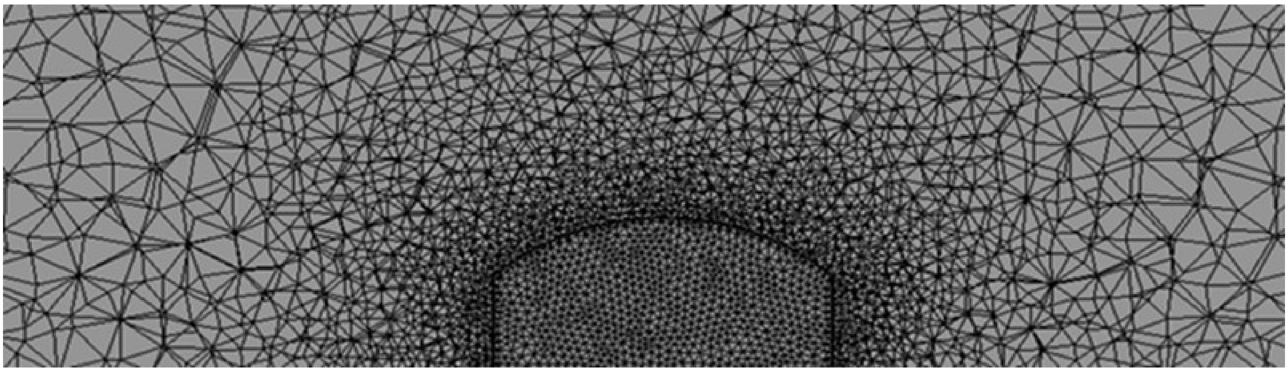

Figure 2 - Mesh used for the analysis with Ansys CFX.
Source: Authors

Table 1. Mechanical resistance of the bamboo species used.
Source: Adapted from Gonçalves *et al.* (2001)

Property	*Dendrocalamus asper*	*Bambusa tuldoides*
Density [Kg/m^3]	744	712
Elastic Modulus [GPa]	21,9	22,5
Poisson's Ratio	0,26	0,26
Longitudinal Tensile Strength [MPa]	103,9	85,5
Longitudinal Compressive strength [MPa]	30,8	26,2
Flexural Strength [MPa]	83,2	71,6
Transverse Shear strength [MPa]	35,4	41,6

According to Takano (2019) 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.

$$y = \frac{Y^{+}\mu}{\rho u^{*}} \quad (1)$$

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 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.

Orthogonality, aspect ratio and Skewness checks of the constituent elements were used to evaluate the mesh quality. In addition, the size of the first layer was evaluated, thus gauging whether the value adopted for Y+ satisfies the premise made based on the turbulence model used.

Orthogonality refers to the deviation of the angle between the vector connecting the center of adjacent volumes and the vector normal to the surface between them. Therefore, by recommendation of Ansys (2016) the closer to 1.0 the better the orthogonal quality of the mesh in question, moreover the minimum accepted values should be between 0.15 and 0.20.

The aspect ratio is the ratio between the largest and the smallest edge of the element. Therefore, the value of the aspect ratio should be 1 to ensure the regularity of the element and consequently better results. For three-dimensional elements the aspect ratio is given by the ratio between the radius of the circumscribed circle and the radius of the inscribed circle in the element.

The skewness parameter is directly related to the deviation of the vector connecting the centers of the volumes and the vector normal to the face, and therefore directly affects the

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accuracy of the numerical approximation of the flows. Thus, high values of skewness can easily degrade the numerical solution. The closer to zero the better the quality of the mesh and per Ansys (2016) recommendation, maximum acceptable values are between 0.80 and 0.94.

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).

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

This equation matches the average velocity V_Z at Z meters over the terrain to an average velocity $V_{(ref)}$ 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

With the application of the boundary conditions in the model, the convergence criteria for the solution of the analysis were then determined. For this the standard root-mean-square (RMS) was used until a residual value smaller than 10^{-4} was reached.

3.2 Structural analysis with the finite element method

Because it is a reticulated structure and does not present localized stresses, the model was elaborated from beam type elements, in other words, elements in which the length is predominant in relation to the cross-section. With this it was not necessary to create a mesh, since the interpolation function of the one-dimensional element is exact and its discretization does not alter the results. For simplification of the structural model, the bamboo was considered as a uniform cylindrical element, without diaphragms and taper effect.

To determine the loads acting in a greenhouse construction, the criteria defined by ABNT NBR16032:2012 were followed. According to this standard, the main action that can occur in a greenhouse is the wind load. To determine the load acting on the structural frames used was Equation (3) where C_p is the difference between the external and internal pressure coefficients and L is the distance between the frames.

$$F = C_p \cdot q \cdot L \quad (3)$$

The dynamic wind pressure (q) defined by NBR6123:1988 is presented by Equation (4), where V_k is the characteristic wind speed and evidenced in Equation (5).

$$q = 0{,}613.V_k^{\,2} \quad (4)$$

$$V_k = V_0 * S_1 * S_2 * S_3 \quad (5)$$

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.

To consider the loads due to the use of the greenhouse it was considered according to ABNT NBR16032:2012 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 the volume of the components.

As a form of restriction, it was considered fixed supports at the base of the columns, at the joints between the arches and the beams, and between the beams and the columns. With this, added to the application of loads on the model, a static linear analysis was then determined, aiming to obtain the displacement and the nominal stresses acting on the structure.

3.3 Sizing and checking

A limit state method proposed by Kaminski *et al.* (2016) was used to verify the sections. The characteristic strength of the design ($X_{i,d}$) is obtained through the characteristic strength of the material (X_k) determined by tests, by factors that consider the class of service, the duration of force and the load applied to the system (k_{mod}). In addition, a safety factor (y_m) is used as presented in Equation (6).

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$$X_{i,d} = k_{mod} \, k_{sys} \, \frac{X_k}{\gamma_m} \quad (6)$$

The value of k_{sys} for a continuous load distribution that supports load redistribution can be adopted as 1.1, in this same case a factor of safety (γ_m) as 1.5 was adopted.

To determine the maximum bending moment (M_n) Kaminski *et al.* (2016) propose to use the elastic modulus ($S_{elastic}$) combined with the design shear strength (X_{md}). Equations (7) and (8) define this procedure.

$$S_{elasti\ c} = \frac{\pi(D_e^4 - [D_e - 2t]^4)}{32 D_e} \quad (7)$$

Where D_e is the outer diameter of the bamboo, and t is the thickness.

$$M_m = X_{md} \, S_{elastic} \quad (8)$$

The verification regarding the maximum shear force F_v is performed through Equation (9) where the capacity of the element to withstand shear stress is analyzed.

$$F_v = X_{vd} K_{cr} \frac{3\pi t(D_e^4 - [D_e - 2t]^4)}{8(D_e^3 - [D_e - 2t]^3)} \quad (9)$$

The risk of a single split by thatch cracking K_{cr} should be adopted as 0.5 For analysis as to maximum axial tension F_T, the net-section area (A) by the design axial stress X_{r0d} was used, as shown in Equation (10).

$$F_T = X_{t0d} A \quad (10)$$

According to Kaminski *et. al.* (2016) the parts analyzed for axial compression, should be sized according to their slenderness ratio (λ), this is because local fiber crushing can occur in short parts, fiber separation in medium parts, and global Euler buckling in long parts.

The Equation (11) is used to rate the compressed element by its slenderness ratio.

$$\lambda = \frac{l_e}{r} \quad (11)$$

$$l_e = kL \quad (12)$$

The coefficient k in Equation (12) is defined by the condition of the supports, where k=1 for both hinged ends and k=2.1 for one end with restriction to rotation and displacement and the other free. This coefficient multiplied by the element length L defines the effective length of the element l_e.

The radius of gyration (r) is obtained from Equation (13), where the moment of inertia (I) and the cross-sectional area (A) of the element are related.

$$r = \sqrt{\frac{0{,}9I}{A}} \quad (13)$$

To verify the slenderness of the elements, the limit slenderness between the short and long parts C_k is calculated according to Equation (14).

$$C_k = \pi \sqrt{\frac{E_{0,05}}{\gamma_E X_{c0d}}} \quad (14)$$

Where $E_{0,05}$ is the modulus of elasticity in the 5th percentile of the tests and is between the range of (7500-13000), t_E is the safety factor for the material, adopting it as 1.5, and X_{c0d} is the design characteristic compressive stress. With this and the slenderness index it is possible, analyzing Table 2, to classify the part as short, intermediate or long.

Table 2 - Classification of the elements as to slenderness index.
Source: Kaminski *et. al.* (2016).

Elements	Slenderness
Short	λ < 30
Intermediate	30 < λ < Ck
Long	Ck < λ < 150

For elements with λ < 30 Equation (15) is used.

$$F_C = X_{c0d} A_{tot} \quad (15)$$

For elements with 30 < λ < Ck Equation (16) is used.

$$F_C = X_{c0d} A_{tot} \left(1 - \frac{2}{5}\left[\frac{\lambda}{C_k}\right]^3\right) \quad (16)$$

For elements with Ck < λ < 150 Equation (17) is used.

Table 3 - Mesh quality parameters used in the model.
Source: Authors

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

$$F_C = \frac{0{,}6\pi^2 A_{tot} E_{0{,}05}}{\gamma_E \lambda^2} \quad (17)$$

Structural elements that are simultaneously subjected to compressive and bending forces must be calculated using the allowable stresses to comply with Equation (18).

$$\frac{f_c}{F_c} + \frac{k_m f_b}{F_b} \leq 1 \quad (18)$$

Where $f_c$is the acting compressive stress parallel to the fibers, F_{ic} is the admissible compressive stress parallel to the fibers, f_b is the acting bending stress and F_b is the admissible bending stress. The moment expansion coefficient k_m can be calculated by Equation (19). Where N_a is the acting compressive load and N_c is the Euler's critical load, that can be calculated by Equation (20).

$$k_m = \frac{1}{1 - 1{,}5\left(\frac{N_a}{N_c}\right)} \quad (19)$$

$$N_c = \frac{\pi^2 E_{0{,}05} I}{{l_e}^2} \quad (20)$$

Structure members that are simultaneously subjected to axial tensile and bending forces should be designed to comply with Equation (21). Where f_t and F_{it} represent the acting and admissible tensile stress respectively.

$$\frac{f_t}{F'_t} + \frac{f_b}{F_b} \leq 1 \quad (21)$$

The Safety margins are calculated to show how far a part is from structural failure. Equation (22) represents how these margins are obtained.

$$MS_{\%} = \left(\frac{Admissible}{Operating} - 1\right) \times 100 \quad (22)$$

4. RESULT AND DISCUSSION

4.1 Computational fluid dynamics

Table 3 presents the results obtained with the mesh quality check. The values presented in the orthogonal quality are 13% lower than the minimum limit recommended by Ansys (2016), but as they are in a tiny amount 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 other parameters present values within the expected limits.

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

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 mode.

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 4.

Through parameters catalogued by the standard ABNT NBR16032:2012 and with the pressure coefficients obtained previously it was possible to determine the wind loads acting on the structure. These loads are presented in Table 5.

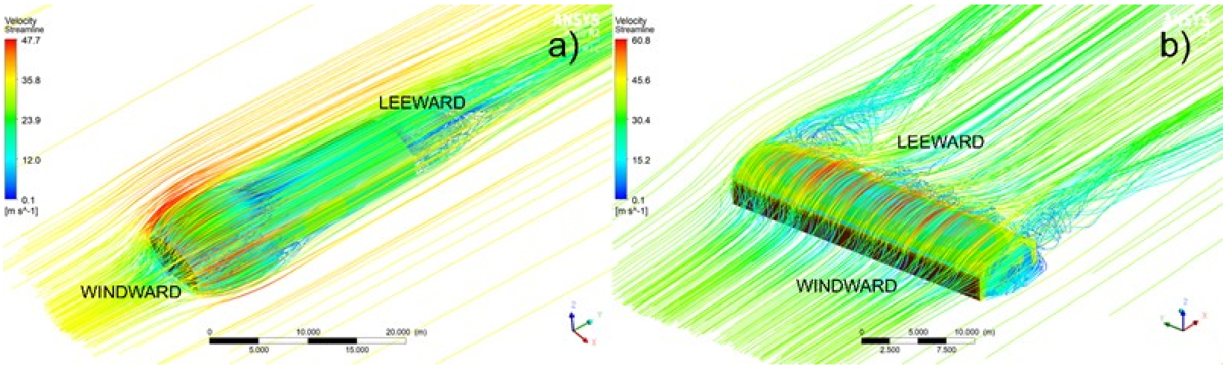

Figure 3. a) Flow lines for wind 0° b) Flow lines for wind 90°.
Source: Authors

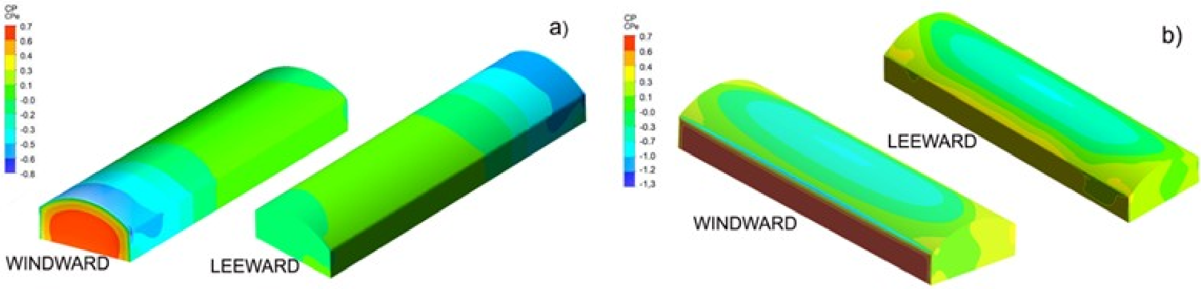

Figure 4. a) External pressure coefficients for wind 0° b) External pressure coefficient for wind 90°.
Source: Authors

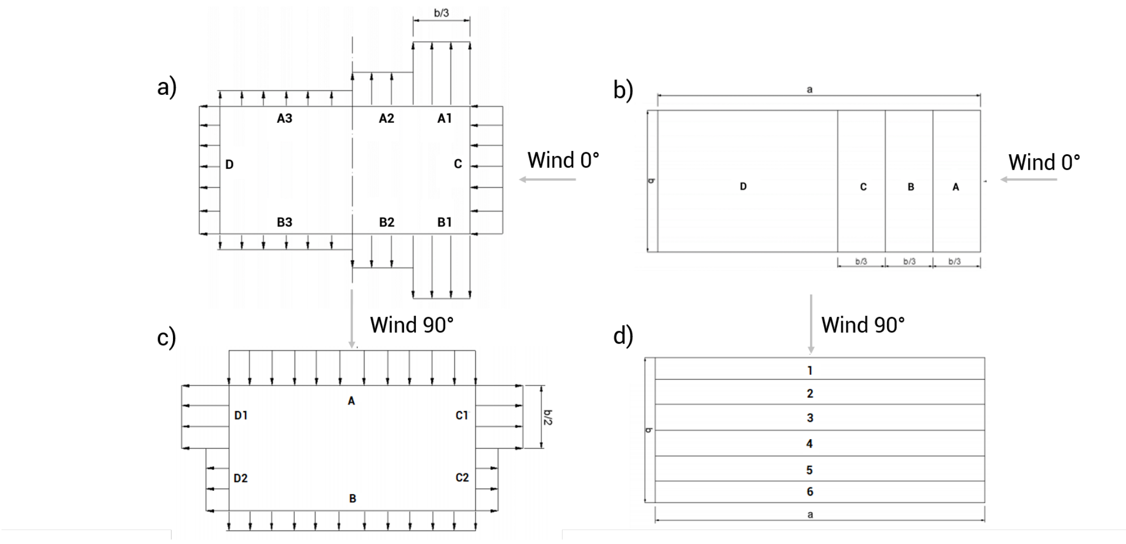

Figure 5. a) Incidence of wind 0º on the walls b) Incidence of wind at 0º on the roof c) Incidence of wind 90º on the walls d) Incidence of wind 90º on the roof.
Source: Adapted from ABNT NBR6123:1988

4.2 Structural analysis with the finite element method

The bamboos culms 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.

Table 4. Values of external pressure coefficients for wind conditions at 0° and 90° in different regions of the structure.
Source: Authors

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						

Table 5. Load due to wind per unit area in different regions of the structure.
Source: Authors

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						

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.
Source: Authors

Operating	**Columns**	**Beams**	**Arches**
Maximum deflection [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

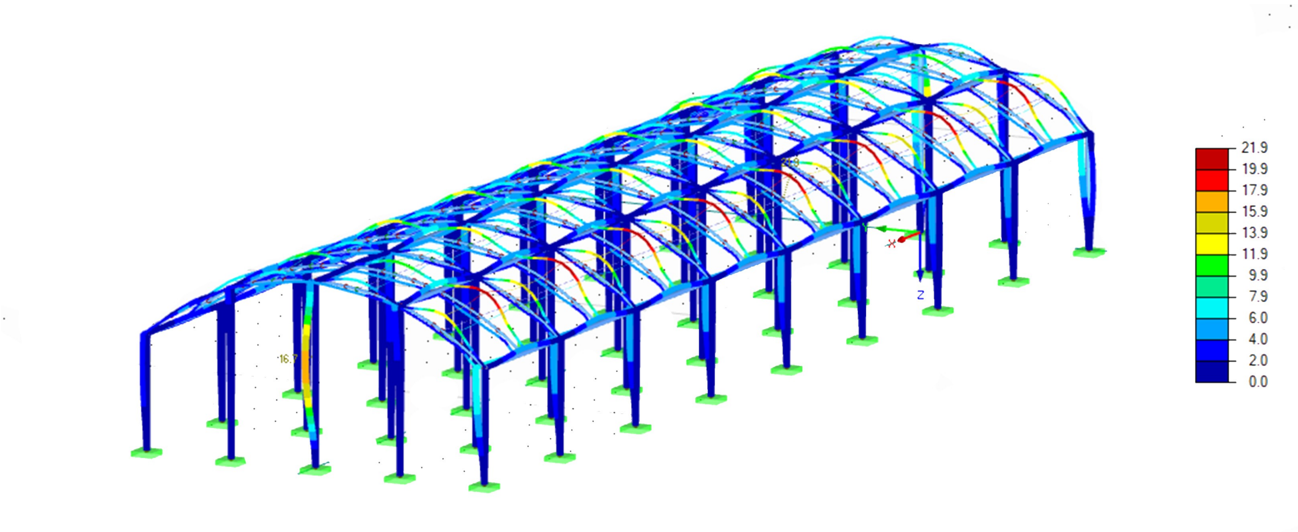

Figure 6. Displacements acting on the structure.
Source: Authors

4.3 Sizing and checking

With the data of mechanical and geometric properties, it was then used the limit state equations proposed by Kaminski *et al* (2016), with this, together with the acting loads obtained by finite element analysis it was obtained the safety margins for the structure through Equation (22), presented in Table 7. As a design requirement was adopted a minimum safety margin of 15% and analyzing the results obtained it was found that for all cases the minimum margin was achieved.

Table 7. Safety margins for the structural elements analyzed in relation to different loads.
Source: Authors.

Safety margins	Columns	Beams	Arches
Minimum safety margin	15%	15%	15%
Displacement	58%	54%	33%
Bending moment	93%	171%	19%
Shear force	486%	1589%	599%
Axial tensile	10464%	5619%	2132%
Axial Compressive	244%	56%	63%
Axial tensile + bending	99%	98%	95%
Axial Compressive + bending	99%	98%	95%

5. CONCLUSION

In this study, developed based on an agricultural greenhouse, applying the numerical analysis method of wind actions through computational fluid dynamics and later a finite element structural analysis, it was verified that bamboo culms can be incorporated in these structures as an alternative to conventional materials, because it presents technical feasibility determined by the safety margins presented in Table 7. It is worth pointing out for future works the importance of mechanical and thermal tests to determine the properties of this material, the types of treatment applied to the bamboo, as well as an in-depth practical study on the joints between the structural elements used.

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