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CASE REPORT

Structural analysis of a *Guadua* bamboo bridge in Colombia

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Abstract: In recent years, scientists have focused their attention in developing sustainable materials that can boost the construction industry without causing damage to the environment. In South and Central American forests grows a tropical species of bamboo known as *Guadua angustifolia Kunth*, which has been widely used for construction purposes since ancient times. Offering advantages such as: environmental friendliness, fast-growing and high strength-to-weight ratio. This paper analyzes the structural behavior of an existing multi-culm *Guadua* bamboo truss type footbridge located in Colombia, according to national regulations NSR-10. A model of the structure is implemented using a commercial finite element software, details for an accurate description of the structure's behavior through the proposed model are offered. Furthermore, an exhaustive description of the structure's load transfer and its materials mechanical properties is performed, as well as a review on connections and immunization process. Finally, improvement opportunities for the building codes used for the analysis and investigation opportunities are identified. The purpose of this paper is stepping into the right direction thus, one day *Guadua angustifolia Kunth* and bamboo in general can be fully exploited in the construction industry.

Keywords: Sustainable materials; *Guadua angustifolia Kunth*; structural behavior; truss type footbridge.

1 Introduction

Bamboo is a grass-like plant that belongs to the family of *Bambusoideae*, and it is composed by cylindrical culms that present horizontal diaphragms at its nodes. Being an anisotropic material, it is stronger along its fibers. When used as an engineered structural material, bamboo tends to fail due to longitudinal splitting, caused by tension and shear stress [1]. The nodes spread along bamboo stems seem to have evolved to enable branch points for the leaves. Nevertheless, the irregular fibers near the nodes make them a point of weakness when loaded in tension [2].

Bamboo has been used as a natural building material since ancient times in different places around the world. Due to its strength-weight ratio and relatively fast harvesting it has been widely studied to promote its use in the modern construction industry [3]. Furthermore, using a renewable material is

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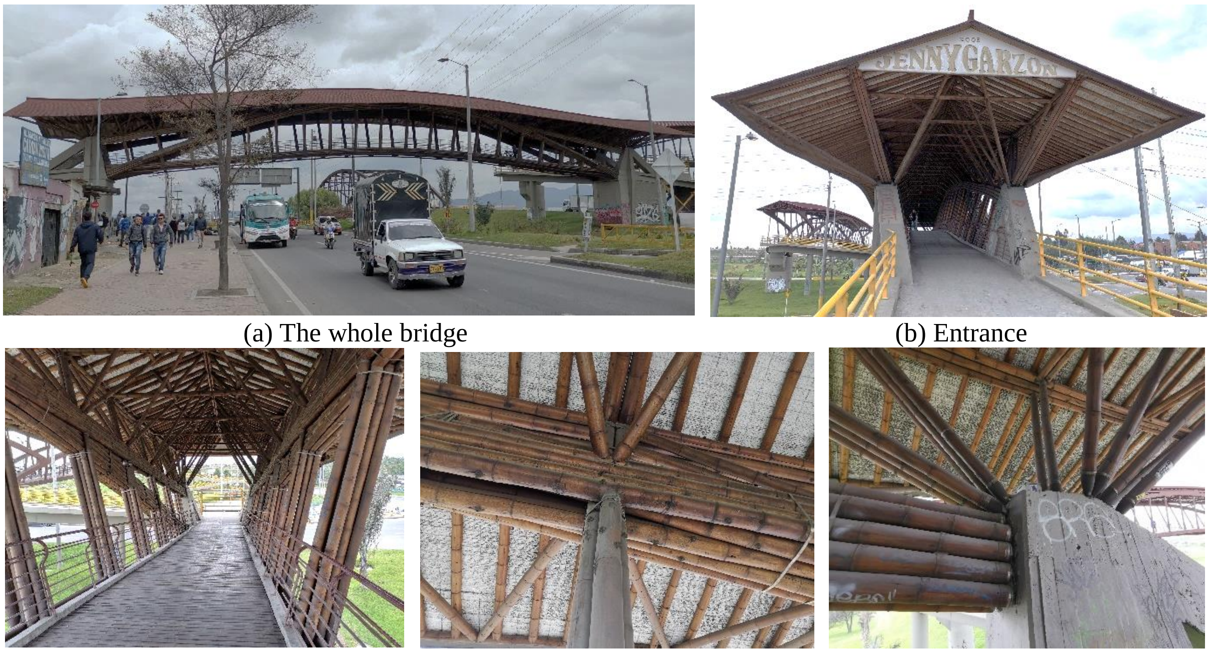
crucial on a strive to lower the ecological footprint of one of the most polluting industries in the world [4]. *Guadua angustifolia Kunth* is a tropical species of bamboo endemic to South and Central America. Its use for construction purposes dates back to the pre-Columbian era, where some indigenous cultures used it as building material, such is the case of the hanging bridges developed by the Incas; in the Colombian territory the Páez Indians crafted false arches with braces [5].

Researchers' effort is valuable in the development of building codes. Mechanical properties of bamboo, and natural materials in general may vary depending on variables such as the age, moisture content, specific weight and density. Furthermore, being *Guadua* an anisotropic material, its mechanical behavior drastically varies along the length of the stems and from culm to culm as well [6-7] .

Multiple investigations have led to different values for the mechanical properties of *Guadua angustifolia Kunth* in the Colombian territory such as: elastic modulus, flexion resistance, tension parallel to the grain and compression parallel to the grain [8-13] . The variation found in the former mentioned studies, highlights the importance of characterizing the *Guadua* bamboo when used as structural material. Especially, since its mechanical properties may vary due to weather and soil conditions. In addition, the part of the stem that a bamboo sample belongs to and the presence of nodes, affect its mechanical properties as well. The highest values for flexion strength, tension and compression parallel to the grain are obtained from samples coming from the top of the stems [2,14-15] .

In contrast to its high tensile stress, raw bamboo displays a low compressive bearing capacity. Li, et al. [16] tested the effect of concrete and cement mortar infill as horizontal stiffeners, and found a synergy triggered by a confinement effect between the bamboo and the infilled material that increases the axial load bearing capacity of the composite element. Moreover, Paraskeva et al. [7] increased the load bearing capacity of bamboo members on a Pratt truss bridge and avoided splitting failure by confining bamboo culms with hose clamps.

The developments in bamboo protection methods and engineered bamboo in recent decades have led to a better acceptance of bamboo as a structural material, especially for bridges. Urazán, et al [17-18] have developed manuals for bridge construction with raw *Guadua* bamboo. Tazarv et al. [19] tested the bearing capacity and cost-effective viability of glulam girder and glulam slab bridge for local roads in the state of South Dakota, USA. Simon Velez's team have designed and set up a *Guadua* bamboo bridge (**Fig. 1**) in Bogota, Colombia.



(a) The whole bridge (b) Entrance

(c) Inside of the bridge (d) Joint (e) Support

Fig. 1. *Guadua* bamboo bridge in Bogota, Colombia.

Besides the afore mentioned environmental benefits, raw bamboo is an inexpensive material that can be locally harvested and easily assembled by people in remote regions of developing countries as a solution to the lack of infrastructure [7,20]. This work strives to demonstrate the feasibility of performing the structural design of a truss type footbridge. A model of the structure is implemented using a commercial finite element software, details for an accurate description of the structure's behavior through the proposed model are offered. The applied loads, and the safety verifications follow Colombian and American regulations. Moreover, a review on connections and immunization process is performed. Finally, design advice and research opportunities for the development of this type of structures are mentioned.

2 Structural system and geometry

The structural system of the 20 m long footbridge is a Howe truss braced at the top and bottom chords. Patented by William Howe in 1840 this type of truss has been widely implemented in railroad bridges due to its constructive ease and resistance over longer spans. A characteristic of the Howe truss is that under gravity loads, the diagonals are compressed while the posts are tensioned [21].

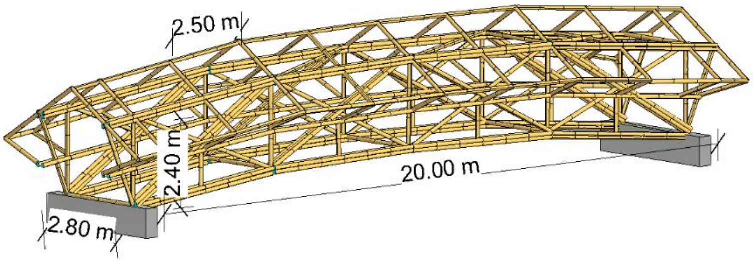


Fig. 2. Isometric view of the footbridge.

The footbridge is located over the Panamericana highway at the Chimayoy Natural Reserve in the region of Nariño, Colombia. The structure is 2.8 m wide and 2.4 m high. Moreover, it offers the advantage of being modular (See **Fig. 2**).

Fig. 3. (a) Section of *Guadua* elements, (b) Details of joints between elements.

Raw Guadua *angustifolia* stems aged 3 to 5 years, with an external diameter of 110 mm and 30 mm wall thickness as shown in **Fig. 3** (a) make up the bridge. The structure rests upon reinforced concrete abutments. Furthermore, the upper and bottom chords are composed by 4 culms.

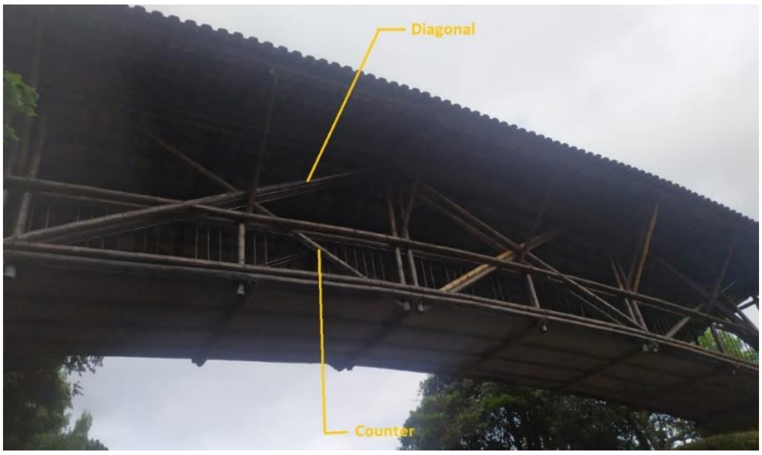


Fig. 4. Howe truss.

The specific weight and the elastic modulus of the *Guadua* elements were supposed to be 7.84 kN/m^3 and 9500 MPa respectively, as suggested by the Colombian national design regulation NSR-10 [22]. As previously mentioned, the diagonals on a Howe truss are compressed under gravity loads, hence counter elements were added to stabilize the diagonals against buckling (see **Fig. 4**). The footbridge has three different kind of sections, composed by 1, 2 and 4 *Guadua* stems (see **Fig. 5-Fig. 7**). **Table 1** summarizes the mechanical properties of the sections.

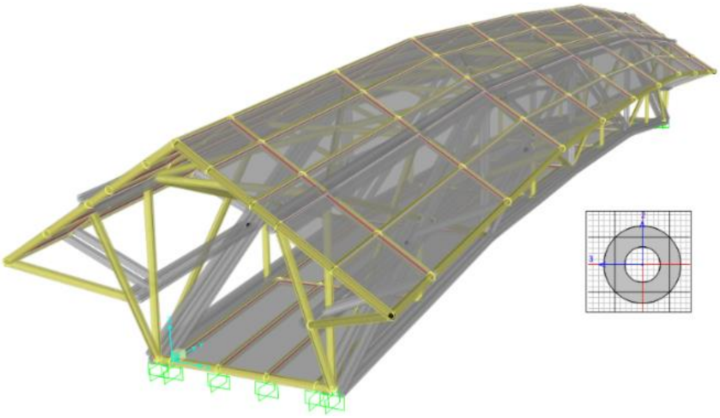


Fig. 5. One culm elements (yellow).

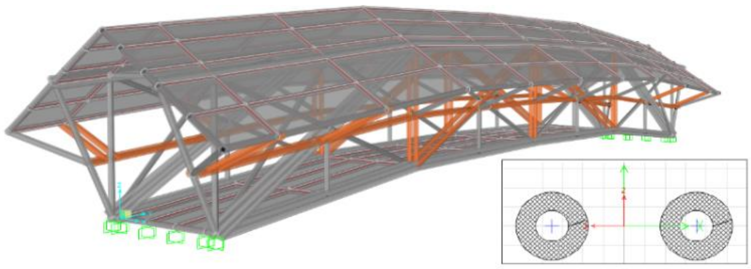


Fig. 6. Two culm elements (orange).

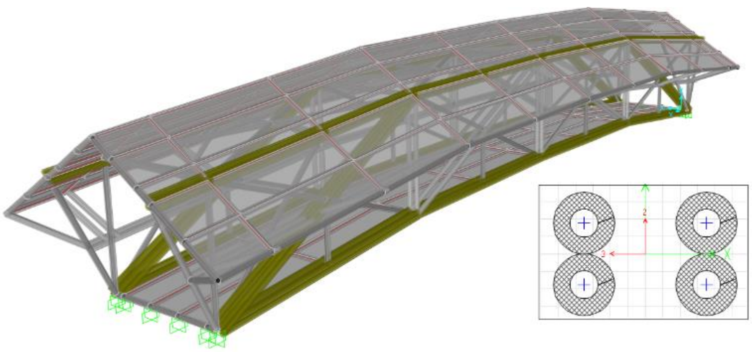


Fig. 7. Four culm elements (olive green).

Fig. 8. (a) Concrete slab, (b) transversal framing.

The deck of the bridge consists of a 50 mm concrete slab as shown in **Fig. 8** (a), placed over *Guadua* mat and held by *Guadua* framing, see **Fig. 8** (b).

As for the roof, the clay tiles that protect the structure against environmental hazards are held by *Guadua* framing that rests upon the trusses and diagonals with single-culm and double-culm sections located at the corners and the middle of each module, the diagonals transmit part of the roof load to the railings of the bridge as shown in **Fig. 9** (a) and 9 (b).

Fig. 9. (a) Perspective view of the bridge, (b) Frontal view of the bridge.

The upper frame displays horizontal single-culm elements at the beginning, the middle and the end of the modules that make up the structure. Furthermore, single-culm stiffeners rest upon the top chords of the trusses as shown in **Fig. 10**.

Table 1. Mechanical properties of element sections.

Number of stems	Cross section area /mm^2	I_{xx} /mm^4	I_{yy} /mm^4	R_{xx} /mm	R_{yy} /mm
1	3961	4742964	4742964	34.6	34.6
2	7923	9485927	105400000	34.6	115.3
4	15846	66906590	210700000	64.9	115.3

2.1 Connections

Joints are key to ensure an appropriate load transfer and resistance of a structure. Due to its round, hollow and tapered cross-section, connecting raw bamboo elements is a difficult task. Furthermore, when designing *Guadua* connections, it has to be acknowledged that its strength along the fibers is higher, thus stress perpendicular to the fibers must be avoided as much as possible [23].

Fig. 10. Detail of the upper frame.

The analyzed structure displays a type of connection known as Bolted-Mortar Infill (BMI), where the bamboo cavity is filled with mortar to provide stiffness and then connected by bolts as shown in **Fig. 11**. It is worth mentioning that BMI connections increase the weight of the structures and eventually materials do not work together due to the different shrinkage-swelling rates of cement mortar and bamboo, originating cracks [24].

Correal et al. [25-26] proposed a yield model to estimate the strength of BMI bamboo connections based on the European Yield Model (EYM). It was found that the compressive strength of cement mortar played a decisive role in the bearing capacity of the joints. On the other hand, the diameter of the dowel does not affect the bearing strength parallel to the fiber. Nevertheless, when the dowel diameter is reduced the strength perpendicular to the fiber increases. Furthermore, the load capacity of BMI connections increases as the angle between the elements approaches 0 °.

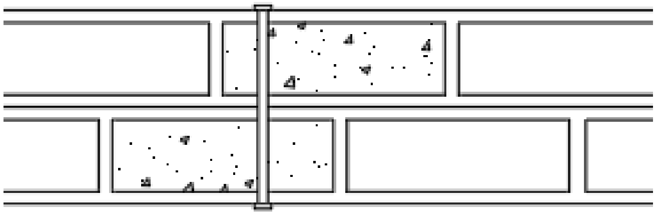


Fig. 11. Parallel Bolted-Mortar Infill connection.

2.2 Immunization process

Different methodologies and chemicals such as borax, boric acid, sodium dichromate and copper sulphate are used to protect bamboo against insect and fungi attacks. Curing and drying processes also affect the absorption percentage of these chemicals. *Guadua* curing may occur (1) by immersing the cut culms into water during a period below four weeks, (2) by heating the culms over fire without burning them and (3) by leaving the cut stem lying vertically on the uncut culms while isolating them from the ground during four to eight weeks. As for the drying process, it is intended to reach an optimum moisture content around 10% to 15%. It can be achieved by pilling the stems horizontally in a covered place over a period of two months or using ovens. Moisture content can be calculated according to equation 1[8]. Researchers have also found that the basal zone of the stem displays a higher moisture content than the rest of the culm thus it is prone to the previously mentioned attacks [27].

$$CH = \frac{m - m_0}{m_0} * 100 \tag{1}$$

Where: *CH*: Moisture content, *m*: Wet sample mass, m_0 : Dry sample mass.

For the analyzed structure, mature *Guadua* stems (around three to five years) were used. Since mature culms have less carbohydrates content, are less prone to insects and fungi attacks. Once collected, the nodes of the culms were drilled longitudinally, washed and cleaned using a water pressure machine and then submerged for a period of five days in a solution containing 5% boric acid and borax for immunization purposes [28].

3 Structural model

A 3D analytical model was carried out using the finite element software SAP2000. The elements that make up the bridge were modeled as “frame elements” with an average elastic modulus ($E_{0.5}$) of 9500 MPa, and display three different cross sections composed by one, two and four *Guadua* stems as shown in **Fig. 4-Fig. 6**. Additionally, all the joints were simulated with releases at both ends as suggested by the Colombian national design regulation NSR-10 [29], meaning that the joints do not transmit moment solicitations and work as a truss, being axially loaded (see **Fig. 12**). Although in article G.12.13 of NSR-10 [29] it is specified that the code does not apply to bridge structures, the code does cover truss structures which is the structural system of the analyzed bridge.

3.1 Self-weight loads (SW)

The self-weight for the different materials composing the structure were considered as suggested by title B of the Colombian national design regulation NSR-10 [22]. *Guadua* elements were modeled with a specific weight of 7.84 kN/m^3. Moreover, a load of 0.8 kN/m^2 was assigned to the roof, due to the clay tiles that protect the bridge against environmental hazards, and a distributed load of 1.2 kN/m^2 was added to the floor, due to the 50 mm thickness concrete slab.

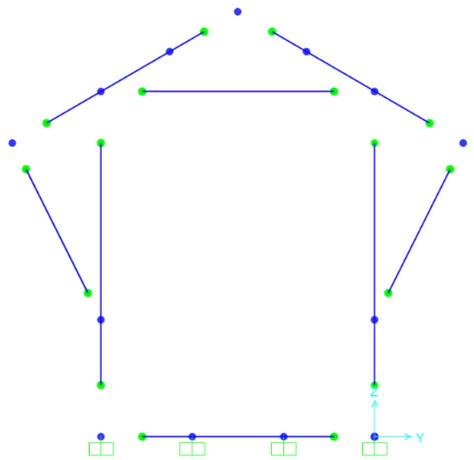


Fig. 12. Releases in frame elements (green dots).

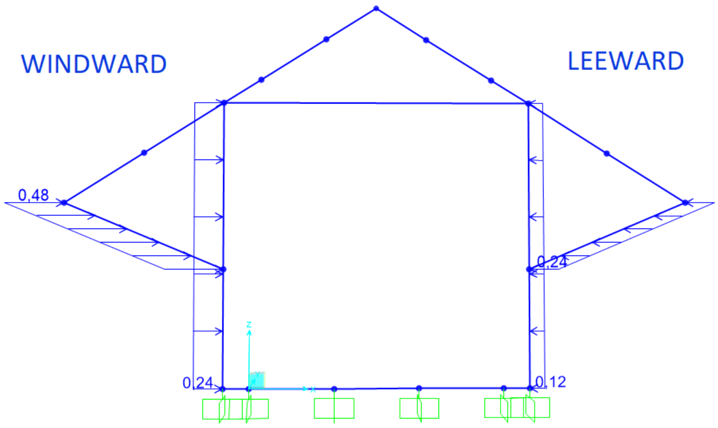


Fig. 13. Wind load applied to frame elements.

3.2 Live load (L, Lr)

According to AASHTO LRFD Guide Specifications for the Design of Pedestrian Bridges [30], a live load (L) of 90 pfs≈4.309 kN/m^2 was applied to the deck of the footbridge. For the roof it was assigned a live load (L_r) of 0.35 kN/m^2 as suggested by the NSR-10 [22].

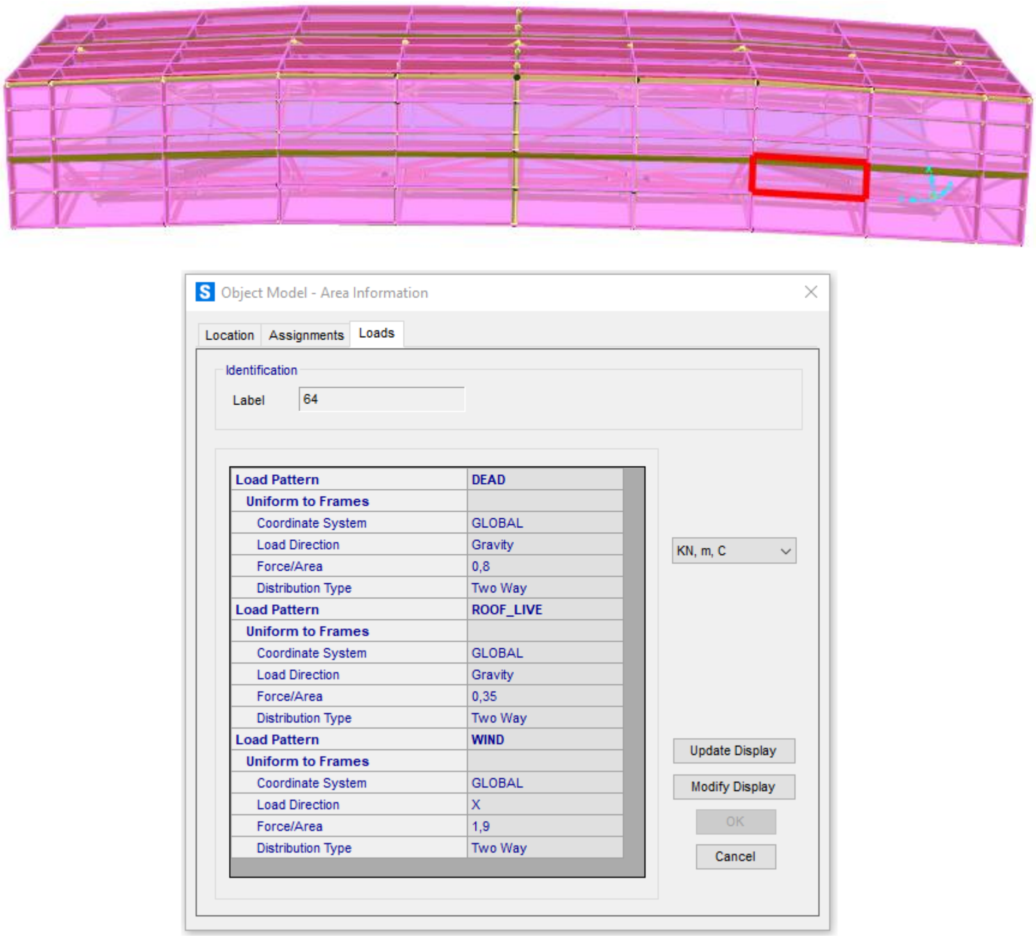


Fig. 14. Wind load applied to roof area elements.

3.3 Wind load (W)

The CCP-14 [31] code establishes a distributed wind load, applied to the exposed areas of the structure as shown in **Table 2**.

Table 2. Wind stress according to CCP-14 [31].

Substructure component	Windward stress (MPa)	Leeward stress (MPa)
Trusses, columns and arches	0.0024	0.0012
Beams	0.0024	NA
Large flat surfaces	0.0019	NA

Fig. 13 and **Fig. 14** show the wind load applied to frame and area elements in the model according to the values in **Table 3**. It is worth mentioning that the load applied to frame elements depend on the direction of the wind (windward or leeward) and the thickness of the elements.

Table 3. Seismic parameters, 5% critic damping. NSR-10 [34].

Index	Parameter	Value
A_a	Peak effective horizontal acceleration	0.25
A_v	Peak effective horizontal velocity	0.25
F_a	Acceleration amplification factor	1.30
F_v	Acceleration amplification factor in the interval of constant velocities	1.80

3.4 Earthquake Induced Load (E)

Seismic induced effects were applied to the analyzed structure through a modal spectral analysis. The seismic response spectrum obtained according to the location of the footbridge is shown in **Fig. 15**. A total of 94 modes were considered in order to reach the 90% of mass participation in the principal directions (x and y) suggested by literature [32-33] .

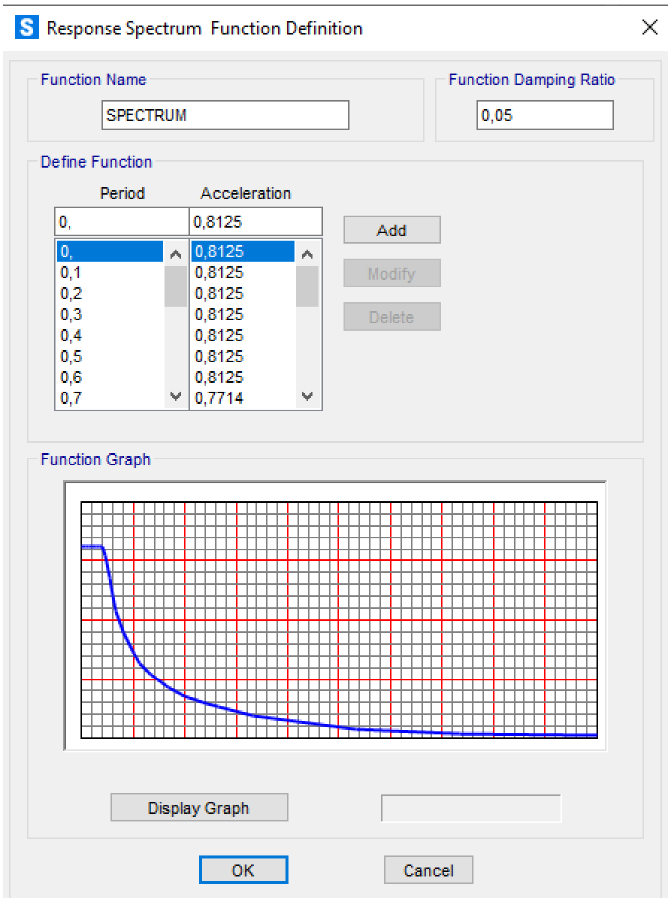


Fig. 15. Seismic response spectrum.

3.5 Load modification coefficients

As previously mentioned, mechanical properties of bamboo are affected by environmental factors; hence, the NSR-10 [29] establishes modification coefficients for the allowable stresses of *Guadua angustifolia Knuth* depending on: load duration (C_d), moisture content (C_m), temperature (C_t) and lateral stability (C_l).

According to the conditions of the region where the bridge is located, the following modification coefficients were chosen.

Table 4. Load modification coefficients and modified allowable stress according to NSR-10 [29].

Index	Use	Unmodified stress (MPa)	Load duration (C_d)	Moisture content (C_m)	Temperature (C_t)	Joint action (C_r)	Lateral stability (C_l)	Modified allowable stress (MPa)
F_t	Tension	18	1.00	0.80	1.00	1.00	-	14.40
F_c	Compression	14	1.00	0.70	1.00	1.00	-	9.80
$E_{0.5}$	Elastic Modulus	9500	1.00	0.90	1.00	1.00	-	8550
$E_{0.05}$	Percentile 5 elastic modulus	7500	-	-	-	-	-	7500

Since the structure behaves like a truss, members are only axially solicitated (tension and compression). **Table 5** explains the design checks carried put according to the Colombian national design regulation NSR-10 [29]. Information about the design check for representative members of the structure is shown in Appendix A and B.

Table 5. Member design checks according to NSR-10 [29].

Solicitations	Check	Parameters
Tension	$f_t = \frac{T}{A_n} \le F'_t$	F_t: Acting tension stress (MPa); T: Acting tension force (N); A_n: Net area of the element (mm^2); F'_t: Modified allowable tension stress (MPa).
Compression	$l_e = l_u k$; $C_k = 2.565\sqrt{\frac{E_{0.05}}{F'_c}}$; $\lambda = \frac{L_e}{r}$; Short elements (λ>30): $f_c = \frac{N}{A_n} \le F'_c$; Intermediate elements (30<λ<C_k): $f_c = \frac{N}{A_n\left(1-\frac{2}{5}\left[\frac{\lambda}{C_k}\right]^3\right)} \le F'_c$; Long elements (C_k <λ<150): $f_c = 3.3\frac{E_{0.05}}{\lambda^2} \le F'_c$	l_e: Effective length (mm); l_u: Length of the element (mm); k: Effective length coefficient; C_k: Slenderness limit value between intermediate and long columns; λ: Slenderness ratio; r: radius of gyration (mm); f_c: Acting compression stress (MPa); N: Compression force (N); A_n: Net area of the element (mm^2).; F'_c: Modified allowable compression stress (MPa).

5 Conclusions

The present paper carries out the structural analysis of an existing bamboo footbridge, in an attempt to demonstrate the feasibility of designing and building this kind of structures. Through a review of literatures, it was found that bamboo structures offer advantages such as being sustainable, inexpensive and easily assembled. Furthermore, this natural material can be used for construction purposes in remote regions of developing countries as a solution to the lack of infrastructure.

Through the analytical results and the literature review, the following conclusions may be established: The implementation of counter elements as support for the diagonals of the trusses is vital for the proper behavior of the analyzed footbridge. Counter elements offer a restriction to the diagonals, reducing its effective length thus, avoiding premature buckling failure. Bamboo elements must be treated (immunized) before being used as structural material. Furthermore, providing protection against environmental hazards contributes to a longer service life of bamboo structures. Preferably, bamboo structures must be designed in a way that critical elements endure tension stress, since the tension allowable stress of bamboo is higher than the compression allowable stress. More investigation related to the live load value for pedestrian bridges submitted to low traffic would allow a more accurate behavior of the structure during its service life. In addition, it would help not to oversize the elements, contributing to a lighter and cheaper structure.

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Conflicts of interests

The authors declare that they have no conflicts of interest to report regarding the present study.

Credit authorship contribution statement

Mario Alejandro Méndez Quintero: Conceptualization Investigation, Formal analysis, Writing – original draft. **Caori Patricia Takeuchi Tam**: Supervision, Revision. **Haitao Li**: Supervision, Revision.

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