CILAMCE 2017
Florianópolis - Santa Catarina - Brazil

DEVELOPMENT OF A DEPLOYABLE BAMBOO BRIDGE FOR NATURAL DISASTER RELIEF

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Abstract. *Natural disasters such as typhoons, storms and earthquakes have severe and unpredictable impacts over cities. In 2011, for example, in Rio de Janeiro, a strong storm caused flood and landslides, damaging more than a hundred bridges having different shapes and sizes, affecting disaster relief materials to be shipped to these areas and victims to be rescued for medical treatment. To enable access to isolated communities, transportable bridges may be used. These bridges are usually dismountable and made of steel, therefore being heavier, having higher fabrication costs and demanding qualified professionals for assembly. These disadvantages limit the reach of their benefits, especially in emergencies situations. The deployable bridge proposed in this work is designed to be lightweight, easy-to-build, -transport and -assembly and also mainly made of bamboo, a cheap sustainable material. The benefits from bamboo's natural composite like structural anatomy are now better known and its complex behavior better understood. In this work, the species Guadua Angustifolia Kunth is used and laboratory tests are conducted to determine mechanical properties for compression and bending considering exposure to environmental changes such as dry/wet cycles. Finally, the paper addresses aspects on the analysis and design of a deployable scissor-like bamboo bridge, discussing the behavior for each different unfolding stage.*

Keywords: *Deployable Bridge, Emergency, Bamboo, Guadua*

1 INTRODUCTION AND MOTIVATION

Rapid assembly bridges have been used for decades with different purposes in a variety of design solutions. Since the first castles' drawbridges, engineers have developed bridges that can fold, curl, lift, retract and float, made of different materials and involving different conception challenges. Their purpose, in general, is to suppress a need or demand, circumstantial or not, to allow passage over a certain span in a short period of time. The kind of need or demand determines the type of bridge better suited for the task.

Most of the modern portable bridges are somewhat based on the concept of the *Bayley Bridge*, developed by the British Army during World War II. Military engineering all over the world has evolved to allow troops to access even the most remote locations, whereas the use of rapid assembly bridges in a civil context is still not very common. However, in situations like earthquakes and other natural disasters, the quick implementation of a bridge can be the difference between life and death. In Brazil, a heavy rain in 2011 made over a hundred bridges collapse at the mountain regions of Rio de Janeiro state, according to the Brazilian government (source, in Portuguese: http://www.brasil.gov.br/infraestrutura/2011/01/reconstrucao-de-pontes-atingidas-na-regiao-serrana-do-rio-deve-comecar-no-fim-de-semana). In 2015, in the same region, over twenty bridges were severely damaged. This can deeply affect the rescue operations and the arrival of materials for those in need.

Dismountable and deployable bridges have been recently proposed by many authors (Teixeira et al, 2014, Yeh et al., 2015, Benjeddou et al., 2017). In Japan, the project of the *Mobile Bridge*, developed by Chikahirio et al. (2016), suggest that bridges for those situations should be as light, strong, quick to be ready for use and easy to install as possible. This bridge is a deployable scissor-like structure made of steel (Fig.1), allowing ease of transportation and only a few people for installation. The deployable bridge proposed in the present work was inspired in the *Mobile Bridge* scissor-like concept, but, to make the bridge lighter, cheaper, more sustainable, bamboo was chosen as the main material. High-strength steel strands were adopted, as well, to enhance bridge stiffness.

Bamboo is a giant woody grass with a tubular macrostructure composed of internodal and nodal areas. Its schlerenquima cells have fibers that are responsible for bamboo stiffness and strength, while parenquima cells provide certain ductility (Liese, 1998). Due to this anatomy, in which two different constituents are combined, bamboo is known as a natural composite material.

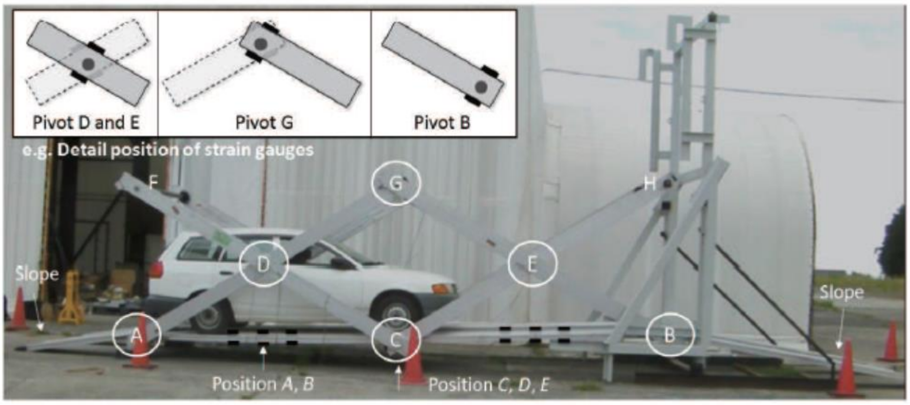
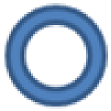
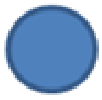
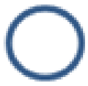


Figure 1. Prototype of the *MobileBridge*. In detail, pivots that allow rotation (Chikahirio et al., 2016).

As wood, there are hundreds of Bamboo species, each one with its unique characteristics in relation with their anatomy and mechanical properties. The species choice was made to minimize the effects of weather condition. In this work, Guadua Angustifolia Kunth is adopted, as this specie is usual to be found in Latin America, therefore reasonable to assume that they adapt better to this climate than most foreign species. In Table 1, adapted from Oberman et al. (2004), a comparison of Guadua properties to those for timber and steel, defined in Eurocodes 5 and 3, respectively, is presented.

Table 1. Comparison between different materials with the same bar weight, adapted from Oberman et al. (2004).

Compression considering a bar of 2.5 m and 8.7 kg of different materials	Guadua	Wood - B type EC5 - S10/MS10	Steel - A36 EC3 - S235
Density ; g/cm^3	0.7	0.55	7.8
E modulus ; MPa	6000	7400	210000
Section	 D = 12/9 cm	 D = 9 cm	 D = 5.1/4.5 cm
Area ; cm^2	49.5	63.6	4.4
Weight ; kg	8.7	8.7	8.7
Max Load ; kN	25.6	15.1	27.6
Cost €/m Colombia/Germany	1 / 3	2 / 5	4 / 8
Environmental Cost (MJ/m^3)/Mpa	30	80	1500

One of the crucial issues with Bamboo in construction is its durability, especially for outdoor use. Fixed treatment may guarantee a longer life use, but with higher environmental costs. Moisture content is also greatly affected by the environment (Xu et al., 2014) and can largely reduce the overall strength of bamboo (Janssen, 1981). The experimental program in this paper tries to bring some additional information about these issues, such as testing bamboo specimens after exposure to wet-and-dry cycles. Full culm samples containing nodes were tested in compression and rods extracted from internodal regions were tested for bending and creep. Finally, an overview on bridge structural system and installation process is described and the results obtained for numerical analyzes using software SAP2000 (v.14) for each stage of the bridge development are presented.

2 EXPERIMENTAL PROGRAM

The experimental program focused on the mechanical properties of bamboo when exposed to weather changes. All samples were extracted from the same culm taken from a local farm located at ocean level in Vargem Grande, Rio de Janeiro (22°59'24.4"S; 43°29'38.5"W). Extraction and sample preparation followed general recommendations found in literature

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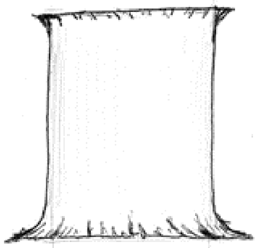
(López, 1981). Specimens were air-dried for 6 weeks and treated with a Borax/Acid Boric solution (1:1) before testing (Kumar et al., 1994).

A total of 36 samples were tested in compression and bending, 18 for each test. To simulate repeated rain events, half of the samples was immersed in water for 24 hours and then oven dried at a temperature of 35°C (+ -°2C) for another 24 hours. This cycle was repeated for 4 times. The other samples were storaged indoors. Tests were carried out after a few weeks so the durability samples could have their moisture content stabilized. To normalize results regarding their moisture content, they were all multiplied by a correction factor. Samples subject to wet-and-dry cycles are denominated 'durability samples' hereafter.

2.1 Compression Tests

Compression tests followed the recommendations of ISO-N314-22157, Jaramillo et al. (2016) and Harries et al. (2012), with a few modifications. The samples for the compression tests all had nodes in their center, to better simulate the real conditions of the bamboo used on the deployable bridge. Previous works have reported that bamboo usually fails due to the crushing of fibers at the top and bottom of the sample (Fig. 2a). To minimize this effect, carbon fiber stripes were attached to the extremities of the sample. On the inside, a one-inch disc of a hard-plastic resin and sand mixture was used, as illustrated in Fig. 2b. Tests were conducted in a universal testing machine until failure, under displacement control rate of 0.6 mm/m.



(a)

(b)

Figure 2. a) Failure by crushing of the end fibers (Quintero et al., 2016); b) Top carbon fiber stripes. After this stage, they were glued with an epoxy sticker.

Table 2 summarizes the results from the compression tests for control and durability samples of the base (B), middle (M) and top (T) of the bamboo culm. The variation coefficient between samples of each case and region is also presented. It is possible to notice that there was little difference between the results of the control and durability groups. Compressive strengths exhibited low coefficient of variation in each region. Considering the modulus of elasticity, the control group showed a slightly bigger stiffness and a little larger variability. The use of full culm bamboo implies in an inherent variability, since each sample has its own geometry and can have pre-existing flaws that alter the end result. To confirm a pattern, more tests are needed. The use of carbon fiber to confine the fibers was very effective to prevent local crushing of top and bottom fibers. From the eighteen samples tested, only one exhibited broom-like failure (end-crushing). All the others failed at the node or through longitudinal cracks. This explains why the average stiffness is reasonably greater than those reported for Guadua compression tests with nodes (Ghavami, 2008).

Table 2. Control and Durability results for full culm samples with nodes compression test

Control	Average B	Average M	Average T
E ; MPa	7062	11667	10071
V.C. %	20.70	23.52	34.05
Max Stress; MPa	89.1	121.7	113.5
V.C. %	1.48	12.17	8.74
Durability	**Average B**	**Average M**	**Average T**
E ; MPa	7041	10853	8192
V.C %	33.90	18.75	13.10
Max Stress; MPa	89.2	115.4	103.5
V.C %	7.06	3.55	1.60

2.2 Bending Tests

For full culm bending tests, the criteria for the sample's length should be at least 30 times the size of the outer diameter (ICBO, 2000). To test the influence of repeated rain events on the material bending characteristics, the use of full culms samples would require very long specimens and material. Therefore, for simplicity, rods extracted from the internodal regions extracted from base, middle and top of the bamboo were used. For all samples, as suggested by Gottron et al. (2015), specimen was positioned so that the outer face of bamboo was in tension (Fig. 3). A four-point test was conducted on each sample, at a displacement control rate of 10mm/m. The free span was 180 mm and strain gages were attached to the top and to the bottom of each sample. The Young modulus was calculated from regression, considering the linear portion of the Moment-Curvature curve.

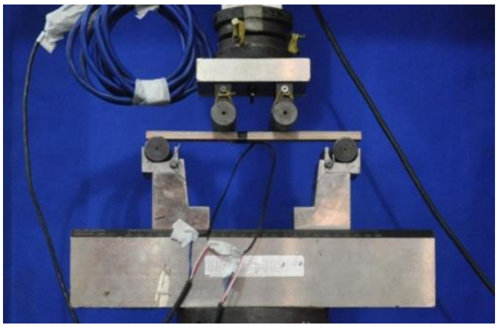


Figure 3. Set up of a four point bending test.

Table 3 summarizes the results from the bending tests of the control and the durability samples of the base (B), middle (M) and top (T) of the bamboo culm. The coefficient of variations are also presented. Because the rods are extracted with almost the same size and shape, and the whole test process does not have so many variables, the comparison between the two groups is clearer. Although, in average, the durability specimens exhibited greater stiffness, the variability increased substantially – approximately 12, 13 and 2.6 times for the base, middle and top regions, respectively. This suggests that repeated rain events may not affect the stiffness of the material, but decrease their trustworthiness. Young modulus resulting from the bending tests are compatible with those found in Obataya et al. (2007) and Gottron et al. (2015). Slight differences can be explained because the present study used specimens extracted from a different bamboo species.

Table 3. Elasticity modulus of control and durability samples.

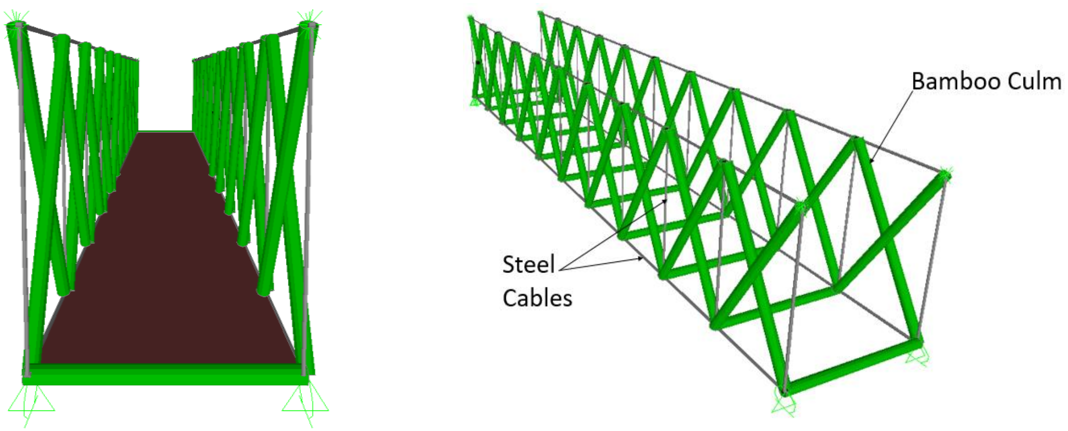
Control	Average B	Average M	Average T
E – MPa	16,927	19,835	18,105
V.C %	2.2	2.96	15.7

Durability	Average B	Average M	Average T
E – MPa	23,404	23,029	21,860
V.C %	26.4	38.5	41.3

3 DEPLOYABLE BRIDGE - CONCEPT DESIGN

The deployable bamboo bridge can be described as a scissor-like self-stressed truss, as presented in Fig. 4. Each component is dismountable and there are no fixed connections, increasing durability and making maintenance and replacement of damaged pieces easier. The proposed bridge allows for ‘adjustable’ spans, but, in this work, a 10 m span and 1.5 m wide bridge is studied. For sizing of members, dead load plus a live load corresponding to the weight of 30 people simultaneously over the bridge is considered. The system was idealized so that bamboo members work mainly in compression whereas steel cables are permanently tensioned.

Connections are one of the main challenges for the bridge. Pinned and lashed connections can be used in a way to allow free rotation when applicable. Bamboo’s one direction fiber orientation makes the tensile strength perpendicular to fibers weak, especially for pinned rigid connections (Janssen, 2000). Lashing the central pivots with a clove hitch can minimize this effect. Connecting elements are still under development, such as localized reinforcement to prevent shear failure induced by pins. Details of connections, therefore, will not be presented in this work.



(a) **(b)**

Figure 4. Bamboo Deployable Bridge Design: a) front view; b) overview.

In the bridge, two different cable systems are adopted: i) border cables, that will function as the truss chords in the final stage; and ii) vertical cables, that will work as ties for the truss. As bridge unfolds, the border and vertical cables are loose and disconnected from the scissor-like units along their lengths. At the end of the unfolding process, the border cables are stressed up to a predefined tensile stress. This is necessary to stabilize the truss against lateral instability as well as to avoid compression during loading. In this work, a 250 kN stress is considered. Finally, the cables are locked at their connections to the scissor-like units.

3.1 The Bamboo Deployable Bridge In 7 Steps

1- The folded structure is transported to the place of installation.

2- The initial and end positions of each girder are defined (foundations).

3- One end of the girder is attached to a mechanical device, responsible for the unfolding process.

4- The device moves the top and bottom ends of the last scissor-like unit inwards, making the bridge deploys until it reaches the required span. At this stage, all cables are loose and can run freely through the joints.

5- When the girder reaches its desired length, struts are positioned at mid-length to lock the scissor-like units against closing. The bridge is, then, disconnected from mechanical device and positioned over the foundations.

6- In this stage, cable length is adjusted and border cables are stressed to the desired tensile stress. The only points of connection of bamboo and cables are at the corners of the truss, where cables are deviated from straightness. As this operation is carried out bamboo struts are subject to compression and flexure. As mentioned previously, cables are loose and disconnected from scissor-like units during this stage.

7- After prestressing the border cables, all cables are locked at their connections to the scissor-like units, thus not allowing any relative movement beyond this stage. The bridge structural system looks like a truss and it is ready for use.

4 NUMERICAL MODEL USING SAP2000

To analyze different loading conditions and the structural behavior of the bridge on four distinct stages, computer models were developed using the software SAP2000. To simulate a connection that is free to rotate, pinned connections and moment releases were defined at all the bamboo joints when necessary. For all cases, the elasticity modulus E considered for the Guada was the average found for durability samples, 8.7 GPa. Poisson Ratio considered is 0.30 (Saraz et al., 2007). Density considered for the bamboo material is 0.7 g/cm³, based on the average values extracted from the samples just after the immersion cycle.

4.1 Unfolding Stage

The first model under study considers only the bamboo elements working at the end of the unfolding process, when the cables are loose and the only load is the self-weight (Fig. 5.) The most critical scenario is when the bridge reaches its limit design span (e.g. 10 m), being supported only at one of the ends. Maximum displacement at the right end node for this case is of 54 mm. Bamboo's low density makes the bridge light enough so the displacements remain modest. Axial forces and bending moments acting on the bars are also very low as shown in Figs. 5b and 5c.

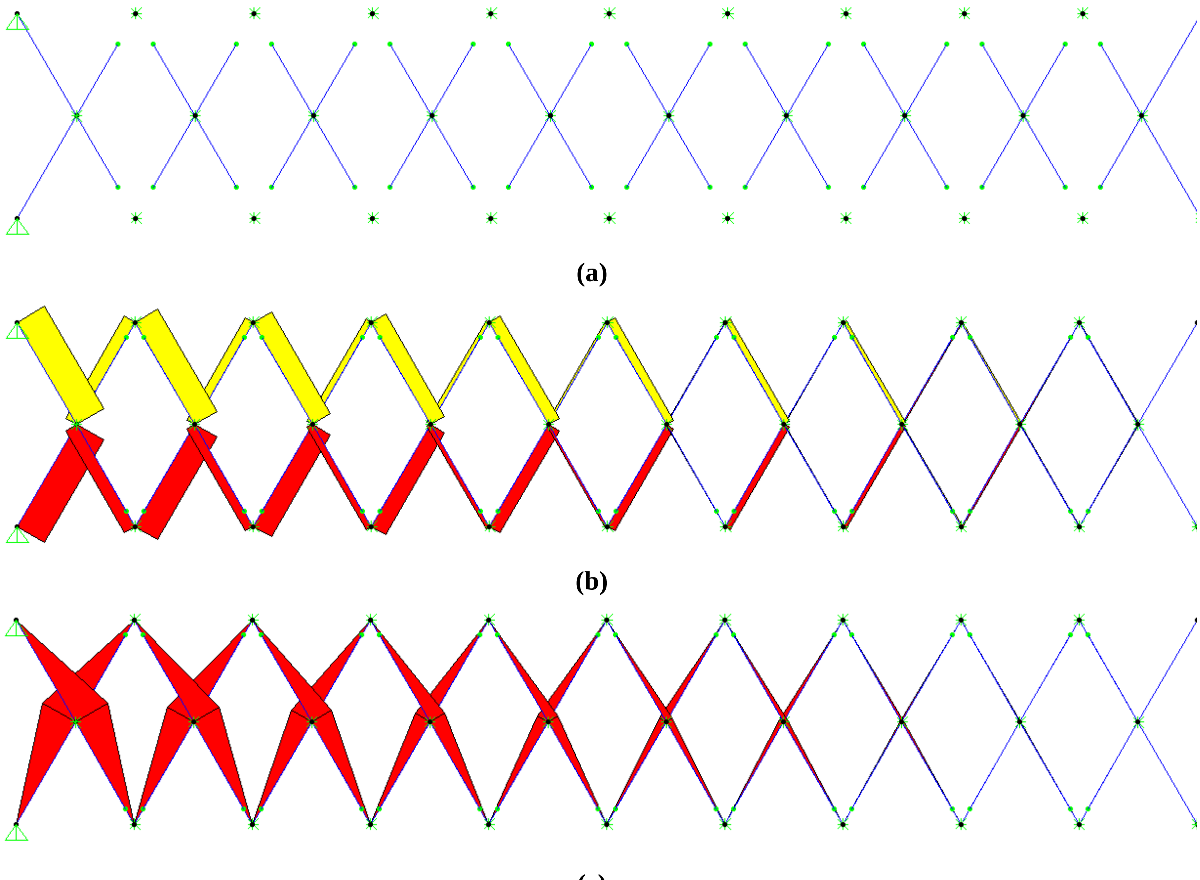


Figure 5. a) Bridge opening system at 10-meter span point; b) Axial Force Diagram: maximum = 0.13 kN; c) Moment Diagram: maximum = -0.16 kN.m.

4.2 Simply Supported Stage

The structure can be positioned over the foundations as a simply supported beam when it is unfolded. Self-weight is still the only load acting over the structure and the cables systems are still not active. To avoid a mechanism, a steel strut is added connecting two adjacent joints of scissor-like units (Fig. 6a.). In this work, a round steel bar having 30 mm diameter was considered. In general, displacements were almost null. For the central lower node, the displacement in the Z direction was 0.014 m. The axial force is less than 1.3N at the inserted steel tie, meaning that a simple lashed reinforcement can hold the structure together. Fortunately, there are several techniques to lash bamboo available to be used in this situation. Axial force and bending moment diagrams are presented in Figures 6b and 6c.

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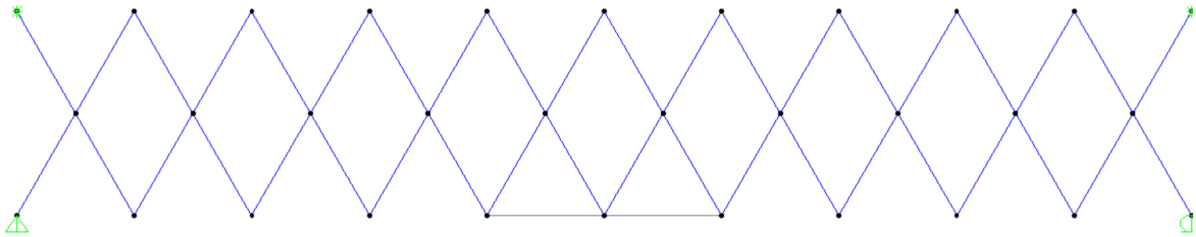
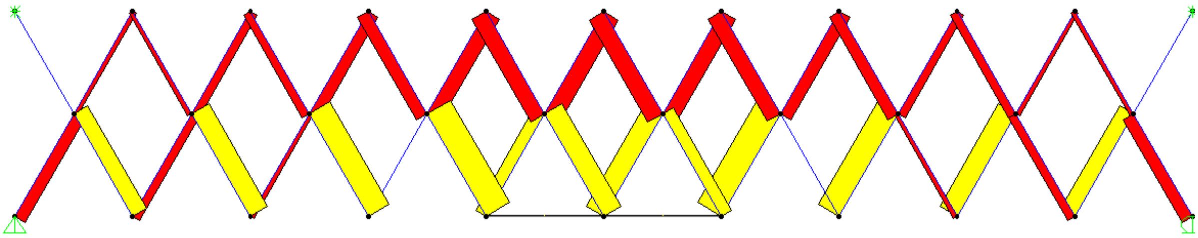
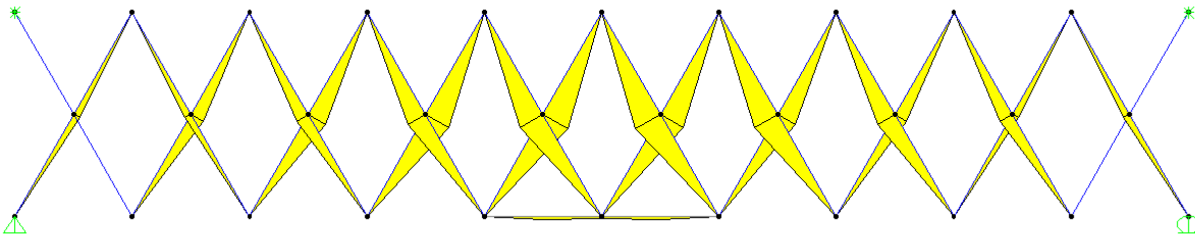


(a)



(b)



(c)

Figure 6. a) Unfolded bridge on the ground with added steel bar the center; b) Axial Force Diagram: maximum = 0.11 Kn; c) Moment Diagram: maximum = 0.12 kN.m.

4.3 Cable stressing stage

At this stage, the required tension is applied to the border cables. It was done by assigning a temperature load at the steel strut that would result in an axial force of +250 kN in the border cables. Now the cables are still allowed to pass through the joints, for the exception of the corners. To allow for this, small rigid members with released shear force in the Y direction were placed between the bamboo joints and the steel bars at each node. Connected to that, the bamboo elements had their respective moment released. Rotation between bamboo elements at the pivot were also released making a pin connection that constrains translational degrees of freedom (DOFs) only. Border cable properties were altered to have their flexure stiffness negligible. To reach 250 kN, a load temperature of -2355°C was assigned to the center inferior horizontal bar only (Fig. 7.) The program ran a nonlinear analysis with a P-Delta for large displacements.

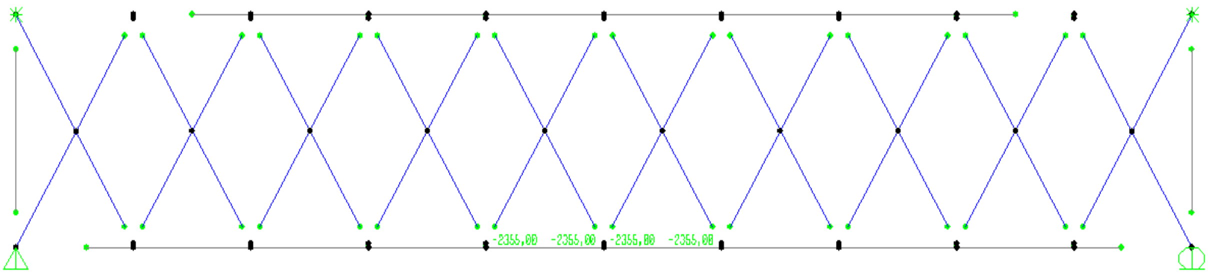
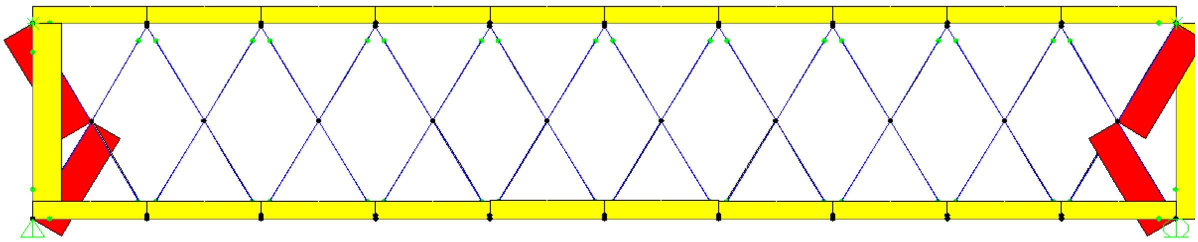
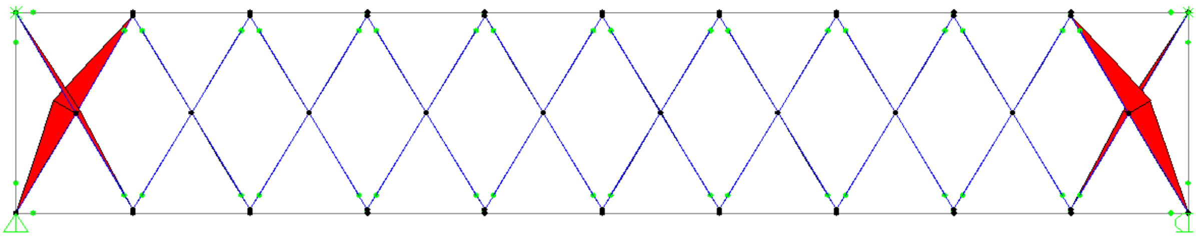


Figure 7. Two-dimensional model with steel bars connected to the main structure by pins with released shear force.



(a)



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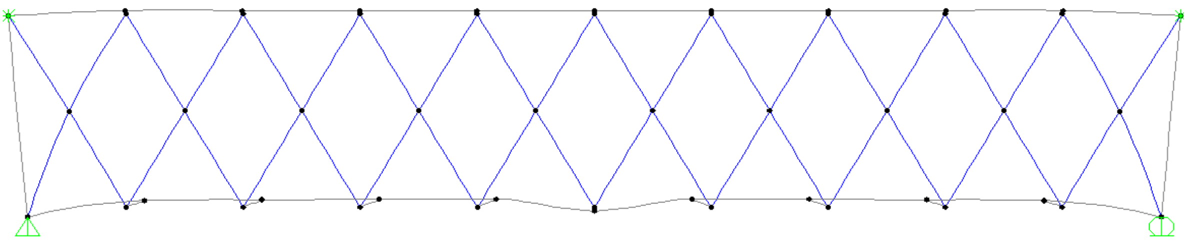


(c)

Figure 8. a) Axial Force Diagram. Highest Tension (Cable): 250kN. Highest Compression (Bamboo): 291Kn; b) Moment Diagram. Highest on Bamboo: -2.2kN.m; c) Deformed shape. Scale factor of 6.

It is possible to notice that the temperature load produced the expected effect on the girder. All bars representing the cables are in tension and the border cable has reached the 250kN force needed to make this a self-stressed rigid structure when loaded (Fig. 8). The bamboo members close to the corners are subject to slight bending moments. Displacements over the structure were modest: at the center, the vertical "cable sag" was 8.7 mm.

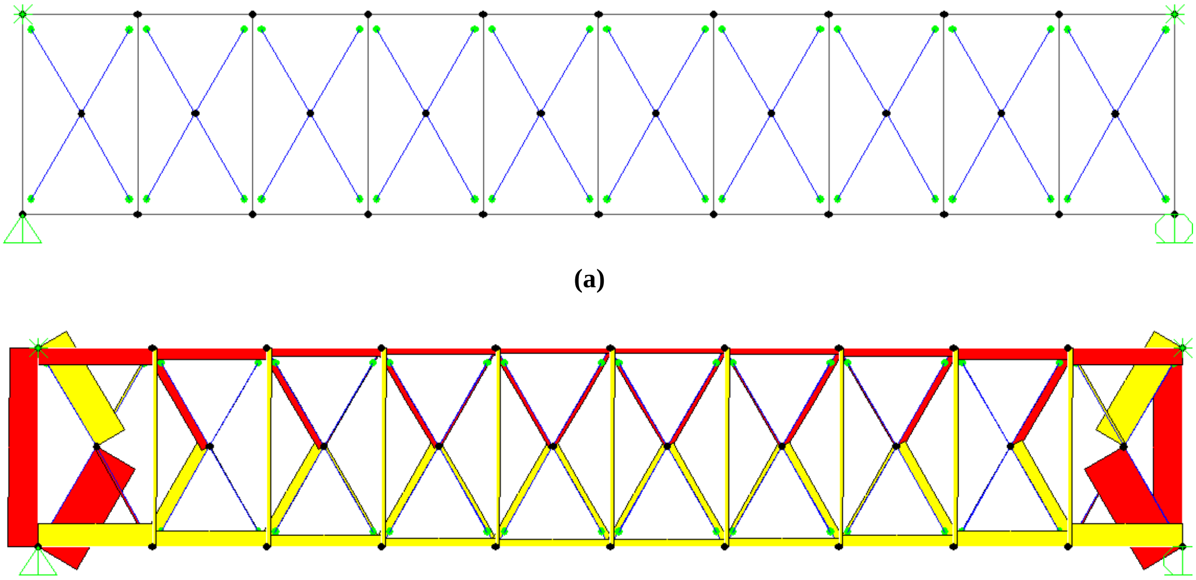
To resist the implemented tension over the cables, the inner elements are under compression. The axial compression of the first and last bamboo elements are over 290 kN. Experimental results found that samples from the base of the Guadua resisted to an average value of around 200 kN. This suggests that these elements will have to be subjected to reinforcement.

4.4 Final Girder Stage

The forth model presented is the final stage of the girder with all the steel cables already working as rigid members. At this stage, they can be represented as bars with the same sectional area. So far, for this study, the history of the development was not taken in to account for this model.

4.4.1 Loading Conditions and Diagrams

The model considers as permanent load the structure's self-weight. For accidental loads, it considers a limit of 30 people (75 kg each) simultaneously on the bridge, applied to where the transverse girders are supported. Primarily, this study contemplates static linear loads only. The results for the case of the combined loads were as expected, showing that the connections and the geometric form of the girders are viable (Fig. 9). The compression forces of the superior bar representing the cable are little enough so the pre-stressing of the cables can overcome it and the forces at the Bamboo components are well behind its strength capacity. The structure's geometry resulted in negligible values on the Moment diagram and displacements at all points were less than 1mm.



(a)

(b)

Figure 9. a) Image of the girder final design; b) Axial Force Diagram. Highest values: -3.9 kN for bamboo elements and –2.5 kN for the steel bars.

5 CONCLUSIONS

The need for a light, strong and quick to assemble bridge for emergency situations such as natural disasters is genuine. Modern projects and solutions are excellent but can be too expensive for a big scale necessity in underdeveloped areas. Using Bamboo for transportable

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structures can be an alternative cheaper than other light materials such as steel and modern composite materials.

The bamboo deployable bridge is a scissor-like structure with a self-stressed cable system that can be assembled and transported quickly. Connections are one of the main challenges and are still being developed. Primary results regarding bamboo mechanical behavior under a cycle of water immersion showed good response in general but greater variability for bending tests with rods.

Finally, independent models from four distinct stages of the development of the bridge were created using the software SAP2000. Two models from the unfolding process resulted in low displacements and a need for strut connecting two adjacent points. The third model applies successfully a nonlinear analysis with a temperature load to simulate a self-stressed state. The results suggest a need for reinforcement at some bamboo elements. The final model considering only self-weight and accidental loads had satisfactory results regarding its diagrams and displacements.

ACKNOWLEDGEMENTS

The first author acknowledges CAPES for financial support through scholarship. The authors would like also to express their gratitude to Dr. Lucas Ripper for the valuable help throughout this research.

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