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Numerical analysis of truss elements on a sustainable bamboo bridge

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Abstract. This paper is concerned with a numerical comparison of truss elements between a steel bridge and a bamboo bridge, both designed for pedestrian traffic. For this purpose, an existing steel bridge in Brasilia was considered and later numerically modeled using the Finite Element Method (FEM). In order to show the efficiency and feasibility of the bamboo as a structural material, another FEM model was considered changing steel elements with sustainable bamboo elements. It was demonstrated that both bridges have satisfactory stiffness and load carrying capacity under the Brazilian standards. Based on the results and the analysis, the sustainable bamboo bridge proved to be lighter and cheaper than the real steel bridge with equal load carrying capacity.

Keywords: Bamboo Bridge, Steel Bridge, Finite Element Method, Numerical Analysis.

1 Introduction

The economical development of the modern world requires from the construction sector a high demand of conventional construction materials, such as steel and concrete. Mainly, the steel production process consume a large amount of energy, generating considerable wastes of water, gas, and residues, which gradually affect the environment around the world. Xiao et al. [1] argued that the sustainable development has become a major concern of the international community and the use of renewable materials such as conventional timber and bamboo, which are environmentally friendly, is an inevitable choice.

Bamboo is a rapidly renewable sustainable resource and has mechanical properties similar to timber. Worldwide, De Flander [2] showed there is a growing interest in the development of bamboo products as a sustainable, cost effective and ecologically responsible alternative construction material. While the potential of bamboo is promising, Xiao et al. [1] and Harries et al. [3] showed that the bamboo is not fully used in modern structures, largely due to the lack of validation based on the theory of mechanics, material science, structural design, and testing.

The bamboo is a fast-growing type of grass. R. Mali and Datta [4] confirmed that it has high strength to weight ratio, about six times higher compared to steel; it reaches its optimum strength in 3–4 years and attains complete maturity in 5 years. It can support both tension and compression parallel to fibers, whereas many other materials cannot withstand compression loading. However, as presented by Imadi et al. [5], being an organic material, durability of the material is a drawback for bamboo.

In Brazil, in contrast with many industrialized countries, such as USA and Europe, timber has not been widely used in bridges and commercial buildings. Although, in the recent year, more complex timber structures are been studied and designed, as demonstrated by Rosalino [6], using Brazilian and international standards. Developing and using modern bamboo materials may provide an alternative in bridge and building construction in Brazil, which is already producing structural bamboo in small quantities.

This paper presents a numerical comparison of truss elements between an existing steel bridge and a theoretical bamboo bridge, in order to verify the feasibility of the bamboo as a sustainable structural material and potential for more complex structures and broader analysis.

2 Steel Bridge

For this study, a pedestrian steel bridge located in the administrative region of Ceilândia, Brasilia – Brazil, was selected and presented in Fig. 1. The steel bridge sections and spans were obtained after site measurements and the DNIT [7] (National Department of Transportation Infrastructure) design report. The steel used is the ASTM

Figure 1. Front view of the steel bridge located in Brasilia, Brazil.

A572 Gr50 and the W250x32.7 section is considered, as presented in Table 1, where f_y is the yield Strength, E is the Young modulus, A is the area, W is the section modulus and I is the the moment of inertia. In addition, the slab section L9.5 is made of the same steel with 9.5 cm thickness.

Table 1. Mechanical and geometrical properties of the steel bridge.

Section	f_y (MPa)	E (GPa)	A (cm^2)	W_x (cm^3)	W_y (cm^3)	I_x (cm^4)	I_y (cm^4)
W250x32.7	250	200	42.1	382.7	64.8	4937	473
L9.5	350	200	950 /m	1504.17 /m	-	7144.79 /m	-

The Finite Element Method (FEM) and SAP2000 software was used to build the numerical model of the steel bridge, considering 537 nodes, 252 shells and 738 frames. The steel sections are represented by three-dimensional frame elements and the slab is represented by shell elements with thin wall. The connection of the slab with the space truss is made exclusively by the transverse sections, therefore the braces do not receive load from the slab. Rotation at the ends of the bars has not been released to more accurately represent the condition of the nodes. Only truss elements will be designed and checked for load carrying capacity on this study, excluding beam, columns, slab, foundation and connections. Figure 2 show the numerical model used on this analysis.

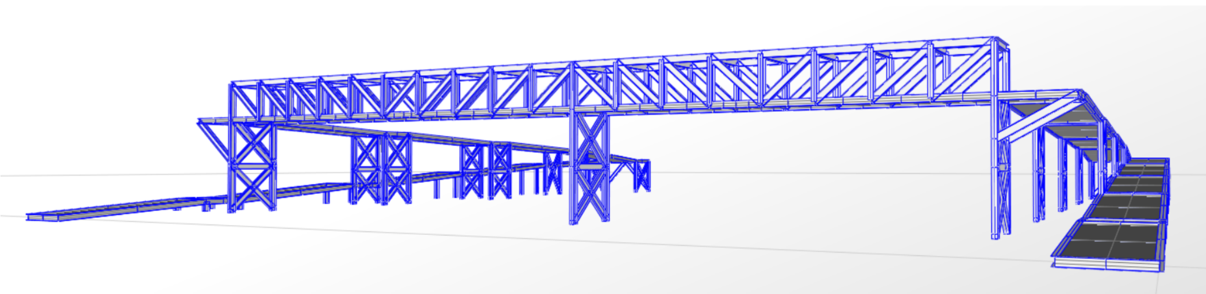

Figure 2. FEM steel bridge numerical model.

3 Bamboo Bridge

The bamboo bridge is made of *Dendrocalamus Giganteus* elements with its natural geometry, presented in Fig. 3, where 30 cm diameter (D) and 2.5 cm and 3.5 cm thickness (t_f) are considered [8, 9]. The theoretical bamboo used in this work follows the treatment process presented by Rosalino [6] and Sharma et al. [10]. The bamboo slab is made of *Phyllostachys pubescens* scrimber sheets and follow the works Yu et al. [11] and Sharma et al. [10]. Since the Brazilian standards do not contemplate the use of bamboo for structural purposes, the Brazilian

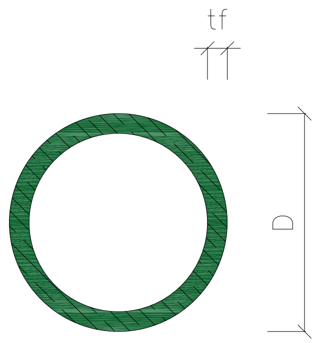

Figure 3. Cross section of bamboo elements. t_f is thickness and D is diameter.

structural timber design standard [12] will be used instead [13, 14]. Therefore, the wood coefficient used is $K_{mod} = 0.6$, considering permanent structure, first class wood and Brasilia humidity level. Also, $\gamma_w = 1.4$ for compression, $\gamma_w = 1.8$ for tension and $f_k = 0.7$ are considered. The material mechanical and geometrical properties are presented in Table 2, where f_t is the Tensile Strength, f_c is the Compression Strength (MPa), E is the Young modulus, A is the cross section area, W is the section modulus and I is the moment of inertia. In addition, the slab section L7.5 is made of bamboo scrimber sheets with 7.5 cm thickness.

Table 2. Project mechanical and geometrical properties of the bamboo bridge.

Section	f_t (MPa)	f_c (MPa)	E (GPa)	A (cm^2)	W_x (cm^3)	W_y (cm^3)	I_x (cm^4)	I_y (cm^4)
G30	28	16.5	8.4	215.98	1372.4	1372.4	20586.02	20586.02
L7.5	32.2	18.6	9	75 /m	937.5 /m	-	3515.63 /m	-

Once more, the FEM and SAP2000 software was used to build the numerical model of the bamboo bridge, considering the same elements and procedures presented in section 2. Only truss elements will be designed and checked for load capacity on this study, excluding beam, columns, slab, foundation and connections. Figure 4 show the numerical model used on this analysis.

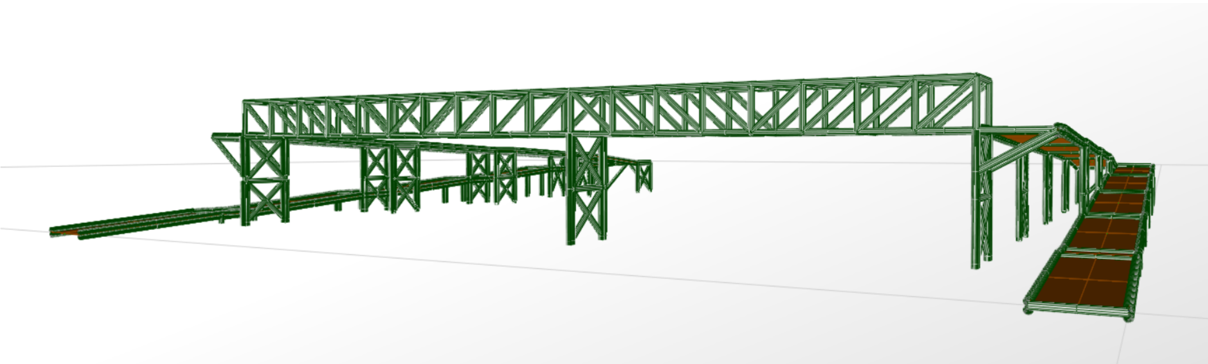

Figure 4. FEM bamboo bridge numerical model.

4 Applied loads and load combination

On both models, considering the steel bridge and the bamboo bridge, three different loads were applied: dead load, live load and wind load. Exceptional loads and temperature were not analyzed on this study [15].

4.1 Self-weight

The self-weight of the structural elements is automatically calculated by SAP2000 software from the specific weight of the materials, in this case, bamboo with $7.845\, kN/m^3$, for *Dendrocalamus Giganteus*, and $6.863\, kN/m^3$, for *Phyllostachys pubescens* scrimber; and steel with $76.973\, kN/m^3$ [15].

4.2 Live Load

According to section 6.1 of ABNT NBR 7188, the live load acting on the slab is $5\, kN/m^2$. The loading is applied directly to the shell elements. Since the structure is simply supported, no load shifting is required to determine the critical position [15].

4.3 Wind Load

The entire structure is subjected to wind load from major directions (North, South, East and West) and applied as a concentrated load on model nodes. For each node, the influence area is considered and used for load concentration. Wind load from different directions will act simultaneously or independently depending on the load combination presented in subsection 4.4 [15].

4.4 Load Combination

Load combinations following the NBR7188 [15] and DNIT [7] design report are considered on this study, with a total of 18 combinations. Only the ones involving exceptional and temperature load are not considered. The structure is designed for ultimate limit state (16 combinations) and service limit state (2 combinations). The envelope, containing major values from all combinations, will be used this point forward.

5 Numerical results

On this section, the results obtained with the Finite Element Analysis (FEA) are presented in Fig. 5 and 6, for truss elements. The envelope of all ultimate limit state load combinations are considered on both models. Only the most solicited elements are presented and considered for the load capacity verification and design obtained in section 6.

From this analysis, it can be seen that the results obtained with steel bridge elements are about 44.25% greater than the ones obtained with the bamboo bridge. This difference, due to the self-weight of the elements, is one of the key advantages of the structural bamboo over traditional materials such as steel.

6 Comparative Analysis

On this section, the numerical results obtained with the FEA are considered to check the load carrying capacity of the bamboo elements.

The compression elements on this study are considered short, both for bamboo and steel sections. All calculations are in agreement with the Brazilian design standard ([16] and [12]).

For tension elements, the tensile strength can be obtained with

$$\sigma_t = \frac{N_t}{A} \ , \tag{1}$$

where N_t is the highest tensile axial force obtained in the element and A is the gross cross section area. For compression elements, the slenderness ratio can be obtained with

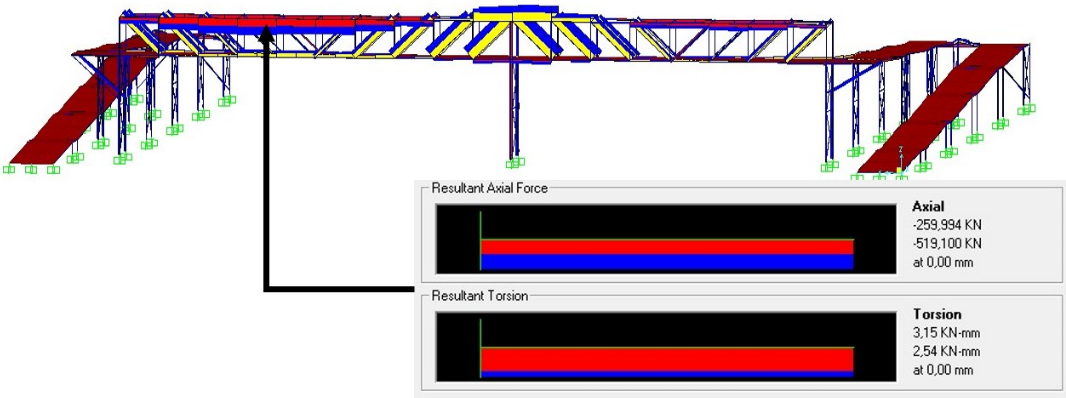

Figure 5. Axial forces FEA - Truss elements - Steel Bridge - SAP2000

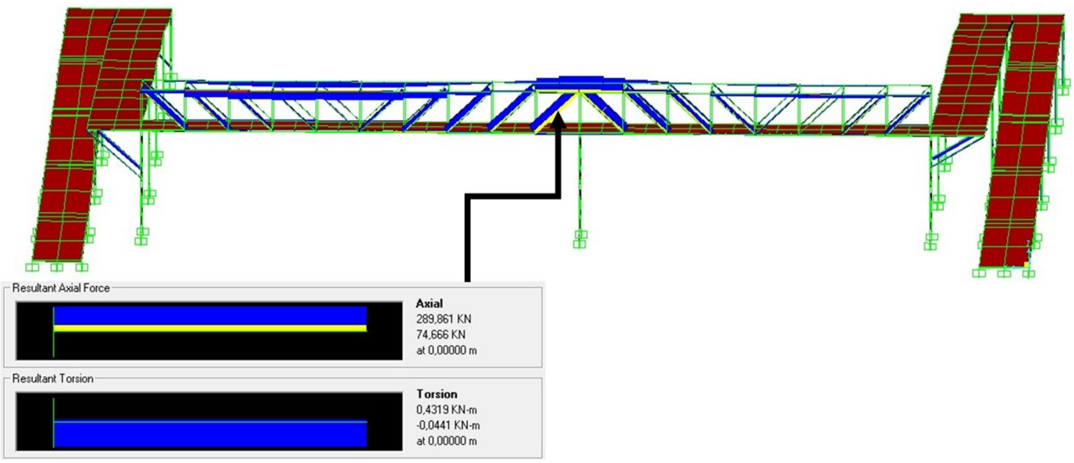

Figure 6. Axial forces FEA - Truss elements - Bamboo Bridge - SAP2000

$$\lambda = \frac{l_e}{r} \ , \tag{2}$$

in which l_e is the effective length accounting for buckling and r radius of gyration. It is important to highlight that $\lambda \leq 40$ is the slenderness ratio for short elements and $40 \leq \lambda \leq 80$ is the slenderness ratio for medium elements. Therefore, axial compressive strength can be obtained with

$$\sigma_c = \frac{N_c}{A} \ , \tag{3}$$

where N_c is the highest compressive axial force obtained in the element.

The results obtained with this analysis are presented in Table 3, where it can be seen that the bamboo elements

Table 3. Capacity check for bamboo axial elements in the model.

Element	σ (MPa)	f (MPa)	Capacity Check
Tension	2.82	28	0.1
Compression	11.30	16.5	0.68

can resist the applied load in all situations. Although Tables 1 and 2 show that the required mechanical properties of steel elements are smaller than the ones required for bamboo elements, the later offers a better strength to mass ratio, which will impact the final cost. The steel elements are in accordance with DNIT [7] design report and therefore were already checked for load carrying capacity.

Lastly, a comparative analysis involving the overall cost was performed for each material. Only truss elements are considered on this analysis. The element cost is measures though linear length in meters (m) and Brazilian real (R$).

In order to not benefit any third party company, the name of suppliers will not be displayed, although the values presented in this paper are still reliable since they were provided by well-known construction companies established in Brazil. Furthermore, for the purpose of this analysis, the overhead cost, workforce cost and overall productivity are not included since it is beyond the scope of this paper, even though it could greatly impact the design decision.

The results obtained with this analysis are displayed on Table 4, where it can be seen that the steel is 308.22% more expensive than the bamboo, proving the feasibility of the material as a structural alternative to conventional building materials.

Table 4. Overall cost of steel bridge elements.

Element	Unit cost (R$)	length (m)	Area (m^2)	Total cost (R$)
W250x32.7	534.95	635.16	-	339,778.842
L9.5	490.28	-	148.1	72,610.468
Overall Cost				412,389.31
G30	189.28	635.16	-	120,223.08
L7.5	47.65	-	148.1	7,056.97
Overall Cost				127,280.05

7 Conclusions

The numerical comparison between truss elements of a steel bridge and a bamboo bridge, both designed for pedestrian traffic was performed on this paper. First, an existing steel bridge in Brasilia was considered and numerically modeled using FEM. The results obtained in this model are in agreement with the Brazilian standards and the bridge design manual.

Second, another FEM model was considered changing all steel elements with sustainable bamboo elements. The bamboo *Dendrocalamus Giganteus* with its natural geometry is considered. The design procedure closely follows the Brazilian structural timber design standard [12], similar to international standards. It was demonstrated that both bridges have satisfactory stiffness and load carrying capacity.

Finally, a simple cost analysis was performed considering only the material overall cost on truss elements, in order to check the feasibility of bamboo structures. In the end, steel elements proved to be 308% more expensive than bamboo elements, for all companies consulted. Based on the results and the analysis, the sustainable bamboo bridge proved to be lighter and cheaper than the real steel bridge with equal load carrying capacity.

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