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# Comparative Analysis of a Sustainable Bamboo Bridge and a Steel Bridge

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**Abstract.** This paper is concerned with a numerical analysis and comparison between a steel bridge and a bamboo bridge, both designed for pedestrian traffic. First, the finite element (FE) method was used to build a numerical model of an existing steel bridge. Later, another FE model was considered changing steel elements with *Dendrocalamus giganteus* sustainable bamboo elements, in order to verify the bamboo feasibility as a structural material. 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:** Steel bridge, Bamboo bridge, Finite Element Method, Numerical Analysis, Dendrocalamus giganteus.

## 1 Introduction

Sustainable development has become a major concern over the international community in recent years [1]. The use of environmentally friendly materials, such as timber and bamboo, as stated by Lima et al. [2], is growing stronger and ideal for the construction industry that is known for excessive consumption of resources.

Sharma et al. [3] showed two examples of engineered bamboo: the bamboo scrimber and the laminated bamboo. Bamboo scrimber, also referred to as strand woven or parallel strand bamboo, consists of crushed fibre bundles saturated in resin and compressed into a dense block. The process maintains the longitudinal direction of the bamboo fibres and utilizes the resin matrix to connect the fibre bundles. In contrast, laminated bamboo maintains both the longitudinal fibres as well as a portion of the original culm matrix. The bamboo culm is split, planed, processed (bleached or caramelized), laminated and pressed to form the board product. On this paper, the natural geometry of the bamboo is considered for all applications, except for slabs, as presented by Chung and Yu [4] and Yu et al. [5].

The connection and bundling of bamboo structures are important since the natural geometry of a single culm, in most cases, is not enough to carry the entire load imposed on conventional structures. Uthaipattrakoon [6] presented a bundle of frames, up to 13 culms of 6 cm diameter, using bamboo fiber. Furthermore, Rittironk [7] studied bundling methods and ideal location of culms, using dowel and rope in the first case, and nuts and bolts in the second case; where the last obtained a better performance. In all cases, these authors proved that the bundle was consolidated in a way that it work as a single element. This paper consider nuts and bolts to bundle bamboo elements when necessary.

Timber has been widely used for small and temporary structures in Brazil, mostly on rural regions; in contrast with other countries, such as Colombia, China and Singapore, where its have been used for bridges and even commercial buildings. Although, in the recent year, more complex timber structures are been studied and designed, as demonstrated by Seixas et al. [8] and Rosalino [9], using Brazilian and international standards. Developing and using modern bamboo materials may provide an alternative in bridge and building construction in Brazil, since the country is already producing structural bamboo in small quantities.

This paper presents a numerical comparison between an existing steel bridge and a theoretical bamboo bridge, as an expansion of the research presented by Oliveira and Oliveira [10], in order to verify the feasibility of the bamboo as a sustainable structural material and potential for more complex structures.

## 2 Steel Bridge

First, the pedestrian steel bridge located in the administrative region of Ceilândia, Brasilia – Brazil, selected by Oliveira and Oliveira [10] and presented in Fig. 1, was considered for this study. The steel bridge sections and spans were obtained after site measurements and the DNIT [11] (National Department of Transportation Infrastructure) design report.

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

The steel used is the ASTM A572 Gr50 and three different frame sections are considered: W360x91, W250x32.7 and L 2" 1/4, 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 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 $(cm^2)$ | $W_x$ $(cm^3)$ | $W_y$ $(cm^3)$ | $I_x$ $(cm^4)$ | $I_y$ $(cm^4)$ |
|---|---|---|---|---|---|---|---|
| W360x91 | 350 | 200 | 115.9 | 1515.9 | 353 | 26755 | 4483 |
| W250x32.7 | 350 | 200 | 42.1 | 382.7 | 64.8 | 4973 | 473 |
| L 2" 1/4 | 350 | 200 | 6.06 | 4.1 | 4.1 | 14.6 | 14.6 |
| 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 beam, columns, slab and truss elements will be designed and checked for load carrying capacity on this study, excluding foundation and connections. Figure 2 show the numerical model used on this analysis.

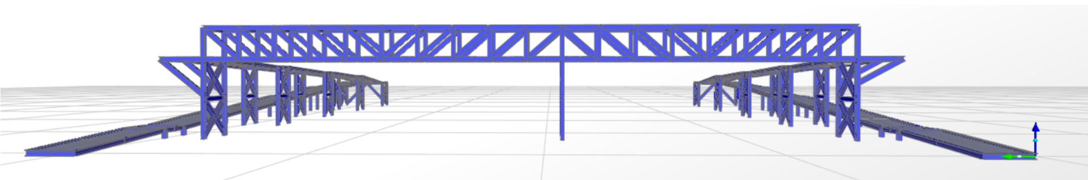
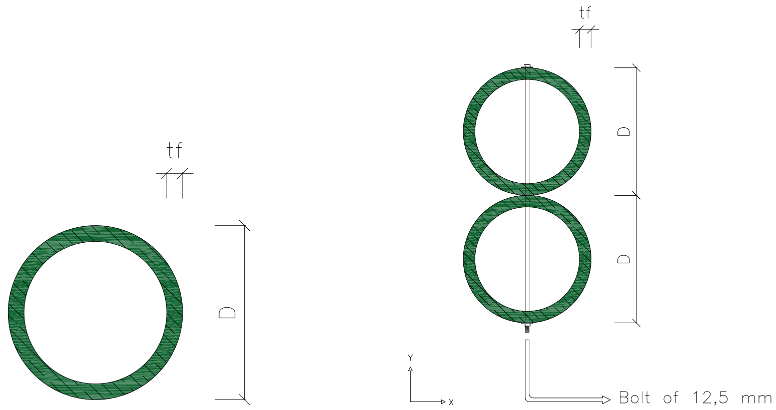


Figure 2. FEM steel bridge numerical model.

## 3 Bamboo Bridge

The bamboo bridge is made of *Dendrocalamus Giganteus* elements with its natural geometry, presented in Fig. 3a, where 30 cm diameter ($D$) and 2.5 cm and 3.5 cm thickness ($t_f$) are considered [12, 13]. Beams and columns are made bundling two culms with nuts and bolts, as show in Fig. 3b and as presented by Rittironk [7], added every $l/3$, where $l$ is the element length. The theoretical bamboo used in this work follows the treatment process presented by Rosalino [9] and Sharma et al. [3]. The bamboo slab is made of *Phyllostachys pubescens* scrimber sheets and follow the works Yu et al. [14] and Sharma et al. [3].




(a) Single section (b) Bundled section

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

Since the Brazilian standards do not contemplate the use of bamboo for structural purposes, the Brazilian structural timber design standard ABNT [15] will be used instead [16, 17]. 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 |
| DG30 | 28 | 16.5 | 8.4 | 782.77 | 6105.68 | 3469.89 | 183170.46 | 52048.24 |
| 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 beam, columns and slabs will be designed and checked for load capacity on this study, since Oliveira and Oliveira [10] presented the results obtained for truss elements. Figure 4 show the numerical model used on this analysis.

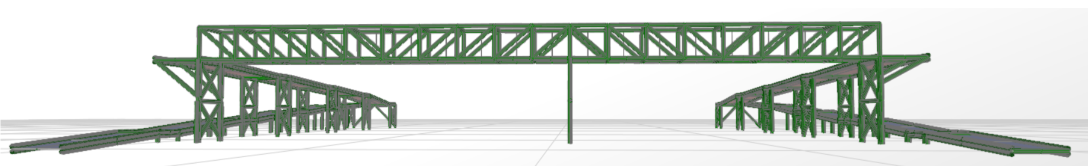


Figure 4. FEM bamboo bridge numerical model.

## 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 [18].

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 $76.973\,kN/m^3$.

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.

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.

Load combinations following the NBR7188 [18] and DNIT [11] 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

The results obtained with the Finite Element Analysis (FEA) are presented in Fig. 5 and 6 for beams, columns and slabs; respectively for the bamboo bridge and steel bridge. The bending moment (M22) from slabs is represented by the color scale in the bottom of both pictures, in $kN.m$.

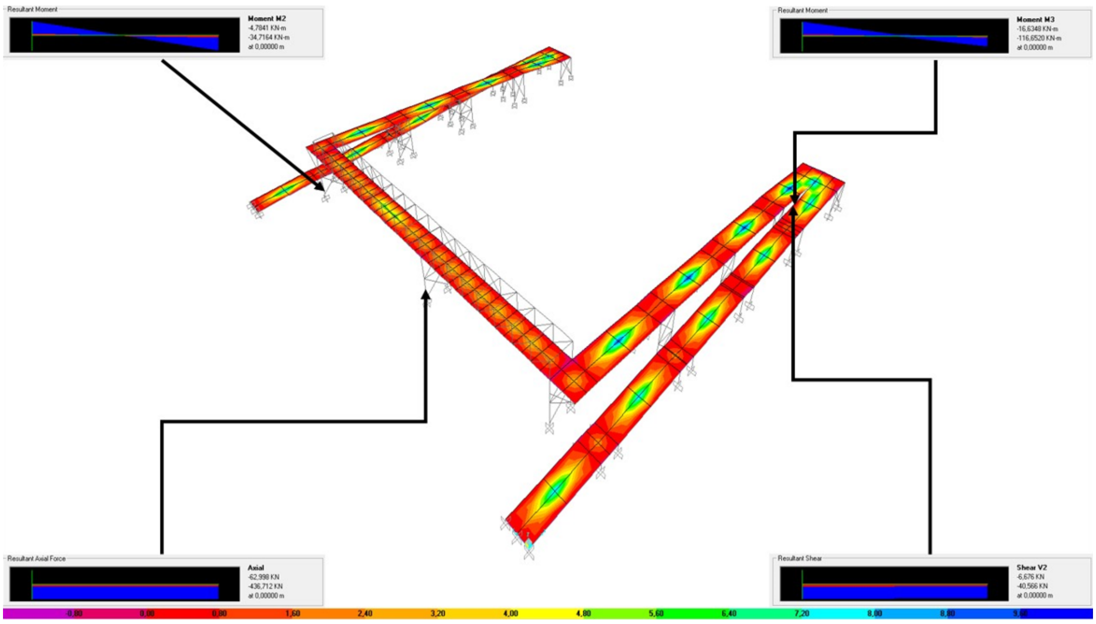



Figure 5. Axial force, shear forces and bending moments FEA - Columns, beams and slabs - Bamboo Bridge - SAP2000.

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 the analysis, it can be seen that the results obtained for the bamboo bridge is about $52.52\%$ lesser than the ones obtained with the steel bridge, similar to the results obtained by Oliveira and Oliveira [10]. The reduced self-weight of bamboo elements is a key advantage of the material and can be evidenced by these results.

Furthermore, deflection results obtained with the FEA are showed in Fig. 7 and 8 for both bridges.

The envelope of all service limit state load combinations are considered on both models. Only the most solicited elements are presented and considered for the serviceability limit check and design obtained in section 6.

The analysis show that the deflection obtained with bamboo elements are $54.9\%$ greater than the ones obtained with steel elements. This main drawback is mostly due to the lower Young modulus (E), which is $95.8\%$

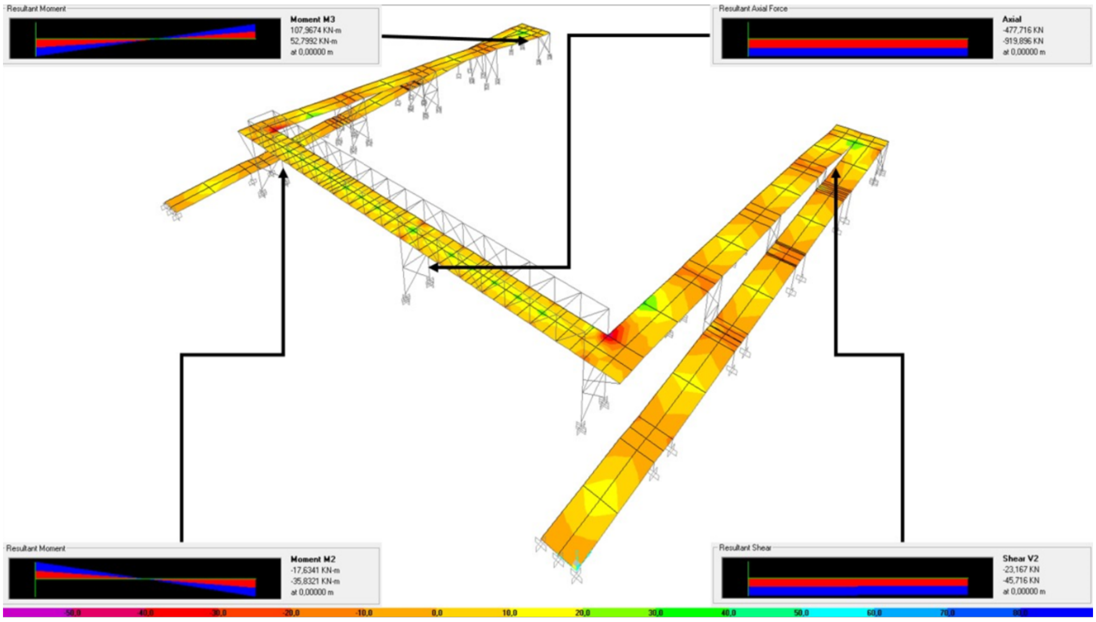



Figure 6. Axial forces, shear forces and bending moments FEA - Columns, beams and slabs - Steel Bridge - SAP2000.

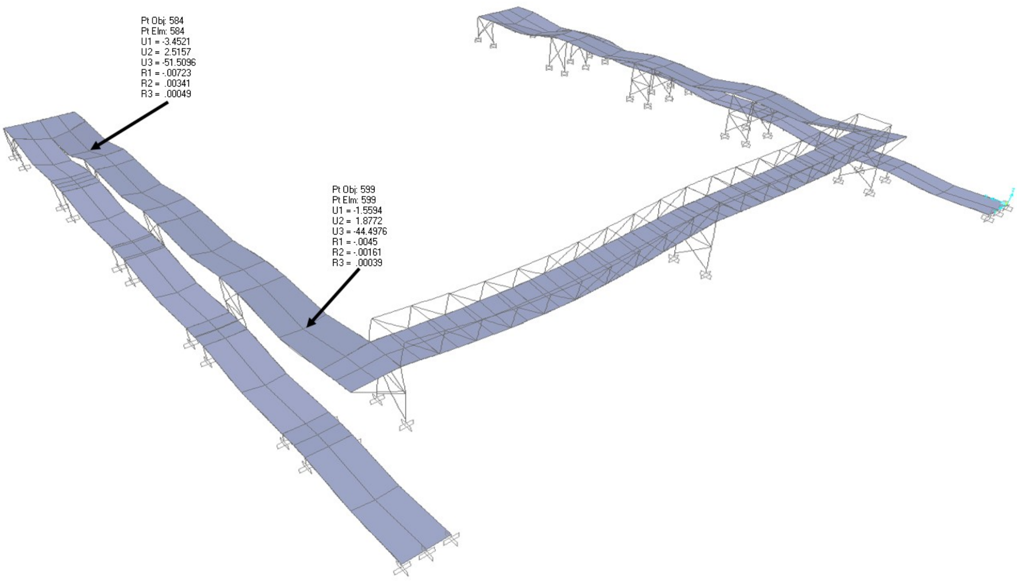



Figure 7. Deflection (mm) - Bamboo Bridge - SAP2000

lower for bamboo elements when compared to steel elements.

## 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 results obtained with this analysis are presented in Table 3, where it can be seen that the bamboo elements can resist the applied load in all situations. Truss elements were checked for load carrying capacity and the results presented by Oliveira and Oliveira [10]. Moreover, the combined strength ratio $\sigma_{u_c}$ for the columns is $0.69 \leq 1$, which is also in accordance with the Brazilian standards. The results show that bundled sections were required in order to resist the intensity of the load carried on beams and columns. 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 performance. The steel elements are in accordance with DNIT [11] design report and therefore were already checked for load carrying capacity.

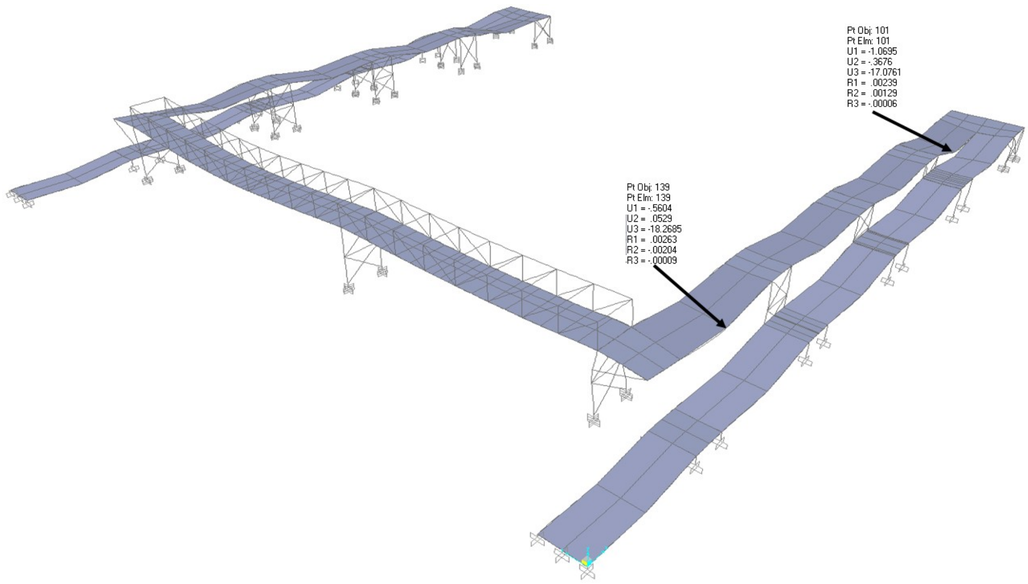



Figure 8. Deflection (mm) - Steel Bridge - SAP2000

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

| Element | $\sigma$ (MPa) | $\tau_d$ (MPa) | Capacity Check |
|---|---|---|---|
| Beam | 15.56 | 0.14 | 0.94 |
| Slab | 10.33 | 0.17 | 0.56 |
| Column | 7.75 | 0.10 | 0.47 |

The connection between elements and the bundling of culms are of utmost importance when studying bamboo structures, nevertheless the complexity required to properly address this issue is not on the scope of this paper and will be addressed in another research.

Table 4 show the results obtained for the serviceability check where it can be seen that the bamboo elements

Table 4. Capacity check for bamboo flexural elements in the model.

| Element | $f_v$ (mm) | $f_{max}$ (mm) | Capacity Check |
|---|---|---|---|
| Beam | 44.17 | 61.25 | 0.72 |
| Slab | 51.51 | 85.76 | 0.60 |
| Column | 2.41 | 8 | 0.30 |

are within the service deflection limit in all situations. Even though the bamboo has a considerably lower Young modulus ($E$), the overall deflection is still manageable, mostly due to bundled beams and the thick slab. The steel elements are in accordance with DNIT [11] design report and therefore were already checked for serviceability limits.

## 7 Conclusions

The numerical comparison between 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 for truss elements and bundling two culms with nuts and bolts for beams and columns were considered. Meanwhile the *Phyllostachys pubescens* scrimber was considered for slabs. The design procedure closely follows the Brazilian structural timber design standard ABNT [15], similar to international standards.

It was demonstrated that both bridges have satisfactory stiffness and load carrying capacity. For the bamboo bridge, truss elements were capable of resisting the load just with a single culm, but the bundled sections were required in order to resist the intensity of the load imposed on beams and columns. Even with considerably lower Young modulus, the bamboo elements obtained deflections within the maximum limit in all cases.

The results presented show the feasibility of the sustainable bamboo bridge as a viable alternative to conventional materials, since the bamboo bridge proved to be lighter than the real steel bridge with equal load carrying capacity.

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