Numerical Modeling of Dencrocalamus Asper Densified Bamboo under Flexure

Ícaro B. M. Carvalho[1], Tiago S. Oliveira[2]

[1]*Bueno e Bruno Architecture and Engineering LTDA*
Rua das Camélias 19 Quadra C Sala 01 Floriano, 64804-438, Piauí, Brazil
icaro.bruno1990@gmail.com
[2]*Dept. of Civil Engineering, IESB University Center*
SGAS Quadra 613/614 Asa Sul, 70200-730, Brasília, Brazil
tiago.oliveira@iesb.br

Abstract. The concern of the paper is the numerical analysis of a densified bamboo plate of the species *Dencrocalamus Asper*. Nonlinear finite element (FE) models utilizing ABAQUS software were developed to study the material behavior when the densification process is performed. Results obtained with experimental tests were compared with results obtained from the numerical model, in order to validate the model. The numerical analysis showed the improved performance obtained with the densification process when compared to plain bamboo specimens, where the maximum load carrying capacity was increased depending on the densification ratio. The results obtained with the numerical model are in good agreement with those obtained on the experimental tests. Overall, densified bamboo specimens proved to be reliable substitute for the conventional bamboo and can be safely introduced for other uses.

Keywords: Sustainable bamboo, Dencrocalamus Asper, Finite Element Method, Numerical Analysis.

1 Introduction

The construction sector has as high demand for conventional construction materials, such as steel and concrete, which 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 a must.

Among sustainable materials, bamboo is a fast growing and renewable resource, usually found in the tropics, especially in areas like Africa, Asia, and Latin America [2]. The bamboo high strength to weight ratio, about six times higher when compared to steel, is evident and presented by R. Mali and Datta [3]. Furthermore, obtained a good performance under tension and compression parallel to fibers, and even better in flexure [4]. Moreover, Laroque [4] showed the mechanical performance of bamboo is largely dependent on its specific weight.

One of the main drawbacks of bamboo as a structural material is the variability of mechanical properties along the specimen, which led researchers and engineers to standardized the geometrical shape. In that regard, [5] presented the densification of different bamboo elements, which consist in redesigning the microstructure of the material to increase the density. Fang et al. [6] suggested densification as one of the post-treatment improvements performed in flattened bamboo culms, in order to sustain the new geometry and to reduce indentations.

Different authors studied the mechanical and physical properties of bamboo, before and after densification process [7–11]. Kadivar et al. [12] presented a 3-point bending test of *Dencrocalamus Asper* bamboo specimens under different moisture conditions, obtaining optimal results at 10% moisture content. The present research closely follows the experimental results and findings presented by these authors.

Variable cross section geometry and mechanical properties along the bamboo specimen greatly increases the complexity of the numerical analysis, which is one of the reasons for the lack of numerical studies about this material. The homogenization of the material, a direct consequence of the densification process, can mitigate this problem and expand the research output regarding the mechanical behavior. Hence, this paper aims to perform a numerical analysis of densified bamboo plates under flexural load. The numerical model of the material was validated and closely follows the experimental tests, under similar conditions. The material obtained a good overall performance when compared to un-densified specimens and proved to be a reliable alternative to conventional wood specimens.

2 Material modeling

This work uses the FE program ABAQUS [13] to investigate the behavior of densified and un-densified *Dencrocalamus Asper* specimens for 0% and 10% moisture on a three-point bending test, closely following the experimental tests presented by Kadivar et al. [12] for material properties validation and model calibration. Non-linearities such as specimen geometry and material behavior were included in the model.

For the bamboo modeling, the von Mises criterion and the option (*PLASTIC) in the software used in association with the plastic flow rule was adopted. Moreover, the isotropic yielding is considered with the goal to better represent the behavior of the bamboo in the three-dimensional (3D) stress space [14]. To properly simulate the behavior of the bamboo specimen, the software requires only the uniaxial stress–strain curve, which is represented by the trilinear stress–strain curve shown in Figure 1.

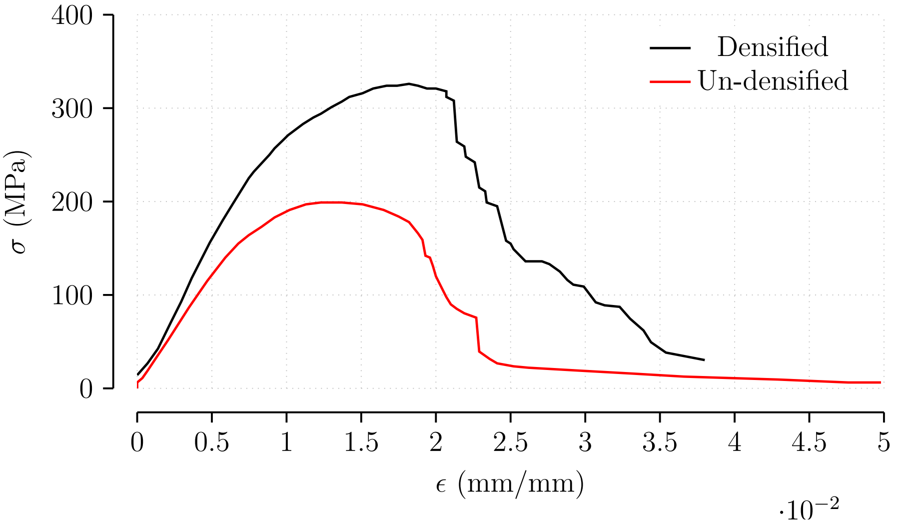

Figure 1. Stress-strain bending plot of un-densified and densified samples with 10% Moisture. Adapted from Kadivar et al. [12].

Kadivar et al. [12] show that the samples with initial moisture of 10% had the highest modulus of rupture, while samples with 20% of water content presented the lowest values and therefore not considered in this paper. As the authors presented, the initial moisture content around 10% can be enough for the required plasticization before densification. Analogous behavior can be observed for the modulus of elasticity results in comparison to the modulus of rupture values, where the densification process increases modulus of elasticity values for every sample, regardless of the moisture.

The same behavior can be observed for the limit of proportionality and specific energy, the area under the stress-strain curve divided by the cross-section of the samples. Samples with 10% MC had the highest energy absorption and limit of proportionality, which confirms that the densification process does not degrade the fibers and also improves its quality to support the load.

Most wood specimens that exhibits large inelastic strains, yield at stress levels that are less than the elastic modulus, which implies that the relevant stress and strain measures are, respectively, the Cauchy Stress and the logarithmic strain. Therefore, according to ABAQUS [14], the data provided by the experimental test need to be given in those measures and had to be treated in most cases. The simple conversion from Nominal Stress (σ_{Norm}) to Cauchy Stress (σ_{Cachy}) can be carried out with

$$\sigma_{Cachy} = \sigma_{Norm} \left(1 + \epsilon_{Norm}\right) \ , \tag{1}$$

and the Logarithmic Plastic Strain (ϵ_{l_n}) with

$$\epsilon_{l_n} = ln \left(1 + \epsilon_{Norm}\right) - \frac{\sigma_{Cachy}}{E} \ , \tag{2}$$

where E is the young modulus. After the data treatment, the numerical analysis can correctly predict the material behavior, as shown in section 4.

3 Specimen modeling

The specimen is modeled considering the eight-node FE (C3D8R) from ABAQUS [13] library, with reduced integration to avoid volumetric locking. Figure 2 show the specimen used in the three-point bending test, with 70 mm x 7 mm x 2 mm and 60 mm distance between supports, for validation of the model and the material.

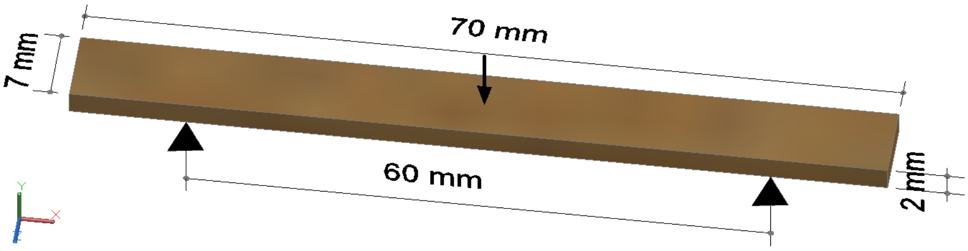

Figure 2. The bamboo specimen considered in the three-point bending test.

Likewise the experimental test, based on the Saint-Venant's principle, the major displacement happens exactly in the middle of the specimen. The displacement is applied in small increments automatically assigned by the software, with a total of 10 increments, based on the condition of numerical convergence of the modified RIKS algorithm [14]. The nodes on the support are restricted from moving in the Y-axis, distant 60 mm from each other.

The mesh is uniform in size and thickness with respective engineering properties assigned. To avoid numerical inconsistencies, the shape of the elements satisfies the limits and aspect ratio recommended by ABAQUS [14]. Figure 3 show the finite element mesh discretization for the specimen used in the three-point bending test, with 2 mm x 2 mm x 2 mm solid elements, resulting in a mesh with 296 nodes and 108 solid elements in total.

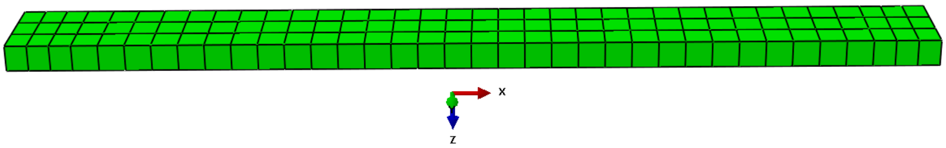

Figure 3. Finite element meshes of the numerical model considered in the three-point bending test.

4 Numerical results

Table 1 shows a comparison of the three-point bending test resistance obtained experimentally and numerically on this study, where σ_y is the yield stress, ϵ_y is the yield strain, σ_u is the ultimate stress, ϵ_u is the ultimate strain and E is the young modulus. It can be seen that the results obtained have a good agreement with those presented by Kadivar et al. [12]. From Figure 4 and 5, showing the displacement and stress obtained with both models during the analysis, it can be seen that the densified bamboo with 10% moisture was 64.7% stronger than the conventional bamboo, without densification.

Table 1. The results of the Finite element model compared to the experimental tests, for densified and un-densified bamboo specimens.

Specimen	σ_y (MPa)	ϵ_y (‰)	σ_u (MPa)	ϵ_u (‰)	E (GPa)
Densified test	223.51	7.46	318	15.1	27.75
Densified FE	231.27	7.67	328.04	16.31	30.02
Un-densified test	147.52	6.24	203.5	15.64	19.63
Un-densified FE	154.89	7.32	201.14	12.76	21.15

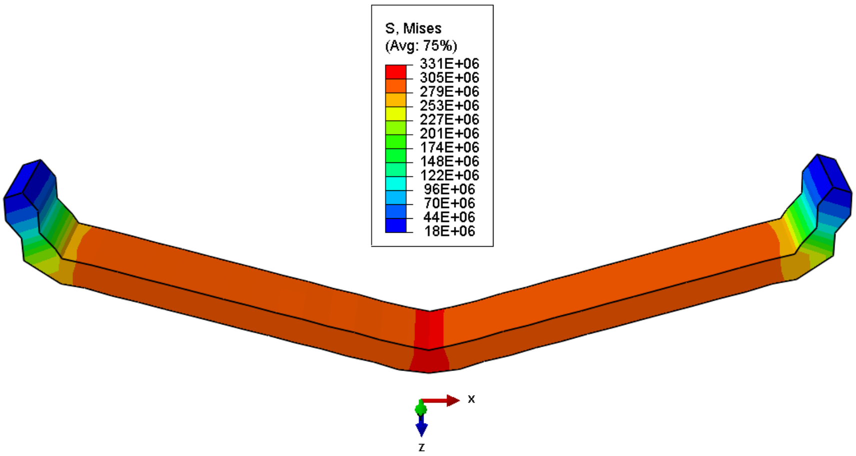

Figure 4. Deformed shape and Von Mises Stress (Pa) of the densified bamboo FE model.

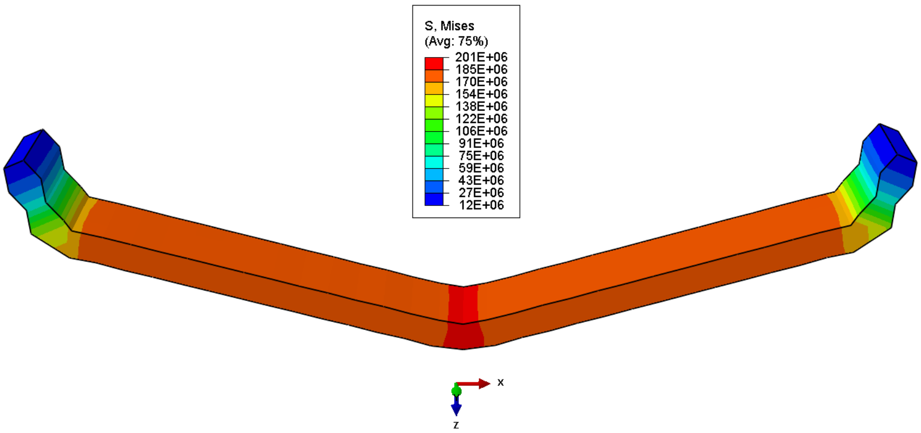

Figure 5. Deformed shape and Von Mises Stress (Pa) of the un-densified bamboo FE model.

The experimental stress–strain curves were compared with the numerical curves obtained from the FE analyses (Figure 6). Once more, good agreements can be observed between experimental and numerical outputs, especially for the elastic region. After the the proportional limit and the yield stress is reached, an accurate behavior is obtained until it is close to the ultimate stress, during the strain hardening on the plastic region. Unlike the experimental test, where the necking region and the fracture stress can be seen, the numerical experiment ends before reaching the ultimate stress. The results show that the material can be correctly modeled under elastic and most of the plastic behavior.

The initial S_{ini} and post yielding tangent stiffness S_{post} are evaluated in order to asses the experimental and FE stiffnesses. S_{ini} and S_{post} are obtained, respectively, for the Elastic Region and for the Plastic Region. Figure 7 and 8 shows the evaluation of S_{ini} and S_{post} using linear fit and based on the average curve for the experimental and the numerical results. The difference between the experimental result and the FE model was about 4.18%, for the densified bamboo; and 7.82%, for the un-densified bamboo, which is a remarkable result and mathematically confirms the good agreements obtained with both models. The densified model obtained a better accuracy when compared to the un-densified one, mostly due to the homogenized mechanical properties of the densified material and therefore easier to model mathematically.

5 Conclusions

The numerical analysis of densified bamboo plates of the species *Dencrocalamus Asper* under flexural mode was performed on this paper. First, ABAQUS software was used to model the finite element bamboo plate, considering densified and un-densified specimens. The model closely follows the procedures presented in the experimental test.

The numerical analysis was performed and showed a good agreement with the results found experimentally. The linear elastic and plastic sections are accurate during the numerical simulation, until it is close to the ultimate

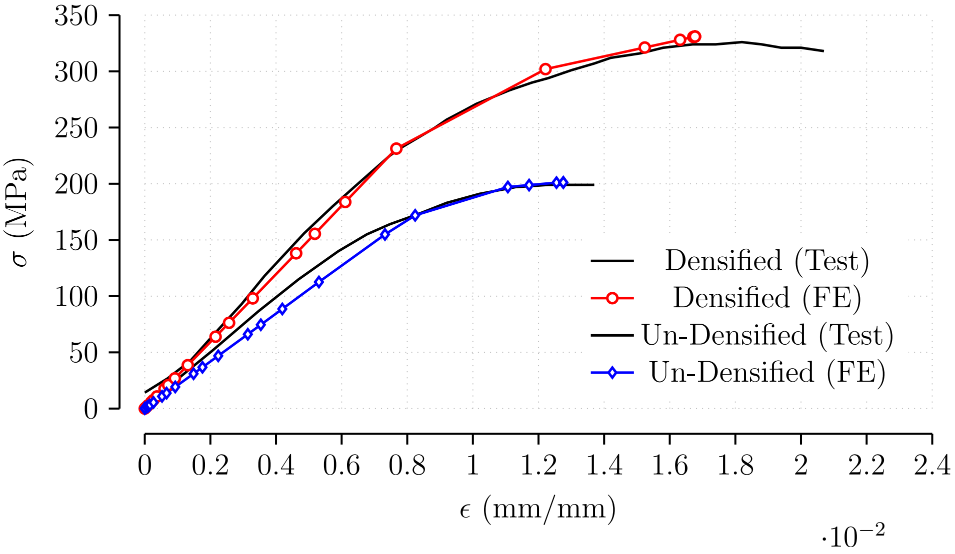

Figure 6. Stress-strain bending plot of un-densified and densified samples with 10% Moisture for experimental results [12] (Test) and numerical results (FE).

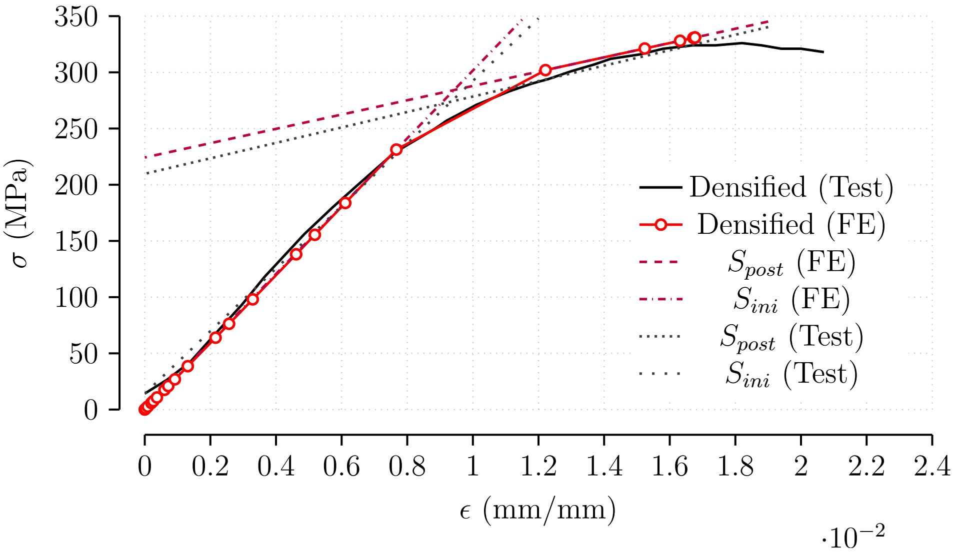

Figure 7. S_{ini} and S_{post} using linear fit and based on the average curve for the experimental and the numerical results, for the densified bamboo.

stress, where the numerical model fails before the experimental test. The initial and post yielding tangent stiffness analysis also provided good results, showing that the stiffness and consequently the precision of the model, are satisfactory throughout the simulation.

Likewise the experimental test, the densified bamboo specimen with 10% moisture obtained better results when compared to un-densified specimens, greatly increasing the overall maximum stress capacity of the material under flexural behavior.

In the end, the results presented clearly validate the material modeling performed in this paper and therefore can be expanded for more complex numerical simulations. Based on the the analysis, the densified *Dencrocalamus Asper* bamboo proved to be a stronger and reliable alternative to conventional bamboo and wood elements.

Acknowledgements. The authors acknowledge the Department of Civil Engineering of IESB University Center, Brasília.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the

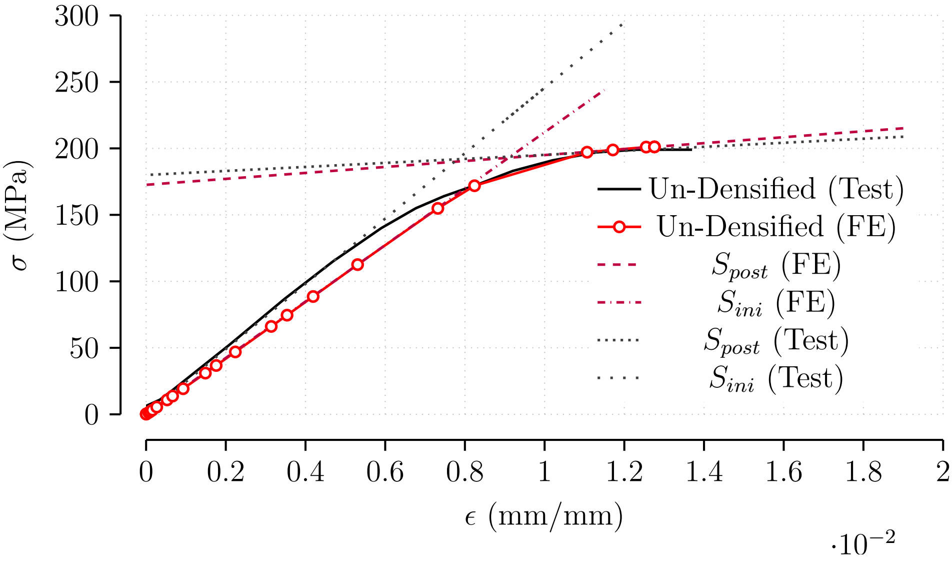

Figure 8. S_{ini} and S_{post} using linear fit and based on the average curve for the experimental and the numerical results, for the un-densified bamboo.

property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Y. Xiao, Q. Zhou, and B. Shan. Design and construction of modern bamboo bridges. *Journal of Bridge Engineering*, vol. 15, 2010.

[2] K. De Flander. *The role of bamboo in global modernity: from traditional to innovative construction material*. PhD thesis, Wageningen University, Wageningen, Netherlands, 2005.

[3] P. R. Mali and D. Datta. Experimental evaluation of bamboo reinforced concrete slab panels. *Construction and Building Materials*, vol. 188, pp. 1092–1100, 2018.

[4] P. Laroque. Design of a low-cost bamboo footbridge., 2007.

[5] M. Kadivar, C. Gauss, K. Ghavami, and H. Savastano Jr. Densification of bamboo: State of the art. *Materials*, vol. 19, n. 4346, pp. 1–25, 2020.

[6] C.-H. Fang, Z.-H. Jiang, Z.-J. Sun, H.-R. Liu, X.-B. Zhang, R. Zhang, and B.-H. Fei. An overview on bamboo culm flattening. *Construction and Building Materials*, vol. 171, pp. 65–74, 2018.

[7] K. Tanaka, M. Inoue, H. Fujihara, H. Adachi, and Y. Goto. Development of bamboo connector strengthened by densified technique. In *Proceedings of the 9th World Conference on Timber Engineering*, pp. 976–983, Portland, USA, 2006.

[8] H. Takagi, A. Mizobuchi, K. Kusano, and Y. Okitsu. Flexural properties of all bamboo green composites. *Materials Characterisation*, vol. 97, pp. 167–173, 2008.

[9] H. Archila-Santos, M. Ansell, and P. Walker. Elastic properties of thermo-hydro-mechanically modified bamboo (guadua angustifolia kunth) measured in tension. *Key Engineering Materials*, vol. 600, n. 1, pp. 111–120, 2014.

[10] G. Semple, F. Kamke, and A. Kutnar. Exploratory thermal-hydro-mechanical modification (thm) of moso bamboo (phyllostachys pubescens mazel). In *Proceedings of the International workshop in Slovenia on Characterization of Modified Wood in Relation To Wood Bonding and Coating Performance*, pp. 220–227, Rogla, Slovenia, 2013.

[11] P. Dixon, K. Semple, A. Kutnar, F. Kamke, G. Smith, and L. Gibson. Comparison of the flexural behavior of natural and thermo-hydro-mechanically densified moso bamboo. *European Journal of Wood and Wood Products*, vol. 74, n. 1, pp. 633–642, 2016.

[12] M. Kadivar, C. Gauss, G. Mármol, de A. Sá, C. Fioroni, K. Ghavami, and H. Savastano. The influence of the initial moisture content on densification process of d. asper bamboo: Physical-chemical and bending characterization. *Construction and Building Materials*, vol. 229, n. 1, pp. 633–642, 2019.

[13] ABAQUS. *User's Manual*. Dassault Systèmes Simulia Corp, 2014a.

[14] ABAQUS. *Theory manual*. Dassault Systèmes Simulia Corp, 2014b.