CILAMCE
PANACM
RIO DE JANEIRO 2021

Numerical Analysis of a Dendrocalamus Sustainable Bamboo Warehouse

Fernando F. Oliveira[1], Layza G. Alves[1], Tiago S. Oliveira[1]

[1]*Dept. of Civil Engineering, IESB University Center*
SGAS Quadra 613/614 Asa Sul, 70200-730, Brasília, Brazil
fernando.oliveira.ferreira@outlook.com, layzag.alves@gmail.com, tiago.oliveira@iesb.br

Abstract. The concern of the paper is a numerical comparison between a steel warehouse and a bamboo warehouse using its natural geometry, both designed for industrial storage. This analysis was performed considering an existing steel warehouse in Brasilia, modeled using the Finite Element Method (FEM). To demonstrate how the bamboo would fare against a traditional material, another FE model was considered changing steel elements with sustainable bamboo elements. The results presented in the paper are in perfect agreement with the Brazilian standards and obtained satisfactory load carrying capacity. Based on the analysis, the sustainable bamboo warehouse proved to be lighter and cheaper than the real steel warehouse counterpart with equal load carrying capacity.

Keywords: Steel warehouse, Bamboo warehouse, Finite Element Method, Numerical Analysis, Dendrocalamus giganteus.

1 Introduction

The modern world population growth resulted in the excessive and unsustainable consumption of natural resources. This excessive consumption also apply to construction materials such as steel and concrete, which the production process consume a large amount of energy and generate considerable wastes. Many natural resources, such as bamboo and wood, have their production close to collapse [1]. Sustainable development, and the use of environmentally friendly materials such as timber and bamboo, has become a major concern over the international community [2].

Construction using bamboo with its natural geometry, also known as full culm bamboo construction, is not widely practiced worldwide, with primary uses of traditional bamboo construction found in Asia, Latin America and East Africa, as seen in Sharma et al. [3]. Liu et al. [4] and Cai and Li [5] presented some applications of bamboo structures, such as low cost social houses, engineered bamboo structures, small transportation facilities, earthquake or natural disasters resistant houses and more. The key features of the full culm bamboo presented by these author are ideal for low occupation buildings, mainly used for storage of materials and equipment, like the warehouse presented in this paper.

In Brazil, timber has been widely use on rural regions for small and temporary buildings due to its relatively low cost and material availability. Recently, more complex timber and bamboo structures are been studied and designed, as demonstrated by Seixas et al. [6], Rosalino [7] and Oliveira and Oliveira [8], using Brazilian and international standards. Using modern bamboo materials may provide an alternative in low-budget building construction in Brazil, which is already producing and working with structural bamboo.

This paper presents a numerical comparison between an existing steel warehouse and theoretical bamboo warehouse, in order to verify the feasibility of the bamboo as a sustainable structural material for small scale and low budget constructions.

2 Steel Warehouse

For the numerical experiment presented in this paper, an industrial warehouse, used for storage of materials, located in the administrative region of Vicente Pires, Brasilia – Brazil, was selected and presented in Figure 1.

The steel sections and spans were obtained after site measurements and the structural design report provided by the property owner. The steel used is the ASTM A36 and three different frame sections are considered: U 93x30

Figure 1. Interior view of the steel industrial warehouse located in Brasilia, Brazil.

#2.65 and U 100x50 #2.65 for truss elements, Ue 100x40x17 #2.00 for beams and Double Ue 100x40x17 #2.00 for columns, 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, cable sections made of the same steel with 12.5 mm thickness are added as bracing elements. The Finite Element Method (FEM) and SAP2000 software was used to

Table 1. Mechanical and geometrical properties of the steel warehouse elements.

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)
U 93x30 #2.65	250	200	3.79	9.62	1.27	44.75	0.87
U 100x50 #2.65	250	200	5.07	15.87	3.47	79.34	12.61
Ue 100x40x17 #2.00	250	200	4.02	12.12	3.54	60.58	9.28
D Ue 100x40x17 #2.00	250	200	8.04	21.27	18.87	106.33	75.49

build the numerical model of the warehouse, considering 176 nodes, 60 shells and 403 frames. The steel sections are represented by three-dimensional frame elements and the roof is represented by shell elements with membrane properties, which transfer all the load to connected elements. Rotation at the ends of the bars has not been released to more accurately represent the condition of the nodes. Only beams, columns 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.

3 Bamboo Warehouse

Dendrocalamus giganteus is the tallest species of bamboo, with large culms between 25 to 35 meters tall and 15 to 30 centimeters in diameter. Culms are thick-walled, ranging between 2 to 2.5 centimeters and internodes are usually 35 to 45 centimeters long, and with roost scars on the lower nodes.

The bamboo warehouse is made of full culm *Dendrocalamus giganteus* elements, presented in Figure 3a, where 20 cm diameter (D) and 2 cm thickness (t_f) are considered [9, 10]. Columns are made bundling two culms with nuts and bolts, as show in Figure 3b and as presented by Rittironk [11], added every $l/3$, where l is the element length. The theoretical bamboo used in this work follows the treatment process presented by Rosalino [7] and Sharma et al. [3]. In addition, like the previous model, steel cable sections with 12.5 mm thickness are added as bracing elements.

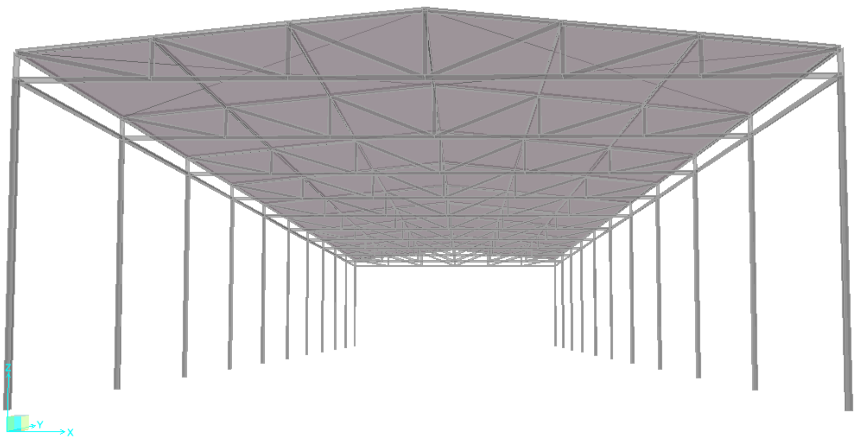
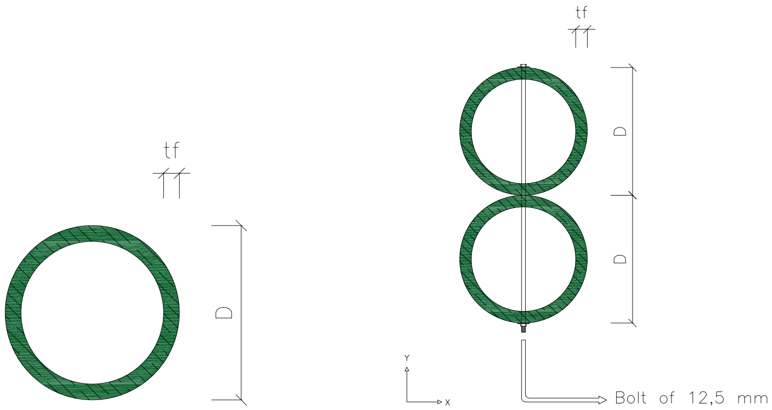


Figure 2. FEM steel warehouse numerical model.



(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 NBR7190 [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. Once more, the FEM and SAP2000 software was used to build the numerical model of the bamboo warehouse, considering the same elements and procedures presented in section 2. Only beam, columns and truss elements will be designed and checked for load capacity on this study, excluding foundation and connections. Figure 4 show the numerical model used on this analysis.

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)
G20	28	16.5	8.4	59.69	463.7	463.7	4637	4637
DG20	28	16.5	8.4	274.89	1911.34	1073.79	38227	10378

4 Applied loads and load combination

On both models, three different loads were applied: dead load, live load and wind load. Exceptional loads and temperature were not analyzed on this study.

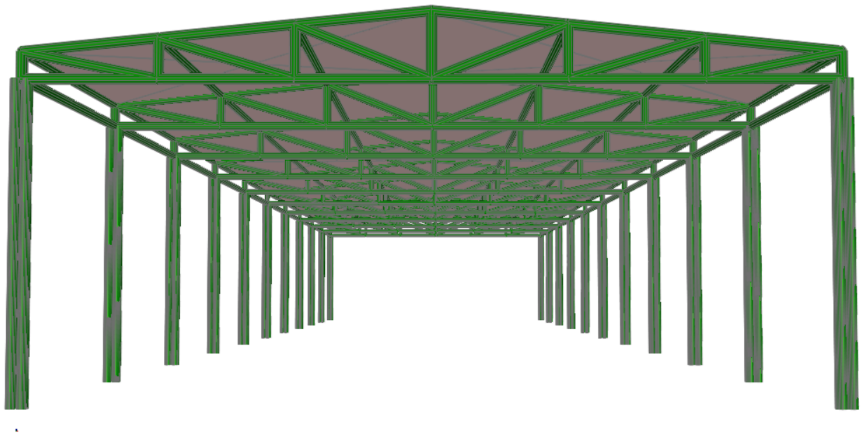


Figure 4. FEM bamboo warehouse numerical model.

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 steel with $76.973\,kN/m^3$.

According to ABNT NBR6120 [15], the live load acting on the roof is $0.25\,kN/m^2$. The loading is applied parallel to the shell surface.

The entire structure is subjected to wind load from major directions (North, South, East and West) and applied as a surface pressure load on roof shell elements. Wind load from different directions will act simultaneously or independently depending on the load combination.

Load combinations following the ABNT NBR7190 [12] and the original structure 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 Figure 5 and 6, for truss elements and columns; respectively for the steel bridge and bamboo bridge. The envelope of all ultimate

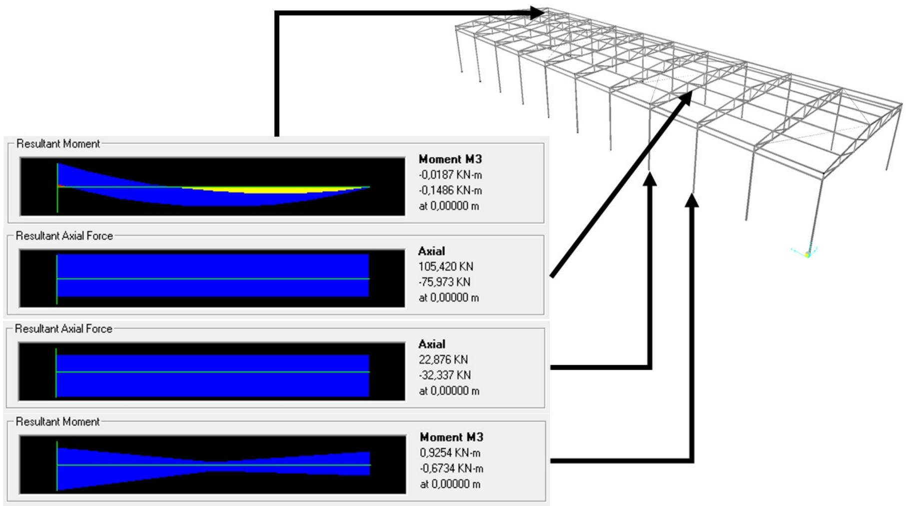


Figure 5. Axial force and Moment component of the FEA - Truss elements, beams and columns - Steel Bridge - SAP2000

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.

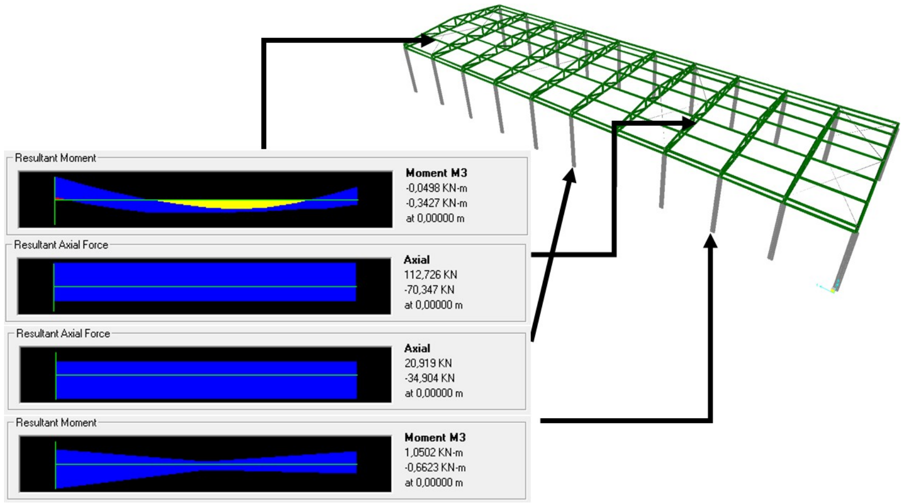


Figure 6. Axial force and Moment component of the FEA - Truss elements, beams and columns - Bamboo Bridge - SAP2000

One of the key advantages of the structural bamboo over traditional materials is the reduced self-weight of the elements, which is more evident after we analyzed the axial results obtained, which clearly show that the output for steel elements are about 7.4% greater than bamboo elements.

Moreover, deflection results obtained with the FEA are showed in Fig. 7 and 8 for both warehouses. The

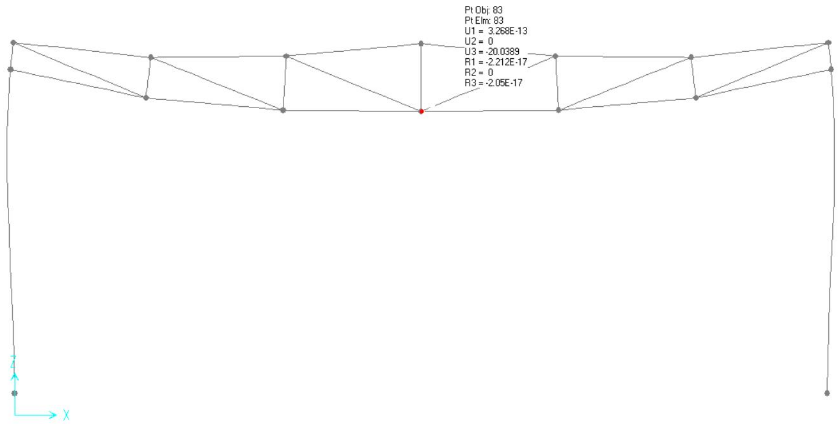


Figure 7. Deflection (mm) - Steel Bridge - SAP2000

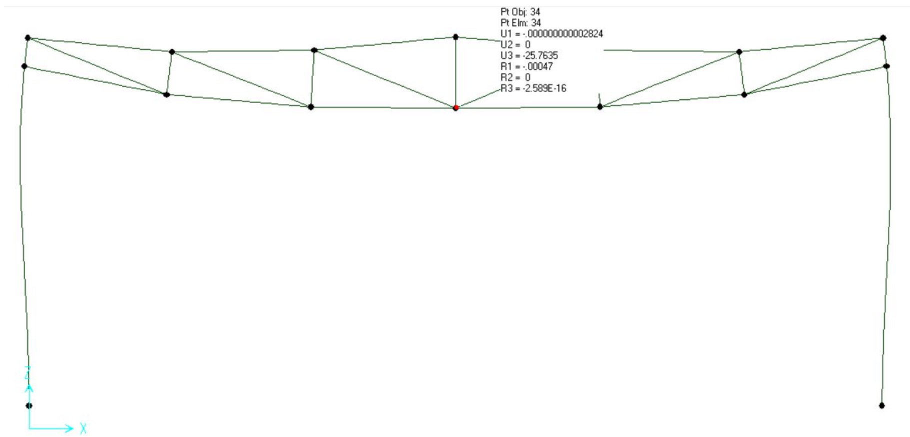


Figure 8. Deflection (mm) - Bamboo Bridge - SAP2000

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.

It can be seen from the analysis that bamboo elements obtained greater deflections (25.91%) when compared to steel ones, mostly due to the Young modulus (E) 95.8% lower. This apparent drawback can be surpassed if smaller sections of different bamboo species are used for beam elements, since their size are over-designed for this situation, as seen in the next section.

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. All calculations are in agreement with the Brazilian design standard.

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 elements in the model.

Element	σ (MPa)	f (MPa)	Capacity Check
Truss	9.93	28	0.35
Beam	1.1	16.5	0.07
Column	9.64	16.5	0.58

can resist the applied load in all situations. Moreover, since the bamboo natural geometry was considered and therefore are not flexible, the beam elements were over-designed for this situation. Tables 1 and 2 show that the required mechanical properties of steel elements are smaller than the ones required for bamboo elements, considering the later offers a better strength to mass ratio, which will impact the final cost and overall performance. The steel elements are in accordance with design report provided by the owner and therefore were already checked for load carrying capacity.

Lastly, a comparative analysis involving the overall cost was performed for each material. Only truss, beams and columns are considered on this analysis. The element cost is measures though linear length in meters (m), Brazilian real (R$) and performed in August 13, 2021. The name of suppliers will not be displayed in order to not benefit any third party company, although only well-established companies were considered. 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 69.75%

Table 4. Overall cost of steel and bamboo elements on a warehouse.

Element	Unit cost (R$)	length (m)	Total cost (R$)
U 93x30 #2.65	72.13	30.11	2,171.78
U 100x50 #2.65	62.26	21.02	1,308.67
Ue 100x40x17 #2.00	63.78	762	48,599.06
Overall Cost			52,079.52
G20	65.27	132	8,615.64
DG20	32.6	681.13	22,204.84
Overall Cost			30,820.48

more expensive than the bamboo, proving the feasibility of the material as a structural alternative to conventional building materials even for smaller structures.

7 Conclusions

The numerical comparison between a steel warehouse and a bamboo warehouse, both designed for industrial storage was performed on this paper. First, an existing steel warehouse in Brasilia was considered and numerically modeled using FEM. The results obtained in this model are in agreement with the Brazilian standards.

Second, another FEM model was considered changing all steel elements with sustainable bamboo elements. The bamboo *Dendrocalamus Giganteus* with its natural geometry is considered, provided by a local bamboo supplier. The design procedure closely follows the Brazilian structural timber design standard [12], similar to international standards. It was demonstrated that both warehouses obtained satisfactory stiffness and load carrying capacity. The beam elements were over-designed for this situation; a drawback that can be easily overcame if industrialized shapes or different bamboo species natural geometry are considered for the structure.

Finally, a simple cost analysis was performed considering only the material overall cost on linear elements, in order to check the feasibility of bamboo structures. For the analysis, the overhead cost, workforce cost and overall productivity are not included. In the end, steel elements proved to be 70% more expensive than bamboo elements, for all companies consulted. The cost of bamboo frames is attached to the frame weight, thus reducing the size of overly designed beams would greatly reduce the overall cost of the bamboo structure. Based on the results and the analysis, the sustainable bamboo warehouse proved to be lighter and cheaper than the real steel warehouse with equal load carrying capacity.

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

References

[1] D. M. Lima, M. M. Amorim, H. C. Lima Júnior, N. P. Barbosa, and F. L. Wilrich. Evaluation of the structural performance howe trusses made of glued laminated bamboo. *Ambiente Construído*, vol. 15, pp. 85–102, 2015.

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

[3] B. Sharma, A. Gatoo, M. Bock, H. Mulligan, and M. Ramage. Engineered bamboo: state of the art. *Proceedings of the Institution of Civil Engineers - Construction Materials*, vol. 168, n. 2, pp. 57–67, 2015.

[4] K. Liu, J. Yang, R. Kaam, and C. Shao. An overview of global modern bamboo construction industry: A summary report of icbs2018. *Modern Engineered Bamboo Structures*, vol. 1, pp. 33–50, 2019.

[5] W. Cai and T. Li. Innovations in round bamboo construction. *Modern Engineered Bamboo Structures*, vol. 1, pp. 99–103, 2019.

[6] M. Seixas, L. E. Moreira, J. Bina, and J. Ripper. Design and analysis of a self-supporting bamboo roof structure applying flexible connections. In *Proceedings of the IASS Symposium 2018*, Boston, USA, 2018.

[7] F. Rosalino. *Sistema de cobertura com feixe de bambusa tuldoides*. PhD thesis, Faculdade de Arquitetura e Urbanismo, Universidade de Brasilia, 2019.

[8] F. Oliveira and T. Oliveira. Numerical analysis of truss elements on a sustainable bamboo bridge. In *XLI Ibero-Latin-American Congress on Computational Methods in Engineering*, Paraná, Brazil, 2020.

[9] K. Ghavami and A. Marinho. Propriedades geométricas e mecâcinas de colmos dos bambus para aplicação de construções. *Revista Brasileira de Engenharia Agrícola e Ambiental*, vol. 23, n. 3, pp. 415–424, 2003.

[10] K. Ghavami and A. Marinho. Physical and mechanical properties of the whole culm of bamboo of the guadua angustifolia species. *Revista Brasileira de Engenharia Agrícola e Ambiental*, vol. 9, n. 1, 2005.

[11] S. Rittironk. Research, education and design in thai bamboo architecture. In *Proceedings of 10th World Bamboo Congress*, South Korea, 2015.

[12] ABNT. Nbr7190:1997 - design of wood structures (translated). volume 1, Brazilian Association of Technical Standards, Brasilia, Brazil, 1997.

[13] S. Kaminski, A. Lawrence, D. Trujillo, and C. King. Structural use of bamboo: Part 3: Design values. *Structural Engineer*, vol. 94, n. 10, 2016a.

[14] S. Kaminski, A. Lawrence, D. Trujillo, and C. King. Structural use of bamboo: Part 4: Element design equations. *Structural Engineer*, vol. 94, n. 10, 2016b.

[15] ABNT. Nbr6120:2019 - design loads for structures (translated). volume 1, Brazilian Association of Technical Standards, Brasilia, Brazil, 2019.