

## Density based resistance model for structural assessment of timber elements using inspection data\*

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### Abstract:

Timber structures require a maintenance plan, along with periodic monitoring of their condition, to ensure their performance is maintained. The most common methods for wood inspection are those classified as non-destructive. Notably, visual inspection is one of the most frequently used methodologies in diagnostic engineering services. These methods lack the capacity to estimate or evaluate the structural resistance and integrity of the elements. The study used data from the inspection conducted in the Maloca building at the University of Brasília to estimate the structural resistance of its elements. The resistance estimate was based on a new resistance model using basic density. This model simplifies the estimative of different resistance parameters using only the basic density of the wood species. The resistance models adopted for various load conditions followed the guidelines of the Brazilian wood standard. The results show that the proposed methodology aligns with the performance and levels of degradation observed during the inspection. In conclusion, the methodology proves to be an important tool for estimating and monitoring the structural capacity of timber structures in inspection contexts without the need for destructive methods.

**Keywords:** Basic density, non-destructive testing, resistance estimates, structural assessment, tropical wood, timber structures.

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## Introduction

## Inspection of timber structures

Wood as a structural material has a marginal history in Brazil. Despite this, the country has great potential for using this material, given the presence of 3000 to 4000 tropical tree species in the Amazon alone. Additionally, some of these species exhibit high resistance capabilities, such as Muirapixuna, with an elasticity modulus of 14800 MPa (Laboratório de Produtos Florestais 2016).

When it comes to timber structures, one of the major concerns is the preservation of the material. Wood is susceptible to various degradation agents that are uncommon in other materials. The main causes of wood degradation are biological, atmospheric, chemical agents, or fire (Arriaga *et al.* 2002). Timber structures can have significant durability potential if used and maintained correctly over time (Laranjeira 2009). As Cruz (2011) points out, these maintenance processes require specific knowledge and experience from those performing them. In another work, Cruz (2012) presents a set of general principles related to the inspection and monitoring of existing structures.

Wood inspection methodologies are traditionally classified into destructive and non-destructive methods (Brito 2014). Among these, the most common and widely used are based on visual inspection (Arriaga *et al.* 2002). However, the non-destructive methods lack the capacity of estimate properties related to the structural integrity and resistance of the elements they analyze.

Martins (2009) presents an inspection and diagnostic methodology based on visual analysis. The proposed methodology is applied in a case study of a monastery in Felgueiras, Portugal, concluding that visual inspection is a suitable method for assessing timber structures.

Similarly, Milani and Kripka (2012) use visual methods and photographs to inspect timber bridge elements in the municipality of Pato Branco, Paraná, Brazil. Abreu *et al.* (2013) also employ non-destructive testing to evaluate timber pieces from Sobrado Ramalho in Tiradentes, Minas Gerais,

Brazil. Both authors reach relevant and accurate conclusions about the origins and pathologies of the various inspected elements.

In another case study, Moreira (2009) utilizes visual inspection in a building in the historical center of Viseu, Portugal. The study demonstrates, in a real-world scenario, how the correct use of inspections in existing structures can significantly contribute to the conservation and rehabilitation of historical buildings.

In all the cited studies, the authors focused on assessing timber elements in a way that did not require causing damage to the structure. However, this approach led to limitations regarding the data that could be obtained. The studies do not provide quantitative information related to the structural integrity of the elements. There is also a lack of information on the current strength values of the elements under the different loads and stresses to which they are subjected.

### **Resistance model based on basic density**

The design of structural steel elements uses the tensile yield stress ( $f_y$ ) as the main design parameter according to ABNT NBR 8800:2008 (2008). For concrete structures, the parameter used is the characteristic compressive strength ( $f_{ck}$ ) as stated in ABNT NBR 6118:2023 (2023). In both cases, these are simple and easily identifiable parameters.

The historical difficulty in designing timber structures stems from the need for multiple parameters to determine each of the structural properties - tensile strength parallel to the grain, shear and compressive strength, modules of elasticity, among others. The use of a single, simple parameter can significantly benefit the design process and the estimation of the strength of timber elements.

It is known that there is a strong correlation between the physical properties of wood, such as its density, and other relevant strength and elastic properties for structural design. In an attempt to identify a single physical parameter that could simplify the process of estimating strength Soares *et al.* (2021) sought to correlate the density of mandioqueira wood with its mechanical parameters. The results of their studies were unsatisfactory, likely due to the small number of samples tested in their work. This indicates the need for a more robust study involving a larger number of samples and species.

The Forest Products Laboratory (LPF), part of the Brazilian Ministry of the Environment, has been conducting the world's largest research program for cataloging tropical wood species since the 1990s, with results available for consultation since 2000 (IBAMA 1997).

De Paula (2023) and Bessa (2018) have advocated for studying these correlations through statistical regression models. The researchers used basic density ( $D_b$ ), a property that is easy to determine and measure accurately, as the independent variable in their statistical study, with the LPF Database serving as a reliable source of representative data.

Research has shown that the mathematical resistance models developed from  $D_b$  are suitable for simulating tropical wood species within the sample that generated the model itself. However, through rigorous statistical analysis, it was proven that this model can be generalized for the entire population. Therefore, it is possible to state that "The proposed mathematical model is capable of simulating the mechanical resistance of any tropical wood species, whether characterized or not, from any tropical forest and any continent (America, Africa, Asia, and Oceania)" (De Paula 2023).

Inspired by this study, Braga and Freitas (Braga and Freitas 2022) developed a software to verify tropical wood structural elements using the basic density resistance model. The program, named DMDB, demonstrated the implementation of the new resistance model in a practical application. It was concluded that the results obtained from the program were consistent with the model.

Thus, using the correlations between basic density and the various mechanical parameters of wood, this study aims to estimate resistance parameters of existing structural elements using information obtained from a conducted inspection.

## **Materials and methods**

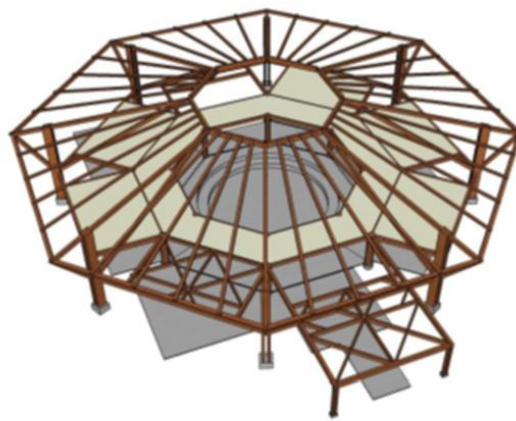
### **The case study of Maloca**

A case study will be carried out at the Maloca of the University of Brasília. The Maloca is a two-story building whose structure is made entirely of round eucalyptus wood. The building is shown in Figure 1.



**Figure 1:** Front facade of the Maloca (Laboratório de Reabilitação do Ambiente Construído 2022).

It is located in an urban environment on flat land, surrounded by trees. The building serves as the headquarters for the Multicultural Coexistence Center of Indigenous Peoples at the University of Brasília (UnB), and thus includes classrooms and laboratories, as well as a ceremonial courtyard. Figure 2 shows a three-dimensional model of the building's structural design.



**Figure 2:** Isometric view of the structural design of the Maloca (Laboratório de Reabilitação do Ambiente Construído 2022).

In Brazil, the standards that regulate the inspection and maintenance of buildings are ABNT NBR 5674:2024 (2024) and ABNT NBR 16747:2020 (2020). Based on these standards, the Laboratory for the Rehabilitation of the Built Environment (LabRAC) at the University of Brasília conducted a Technical Engineering Diagnostic Report for the Maloca building at the University of Brasília (Laboratório de Reabilitação do Ambiente Construído 2022).

The Technical Report on the Maloca was developed based on a checklist of pathological manifestations in timber structures. Beginning with an "as-built" model created by the authors, the building was divided into sections and floors. For each structural element of the building, its characteristics (type of element and dimensions) and the existing pathologies were identified.

Data on the structural components were primarily gathered through visual inspection. Based on the data collected, the condition of the elements was classified according to the intensity and extent of each listed pathology. This information was used to determine the degradation of each inspected element, hereby called Degradation Factor (DF). The degradation is the function resulting from the variables describing the damage relevance, intensity and extent parameterized as presented in Oliveira and Pantoja (2022). Its function is to measure the percentage of deterioration of the elements.

In this study, the selected elements were the columns and beams of the building in question. This selection was performed uniformly throughout the building to avoid favoring any specific environmental or usage condition. Although the report included the degradation of connection elements, they will not be evaluated here due to the greater complexity these elements can present in terms of the stresses to which they are subjected and issues such as steel corrosion and gaps between the timber parts. The methodology proposed is limited to individual elements and does not extend to a comprehensive analysis of the overall structural system and its various interactions and correlations. Several considerations were made in conducting this study: the wood in the elements is in a dry state (12 % moisture content) (De Paula 2023); the strength characteristics of the timber structures are based on the formulations in ABNT NBR 7190-1:2022 (2022); and the wood species used in the design and construction of the Maloca was lemon-scented gum (*Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson) (lemon-scented gum (*Eucalyptus citriodora* Hook.)) (Laboratório de Reabilitação do Ambiente Construído 2022). Additionally, permanent load and moisture class 1 were considered according to ABNT NBR 7190-1:2022 (2022).

For the wood of the lemon-scented gum (*Eucalyptus citriodora* Hook.) species, a basic density of  $0,674 \text{ g/cm}^3$  was adopted (Zanuncio *et al.* 2015). The modification coefficient (Kmod) for sawn wood is composed of two factors according to ABNT NBR 7190-1:2022 (2022): Kmod1 and Kmod2. In this case  $K_{mod1} = 0,60$  and  $K_{mod2} = 1,00$  were used for all elements resulting in  $K_{mod} = 0,60$ .

## Strength parameters

The main strength parameters used in timber design are Modulus of Elasticity in Bending (MOE), Bending Strength (MOR), Compressive Strength Parallel to the Grain (CPA), Compressive Strength Perpendicular to the Grain (CPE), and Longitudinal Shear Strength (CIS).

For each of these parameters, a correlation with basic density was found (De Paula 2023). Table 1 and Table 2 present the results of the correlation functions between the resistance properties for green wood and dry wood, respectively.

**Table 1:** Correlation functions between physical and mechanical properties of tropical wood in the green condition (water-saturated) - independent variable  $D_b$  (De Paula 2023).

Mechanical Property	Wood condition	Correlation Function	R <sup>2</sup>	Sample Size
MOE (MPa)	Green	$MOE = 15428,8644D_b + 1817,4620$	0,861	233
MOR (MPa)	Green	$MOR = 166,0025D_b - 21,7285$	0,932	245
CPA (MPa)	Green	$CPA = 81,6548D_b - 11,3263$	0,928	232
CPE (MPa)	Green	$CPE = 20,7157D_b - 5,9486$	0,833	232
CIS (MPa)	Green	$CIS = 16,8585D_b - 0,6970$	0,841	240

**Table 2:** Correlation functions between physical and mechanical properties of tropical wood in the dry condition (12 % moisture content) - independent variable  $D_b$  (De Paula 2023).

Mechanical Property	Wood condition	Correlation Function	R <sup>2</sup>	Sample Size
MOE (MPa)	Dry (12 %)	$MOE = 16892,6685D_b + 2807,9183$	0,845	234
MOR (MPa)	Dry (12 %)	$MOR = 219,4705D_b - 18,5034$	0,910	238
CPA (MPa)	Dry (12 %)	$CPA = 108,7063D_b - 4,4872$	0,925	232
CPE (MPa)	Dry (12 %)	$CPE = 27,2171D_b - 6,7987$	0,887	221
CIS (MPa)	Dry (12 %)	$CIS = 22,7318D_b - 1,1333$	0,816	222

Based on the DF, the methodology proposed by this study involves reducing the basic density of the studied elements by a percentage equal to the DF. This provides a new reduced basic density, which will be used to carry out the relevant strength assessments for each component.

The structural elements analyzed will follow the formulations presented in ABNT NBR 7190-1:2022 (2022). For each of the aforementioned assessments, the adjusted formulations for basic density were used (De Paula 2023). Utilizing the DMDB software (Braga and Freitas 2022), the assessments were conducted to determine the original strength of the components - considering the original  $D_b$  - and the reduced strength - considering the reduced  $D_b$ .

Finally, comparisons were made between the values obtained to analyze the degree of divergence. This was made according to Equation 1, which expresses the percentual difference ( $\Delta\%$ ) between the original resistance ( $R_0$ ) and the reduced resistance ( $R_r$ ).

$$\Delta\% = 1 - \frac{R_r}{R_0} \quad (1)$$

### **Columns**

For simplicity, it was assumed for the columns that the only load they are subjected to is axial compression parallel to the grain. Therefore, according to ABNT NBR 7190-1:2022 (2022), the evaluations conducted for these elements will focus on crushing for short elements or stability with crushing for slender elements.

The real slenderness of the columns is calculated according to Equation 2, and the reduced slenderness using Equation 3 which uses the CPA and the inferior value of the MOE (0,7\*MOE), both through the basic density. Since all elements have circular cross sections, all axes of inertia are identical.

$$\lambda = \frac{Kl}{i} \quad (2)$$

$$\lambda_{rel} = \frac{\lambda}{\pi} \sqrt{\frac{108,7063D_b - 4,4872}{0,7(16892,6685D_b + 2807,9183)}} \quad (3)$$

Where:  $\lambda$  = real slenderness of the column,  $Kl$  = buckling length of the column (m),  $i$  = radius of gyration of the cross-section (m),  $\lambda_{rel}$  = reduced slenderness of the column,  $D_b$  = Basic density ( $\text{g/cm}^3$ ).

It was assumed that the effective buckling length of the columns is equal to 70 % of their total length, as the column supports are fixed at the base and hinged at the top.

Columns with reduced slenderness greater than 0,3 are classified as Intermediate or Long Columns according to NBR 7190/22-1:2022 (2022). For these, it is necessary to find the coefficient  $K_c$  using Equation 4 and Equation 5.

$$K_c = \frac{1}{K + \sqrt{K^2 - (\lambda_{rel})^2}} \quad (4)$$

$$k = 0,5 \left[ 1 + \beta_c (\lambda_{rel} - 0,3) + (\lambda_{rel})^2 \right] \quad (5)$$

Where:  $\beta_c = 0,2$  for solid sawn and round timber,  $\beta_c = 0,1$  for glued laminated timber (GLT) and laminated veneer lumber (LVL).

The axial compressive load resistance parallel to the fibers for dry wood is calculated according to Equation 6 which uses the CPA through the basic density:

$$N_{cR,d}^S = \phi_c K_c A_g (1087,063 D_b - 44,872) \quad (6)$$

Where:  $N_{cR,d}^S$  = design load resistance for axial compression parallel to the fibers for dry wood (Kgf),  $K_c$  = non-dimensional function for instability resistance in axial compression,  $A_g$  = gross cross-sectional area (cm<sup>2</sup>),  $D_b$  = basic density (g/cm<sup>3</sup>),  $\phi_c = \frac{k_{mod}}{\gamma_w}$  is the weighting factor for axial compression resistance,  $k_{mod}$  = modification coefficient,  $\gamma_w = 1,4$  is the resistance weighting factor for normal stresses.

## Beams

For simplicity, it was assumed for the beams that they are simply supported and subjected to distributed loads. Therefore, according to ABNT NBR 7190-1:2022 (2022), the evaluations conducted for these elements focused solely on resistance to simple straight bending and shear.

The design bending moment for simple bending of dry wood is calculated according to Equation 7 which uses the MOR through the basic density:

$$M_{R,d}^S = \phi_b W (2194,705D_b - 185,034) \quad (7)$$

Where:  $M_{R,d}^S$  = design bending moment relative to the bending axis for dry wood (cm·Kgf),  $W$  = elastic section modulus relative to the bending axis (cm<sup>3</sup>) ( $W = \pi d^3/32$  for circular sections),  $D_b$  = basic density (g/cm<sup>3</sup>),  $\phi_b = \frac{k_{\text{mod}}}{\gamma_w}$  is the weighting factor for tensile resistance,  $k_{\text{mod}}$  = modification coefficient,  $\gamma_w = 1,4$  is the resistance weighting factor for normal stresses in bending.

The shear resistance for dry wood with a circular section is calculated according to Equation 8 which uses the CIS through the basic density:

$$V_{R,d}^S = \phi_v 32d^2 (227,171D_b - 11,333) \quad (8)$$

Where:  $V_{R,d}^S$  = design shear force resistance for dry wood (Kgf),  $D_b$  = basic density (g/cm<sup>3</sup>),  $d$  = diameter of the cross-section (cm),  $\phi_v = \frac{k_{\text{mod}}}{\gamma_w}$  is the weighting factor for shear stress resistance,  $k_{\text{mod}}$  = modification coefficient,  $\gamma_w = 1,8$  is the resistance weighting factor for shear stresses.

## Results and discussion

### Columns

Table 3 presents the selected columns for the study, along with some of their characteristics, including their respective degradation factors and reduced basic density ( $D_{br}$ ). The columns were selected throughout the whole structure, both internal and external.

**Table 3:** Selected columns and degradation factors.

Element	Diameter (cm)	Length (m)	Degradation Factor	$D_{br}$ (kg/m <sup>3</sup> )
P22	30	5,40	0,16 %	673
P40	30	7,00	0,16 %	673
P47	30	5,40	2,49 %	657
P48	30	5,40	2,49 %	657
P38	30	5,40	4,13 %	646

Figure 3 shows photos of some of the columns of the Maloca taken during the inspection.



**Figure 3:** Photos taken of the Maloca's columns (Laboratório de Reabilitação do Ambiente Construído 2022).

The values related to the original slenderness of the columns studied are presented in Table 4. Table 5 presents the new values after the reduction in basic density. As can be seen, all columns in the Maloca are classified as intermediate or long in either condition.

**Table 4:** Values related to the original slenderness of the columns.

Element	Real Slenderness ( $\lambda$ )	Reduced Slenderness ( $\lambda_{rel}$ )	Coefficient $K_c$
P22	50,4	1,344	0,456
P40	65,3	1,742	0,291
P47	50,4	1,344	0,456
P48	50,4	1,344	0,456
P38	50,4	1,344	0,456
P46	50,4	1,344	0,456
P09	65,3	1,742	0,291

**Table 5:** Values related to the slenderness of the columns after reduction in basic density.

Element	Real Slenderness ( $\lambda$ )	Reduced Slenderness ( $\lambda_{rel}$ )	Coefficient $K_c$
P22	50,4	1,344	0,456
P40	65,3	1,742	0,291
P47	50,4	1,339	0,459
P48	50,4	1,339	0,459
P38	50,4	1,335	0,462
P46	50,4	1,335	0,462
P09	65,3	1,084	0,627

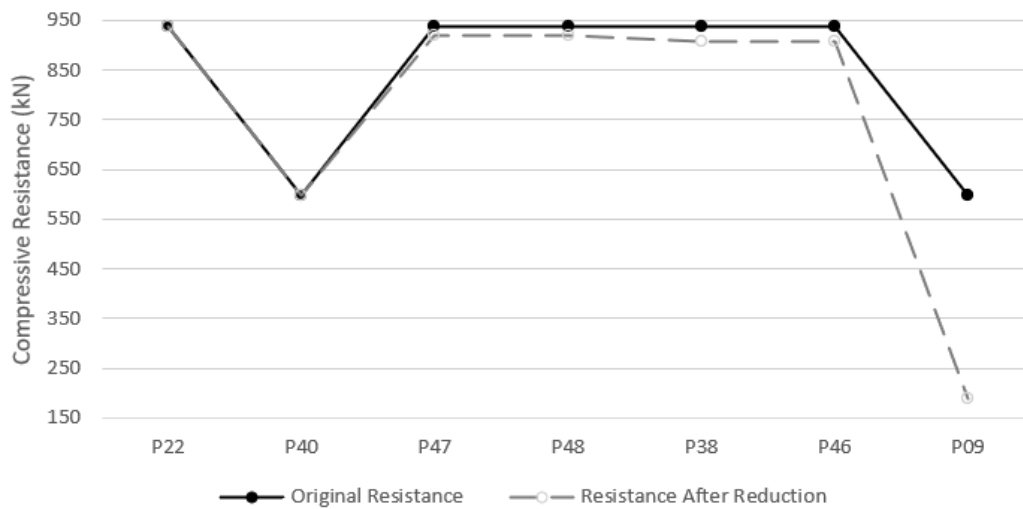
Figure 4 shows one of the verifications conducted using the DMDB program (Braga and Freitas 2022) for the axial compression of Column P22.

**Figure 4:** Verification of column P22 using DMDB.

Table 6 and Figure 5 present the final values found for the compressive resistance of the columns before and after reducing the basic density based on the degradation factors.

**Table 6:** Compressive resistance values for the columns.

Element	Original Resistance (kN)	Resistance After Reduction (kN)
P22	938,29	936,54
P40	597,37	596,32
P47	938,29	918,20
P48	938,29	918,20
P38	938,29	906,42
P46	938,29	906,42
P09	597,37	188,11



**Figure 5:** Compressive resistance values for the columns.

Finally, Table 7 shows the percentage difference between the original resistance values and the estimates derived from the proposed methodology.

**Table 7:** Percentage difference in compressive resistance values of the columns.

P22	P40	P47	P48	P38	P46	P09
-0,19 %	-0,18 %	-2,14 %	-2,14 %	-3,40 %	-3,40 %	-68,51 %

## Beams

Table 8 presents the selected beams for the study, along with some of their characteristics, including their respective degradation factors and reduced basic density ( $D_{br}$ ). The beams were selected throughout the whole structure, both internal and external, covering all levels, from the ground floor to the roof of the second floor.

**Table 8:** Selected beams and degradation factors.

Element	Diameter (cm)	Length (m)	Degradation Factor	$D_{br}$ (kg/m <sup>3</sup> )
VD42	20	2,50	0,05 %	674
VG02	25	1,88	0,11 %	673
VG05h	25	2,50	0,11 %	673
BR31	25	6,75	0,11 %	673
VG25b	20	1,88	0,83 %	668
VG05b	25	2,50	1,26 %	666
VG11	25	2,50	2,67 %	656
VG34	25	2,02	2,67 %	656
VD40	20	3,75	9,05 %	613
VG28	25	3,75	17,36 %	557
VG06	25	1,87	26,30 %	497
VG07	25	1,33	26,30 %	497
VG08	25	1,87	26,30 %	497

Figure 6 shows photos of some of the beams of the Maloca taken during the inspection.



**Figure 6:** Photos taken of the Maloca's beams (Laboratório de Reabilitação do Ambiente Construído 2022).

Figure 7 shows one of the verifications conducted using the DMDB program (Braga and Freitas 2022) for the design bending moment of beam VD42.

Propriedades Tração Compressão Flexão simples Cortante Flexão composta Vibração

Solicitação de cálculo

Flexão reta  Flexão oblíqua

Solicitação (MS,d)  kgf\*cm

Verificação de resistência à flexão simples

Módulo resistente elástico  cm<sup>3</sup>

Momento fletor admissível (MR,d)  kgf \* cm

MS,d / MR,d

Coeficientes

$\gamma_w$

Kmod

$\phi$

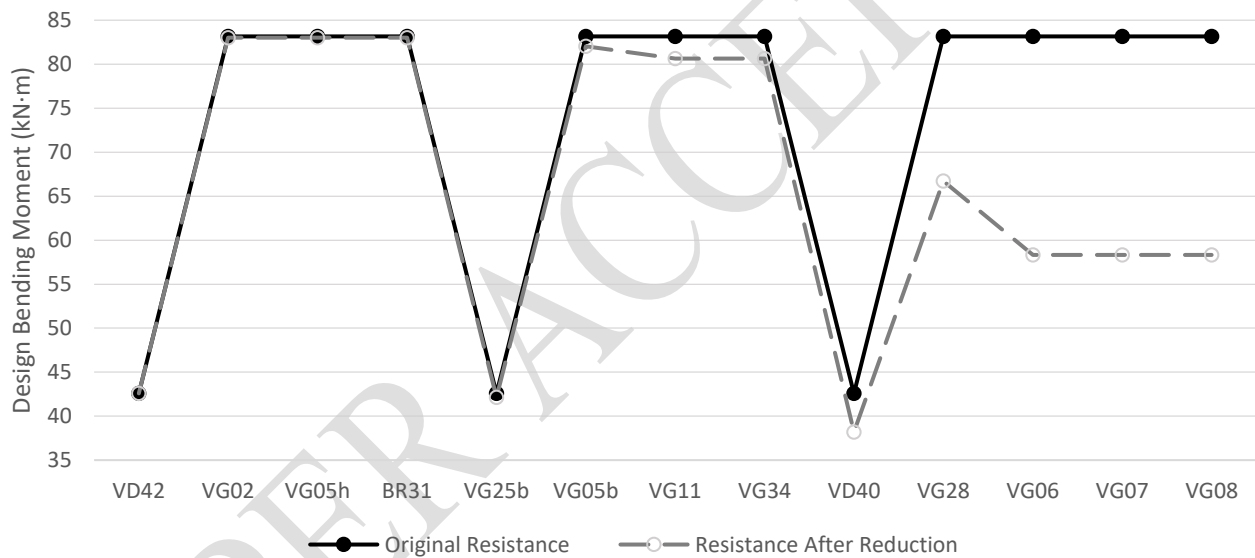
Verificações

**Figure 7:** Verification of beam VD42 using DMDB.

Table 9 and Figure 8 present the final values found for the design bending moment for simple straight bending of the beams, before and after the reduction of basic density based on the degradation factors.

**Table 9:** Bending moment values for simple straight bending of the beams.

Element	Original Resistance (kN·m)	Resistance After Reduction (kN·m)
VD42	42,57	42,57
VG02	83,15	83,01
VG05h	83,15	83,01
BR31	83,15	83,01
VG25b	42,57	42,14
VG05b	83,15	82,03
VG11	83,15	80,63
VG34	83,15	80,63
VD40	42,57	38,19
VG28	83,15	66,73
VG06	83,15	58,31
VG07	83,15	58,31
VG08	83,15	58,31



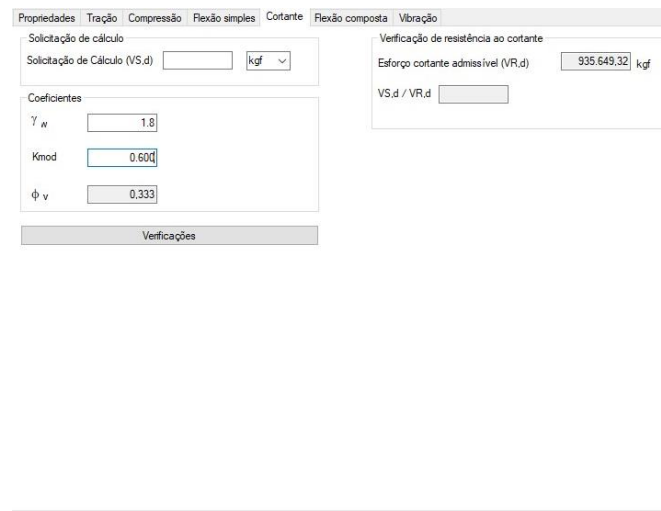
**Figure 8:** Bending moment values for simple straight bending of the beams.

Based on the values above, Table 10 presents the percentage difference between the original resistance values and those estimated through the proposed methodology.

**Table 10:** Percentage difference in bending resistance of the beams.

VD42	VG02	VG05h	BR31	VG25b	VG05b	VG11	VG34	VD40	VG28	VG06	VG07	VG08
-0,00 %	-0,17 %	-0,17 %	-0,17 %	-1,01 %	-1,35 %	-3,04 %	-3,04 %	-10,30 %	-19,75 %	-29,88 %	-29,88 %	-29,88 %

Figure 9 shows one of the verifications done using the DMDB program (Braga and Freitas 2022) for the shear resistance of Beam VG02.

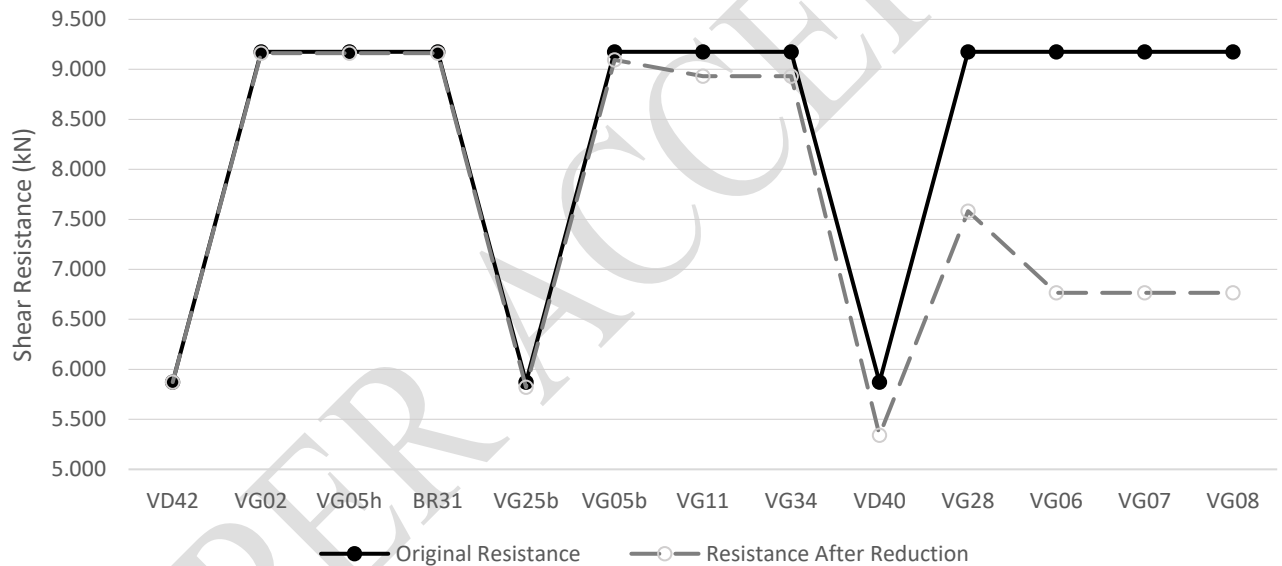


**Figure 9:** Verification of beam VG02 with DMDB.

Table 11 and Figure 10 present the final values found for the shear resistance of the beams, before and after the reduction of basic density based on the degradation factors.

**Table 11:** Shear resistance values for the beams.

Element	Original Resistance (kN)	Resistance After Reduction (kN)
VD42	5872,38	5872,38
VG02	9175,59	9161,97
VG05h	9175,59	9161,97
BR31	9175,59	9161,97
VG25b	5872,38	5820,10
VG05b	9175,59	9093,90
VG11	9175,59	8930,54
VG34	9175,59	8930,54
VD40	5872,38	5340,90
VG28	9175,59	7582,79
VG06	9175,59	6765,97
VG07	9175,59	6765,97
VG08	9175,59	6765,97



**Figure 10:** Shear resistance values for the beams.

Finally, Table 12 presents the percentage difference between the original resistance values and those estimated through the proposed methodology.

**Table 12:** Percentage difference in shear resistance of the beams.

VD42	VG02	VG05h	BR31	VG25b	VG05b	VG11	VG34	VD40	VG28	VG06	VG07	VG08
-0,00 %	-0,15 %	-0,15 %	-0,15 %	-0,89 %	-0,89 %	-2,67 %	-2,67 %	-9,05 %	-17,36 %	-26,26 %	-26,26 %	-26,26 %

The results obtained using the proposed methodology were quite satisfactory. When comparing the new resistance values with the original ones, it is observed that the decreases were mostly below 10 %. These values align with what is expected when compared to the Degradation Factors obtained from the Maloca Report (Laboratório de Reabilitação do Ambiente Construído 2022).

The element with the greatest loss of resistance was Column P09, with a 68,51 % reduction. Since it is a crucial structural element for the stability and safety of the structure, immediate and urgent intervention and maintenance are recommended.

Regarding the beams, elements VG06, VG07, and VG08 showed the greatest resistance losses, with reductions of 29,88 % in bending and 26,26 % in shear. Given these significant reductions - close to 1/3 and 1/4, respectively - these elements should also be prioritized for urgent intervention.

Additionally, it can be observed that the relative losses in shear resistance were smaller, percentagewise, than those in simple bending resistance. This suggests that, in the event of failure of these structures, the collapse mechanism would likely involve the rupture of the wood fibers along the longitudinal direction of the beams.

The other elements - both beams and columns - showed smaller but still significant losses and thus should also be addressed to ensure the building's medium - and long - term performance.

## Conclusions

In conclusion, the methodology proposed in this work produced results consistent with the inspection carried out on the building. It was possible to identify elements with considerable resistance losses and highlight the immediate and urgent need for intervention.

Currently, methods for assessing strength are destructive and may have a direct impact on the element itself. The model presented here represents an excellent tool for inspections, providing specific values regarding the stability and structural performance of various timber elements. This allows the possibility for estimating quantitative parameters related to the structural resistance of inspected elements without the need to apply intrusive methods that may impact the structure.

Although the proposed method has limitations regarding the global assessment of a building's structural system, it still provides valuable information that can complement building inspection data. This set of additional information is particularly relevant, as it directly addresses one of the most critical aspects of building assessment: structural integrity. Furthermore, it can support engineering decision-making and serve as a basis for prioritizing elements to be rehabilitated within the broader context of the structure.

The model appears to be reliable for the assessment of individual timber elements. Although the study has limitations regarding the types of loading to which the elements are subjected, the methodology may be applicable to other loading conditions (such as tensioned bars or combined bending stresses). For future work, it is suggested that this methodology be applied to other load-bearing situations to verify its applicability.

#### **Authorship contributions**

A. A. B.: Writing – original draft, data curation, methodology, software, visualization. J. D. C. P.: Writing – review & editing, conceptualization, project administration, resources, supervision. J. H. M. D. P.: Investigation, resources, validation. M. A. S. B.: Investigation, resources, validation

## Conflicts of interest

The authors declare there are no conflicts of interest for each author.

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