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COMPOSITE WOOD-STEEL STRUCTURES: STRESS ANALYSIS

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Abstract. This study uses the finite elements method in the analyses of the essential tensions presented by composite wood-steel structures used in the restoration of old wooden buildings. First, the numerical model was validated by modeling solely the wooden structure. Then the results were compared with the experimental results from physical tests for axial compression and flexion. The requirements of the Brazilian Standards NBR 6120, NBR 8800 and NBR 7190 were used. Finally, metal profiles were inserted in the wooden model and loads were applied according to the original structure's specifications. The conclusion was that the steel intervention in the wood improves its structural performance, without putting at risk the other parts of the old building; besides it provides a clean construction site during the restoration process of the wooden structure.

1 INTRODUCTION

Over the last decades, the civil construction industry has greatly advanced due to the technological development. With the intent of improving constructive processes, contractors have put effort in diminishing waste and improvisation in all aspects of construction management, which has contributed to technological development and quality improvement.

Project precision and implementation in building restoration has become a fundamental characteristic for achieving success in the utilization of metallic elements. It is also reasonable for the planning process to include the use of standardized models. As such, the planning and standardizing of procedures associated with the technological development of products have created what is called industrialized construction.

In this context, numerical simulation has become an important tool in structural calculation; considerably contributing to the calculation of metallic reinforcements for structural wooden elements. The introduction of a metallic element into wooden pieces in old buildings is analyzed herein, besides defining the type of metallic reinforcement element to be used depending on the beam's transversal section and gap dimensions that must be recuperated.

2 COMPOSITE WOOD-STEEL STRUCTURES

The objective is to propose the utilization of metallic structural elements in the recuperation and/or reinforcement of wooden structural elements present in old conventional buildings, making use of the advantages offered by a more resistant industrialized material. A study and analysis has been performed on the *Candeia* wood beams existing in the Casa de Bernardo Guimarães building in Ouro Preto, MG, Brazil; built in the 19^{th} Century. The studied beam is found in the largest room of the building, which today houses the library of the Fundação de Arte de Ouro Preto (Figure 1).

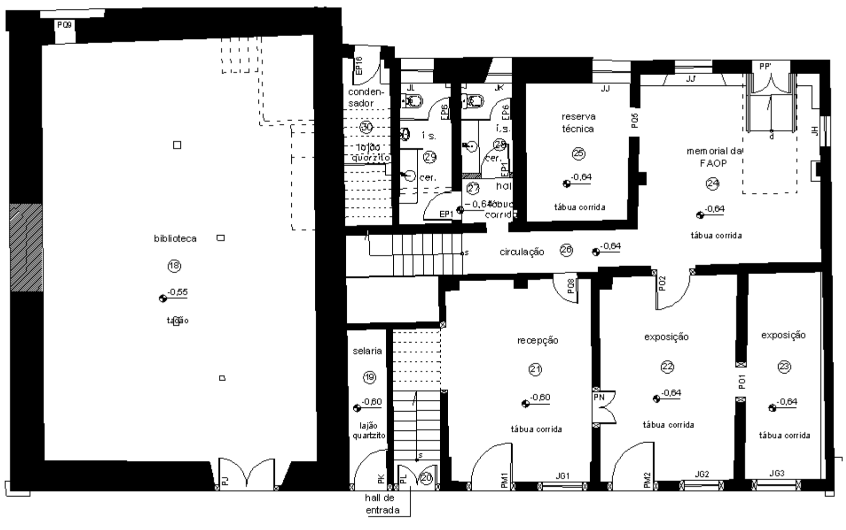

Figure 1: Blueprint of the 1^{st} floor of the Casa de Bernardo Guimarães

The proposed reinforcements are: (a) to insert an inverted T-shaped steel profile (150 x 150 x 5 mm) into the interior of the wooden beam, fixing it with slotted bars; or (b) to glue a steel plate (150 x 5 mm) to the underside of the beam in the tractioned region held in place with a highly resistant adhesive and some bolts along the beam (Figure 2).

(a)

(b)

Figure 2: Reinforcement of a wooden beam: (a) with inverted T-section profile; and (b) horizontal surface of the steel plate glued to the underside of the beam in the tractioned region.

In both cases proposed herein, the main idea is to maintain the aesthetic aspect while preserving the centennial piece of wood. For this purpose, ASTM A-36 steel was used for both the T-section profile and the plate glued with highly resistant adhesive (Figure 3).

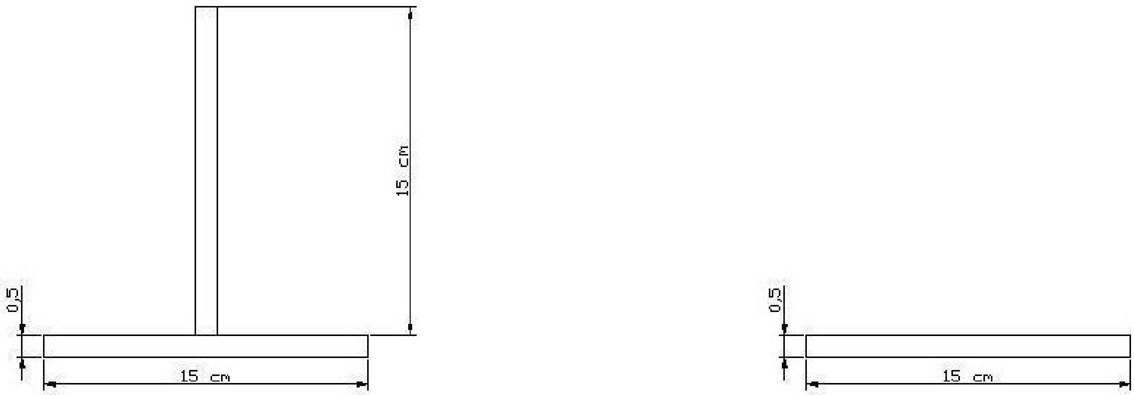

Figure 3: Metallic elements utilized to reinforce the structure: T-section profile and steel plate

The analyzed *Candeia* wood beam has a transversal section of 21 x 31 cm and a length of 6.9 m; it is subjected to an adobe wall load corresponding to $Q_c = 5.13 kN/m$.

A finite element model in the Ansys (2005) software is used, which corresponds to the physical properties of the same, considering its anisotropy; in other words, an element that permits working with anisotropy or orthotropy. As the wood presents a distinct behavior between its parallel-to-fiber, radial and tangential directions (and being the three ones orthogonal to each other), an orthotropic behavior for the finite element was adopted.

In the numerical modeling of the beam, its orthotropic properties were inserted, taking into consideration other information given by Pfeil and Pfeil (2003), such as: 1) the longitudinal elasticity model equal to its value obtained in the laboratory, and 2) its shearing models, equal to 7% of the longitudinal one, which was obtained by means of iteration of its own computational code (Ansys, 2005), so that the model is compiled and approximated to a 5% value, as specified by NBR 7190 Standard (1997). A Poisson's ratio equal to 0.35 was used, which corresponds to the proportion between the specific transversal and longitudinal elongation of the wood (França, 2007)

3 EXPERIMENTAL DETERMINATION OF THE *CANDEIA* WOOD PROPERTIES

Since the study deals with a centennial beam, it is necessary to consider the geometric imperfections of this chiseled piece, and also its state of deterioration. As such, a new reduced transversal section was determined to represent the homogeneity along the whole beam.

To determine the physical property of Candeia wood, parallel-to-the-fiber compression, elasticity and shearing tests were performed at the Forest Department of the Federal University of Viçosa; coordinated by Prof. Márcio Sarmet Sampaio. In these laboratory tests, the longitudinal elasticity model of the wood was determined to be equal to 6,405,200 kN/m^2, and its parallel-to-fiber compression strength was determined to be equal to 63 MPa.

In the parallel-to-fiber compression tests, samples were extracted according to the NBR 7190 Standard (1997) that says that samples should be extracted in 0.05 x 0.05 x 0.15 m dimensions. However, since these samples had to be extracted from centennial wood, it was decided that the dimensions of the samples would be 0.02 x 0.02 x 0.06 m, respecting the proportions of 1 x 1 x 3 stipulated by the NBR 7190 Standard (1997). The transversal sections of the sample were measured within an approximation of 0.0001 m. The samples were tested between the dishes of an articulated Universal test device. The load rate is approximately 980,665 kN/m^2/min (Figure 4).

The maximum load attained for deforming the sample is expressed in kN, and is divided by the transversal section of the same. The module for elasticity under compression is calculated by dividing the specific load corresponding to the proportionality limit by the unit elongation in kN/m^2.

For the static bending test, samples of 0.02 x 0.02 x 0.30 m extracted according to Annex B of the NBR 7190 standard (1997) were used. The test involves charging the samples by means of a central charge, supported at the ends, making the samples bend until they fracture. The samples were supported by steel rollers (Figure 5), of a 0.015 m radius. A load was applied, tangent to the growth rings, by means of a central rod, with the formation and dimension of the supports. The gap that processed the bending was 0.24 m. The speed of the admitted load application was such that a rupture would occur in a minimum two-minute time limit.

Rupture resistance is given by:

$$\sigma_c = \frac{M}{W} = \frac{3}{2}\frac{Pl}{bh^2} \tag{1}$$

where M is the bending resistance moment of the sample, (N.m); P is the rupture load, (N); *b* is the base of the transversal section of the sample, (cm); *h* is the height of the transversal section of the sample, (cm); and W is its resistance module, (m^3).

Figure 4: Parallel-to-fiber compression experimental analysis.

The relationship between the gap and the ruptured bending point (L/f) is the approximate rigidity index of the wood. To test air-dried wooden samples, the results were corrected for 15% humidity, according to the NBR 7190 Standard (1997). The proportional tension limit and the elasticity model are obtained by means of the curve shown in figure 6. In this case, the elasticity model is calculated for its proportional limit using:

$$E = \frac{L^3 Q}{4fbh^3} \tag{2}$$

where L is the length of the sample, (m); Q is the load corresponding to the proportional limit, (N); f is the displacement point read in the middle of the piece, (m); b and h are the size of the transversal section, (m).

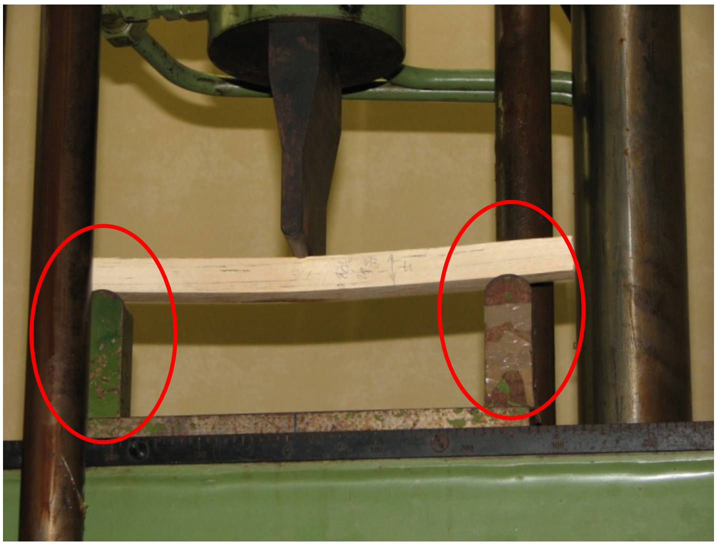

Figure 5: Elasticity test performed on a wooden sample.

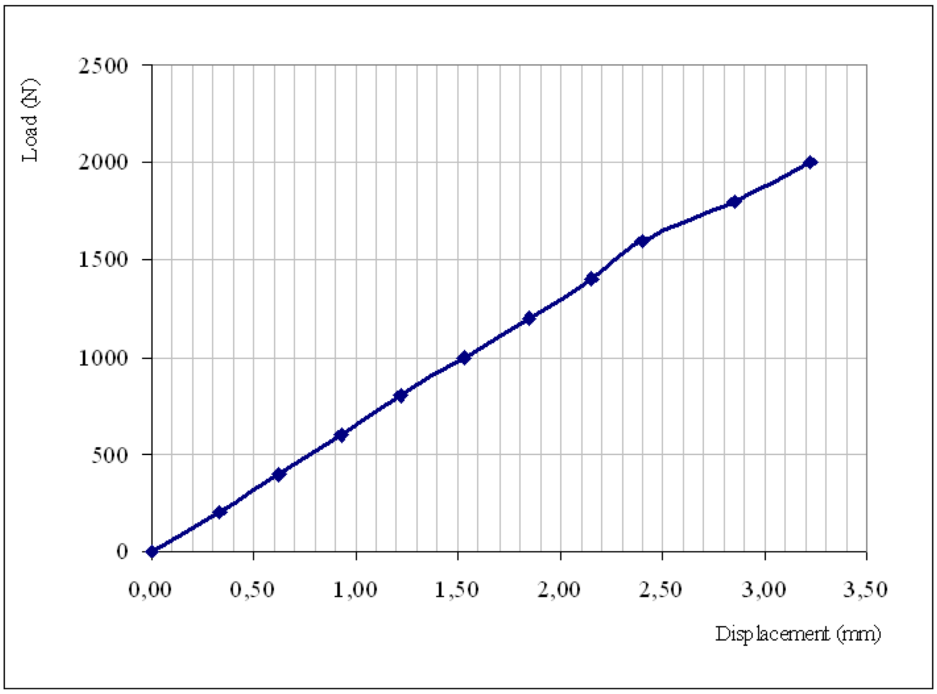

Figure 6: Length-center displacement point x load, determined by elasticity test.

For the parallel-to-fiber shearing, the form and dimensions of the utilized samples were according to the NBR 7190 Standard (1997). The tests were performed with a Universal testing device. In addition, the studied section was measured with an approximation of 0.1 mm and the results are expressed in N/cm^2. Finally, a load was applied at a ratio of 250 N/cm^2 per minute.

3.1 Numerical model validation

To verify if the numerical modeling procedures, including properties, were being correctly discriminated, a numerical model was developed using the same dimensions and physical properties as the laboratory-tested wooden samples. Parallel-to-fiber compression was simulated using the Ansys software, which was then compared to the displacement and the stress obtained by the numerical model (Figure 7).

The structural element involved a rectangular grid with a total of 4,153 (four thousand, one hundred and fifty-three) nodes, and 12,914 (twelve thousand, nine hundred and fourteen) grid elements. A rigid-element prism was fixed at each end of the sample, representing the press plates. On the lower plate, only the vertical movement was restricted, and the upper plate applied the centralized load. To verify this, a gradually increased load was applied to the finite element numerical method, identical to the loads used during the performance of the parallel-to-fiber compression test (Tables 1 and 2).

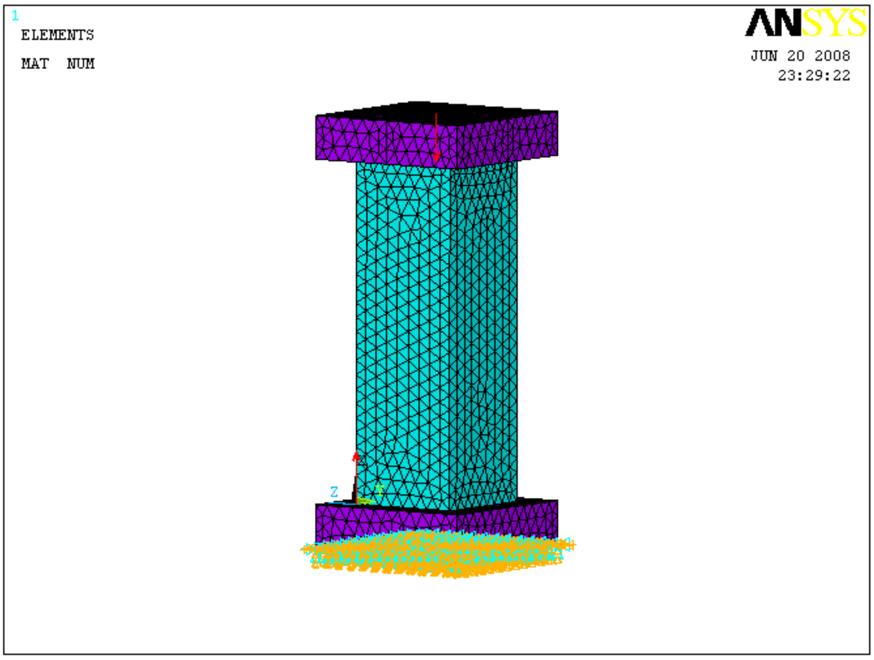

Figure 7: Numerical model of the sample used in the laboratory test.

AXIAL COMPRESSION LOAD EXPERIMENTAL					
Máximum load of compression = 1,005N			Máximum load of compression = 1,005 N		
Subject: CANDEIA	Height (mm):	119.97	Subject: CANDEIA	Height (mm):	119.73
SAMPLE 1	Length (mm):	39.60	SAMPLE 2	Length (mm):	39.39
	Width (mm):	40.21		Width (mm):	40.18
Force (KN)	σ_2 (MPa)	ε_1(mm)	Force (KN)	σ_2 (MPa)	ε_1(mm)
2	1.26	0.000	2	1.26	0.000
5	3.14	0.064	5	3.16	0.046
10	6.28	0.139	10	6.32	0.144
15	9.42	0.221	15	9.48	0.222
20	12.56	0.287	20	12.64	0.282
25	15.70	0.340	25	15.80	0.338
30	18.84	0.385	30	18,96	0.394
35	21.98	0.429	35	22.11	0.445
40	25.12	0.472	40	25.27	0.495
45	28.26	0.514	45	28.43	0.545
50	31.40	0.554	50	31.59	0.593
55	34.55	0.595	55	34.75	0.640
60	37.69	0.637	60	37.91	0.684
65	40.83	0.680	65	41.07	0.733
70	43.97	0.727	70	44.23	0.794
75	47.11	0.774	75	47.39	0.843

Table 1: Results from the experimental analysis.

AXIAL COMPRESSION LOAD TEST		
Máximum load of compression = 1,005 N		
Subject: CANDEIA	Height (mm):	119.97
Numerical model	Length (mm):	39.60
	Width (mm):	40.21
Força (KN)	σ_2 (MPa)	ε_1(mm)
2	1.26	0.000
5	3.14	0.064
10	6.28	0.139
15	9.42	0.221
20	12.56	0.287
25	15.70	0.340
30	18.84	0.385
35	21.98	0.429
40	25.12	0.72
45	28.26	0.514
50	31.40	0.554
55	34.55	0.595
60	37.69	0.637
65	40.83	0.680
70	43.97	0.727
75	47.11	0.774

Table 2: Results obtained from the numerical analysis.

Notice that the results obtained by the finite element analysis model and those obtained from the analysis of the Candeia wood sample experiment present the same behavior and approximate values for elongation and stress, presenting a relative error of 12% and 3% referring to the parallel-to-fiber stress (Figures 8, 9 and 10).

From the values obtained in the two methods, it can be concluded that the finite element numerical method adopted is trustworthy in function of the low error margin presented when compared with the values from the wooden sample experiment.

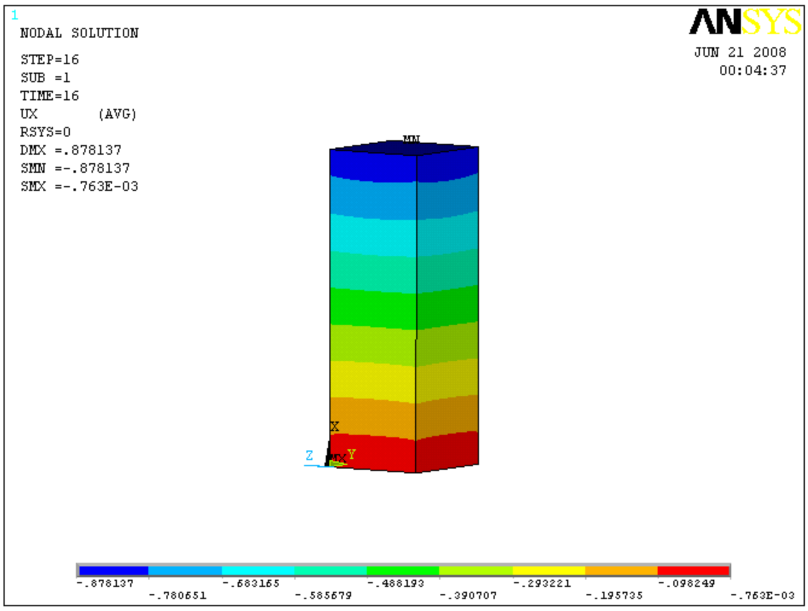

Figure 8: Elongation of the numerical model for the sample under the last applied load.

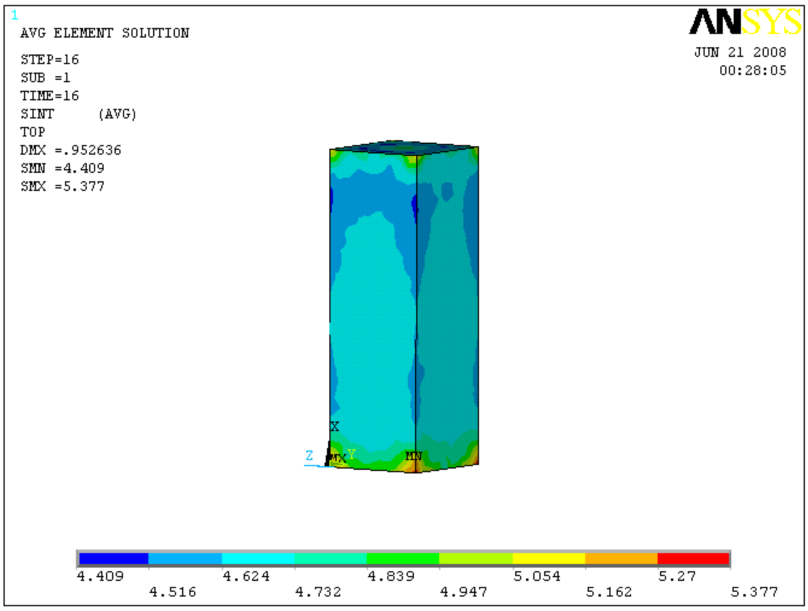

Figure 9: Parallel-to-fiber stress of the numerical model for the sample under the last step load.

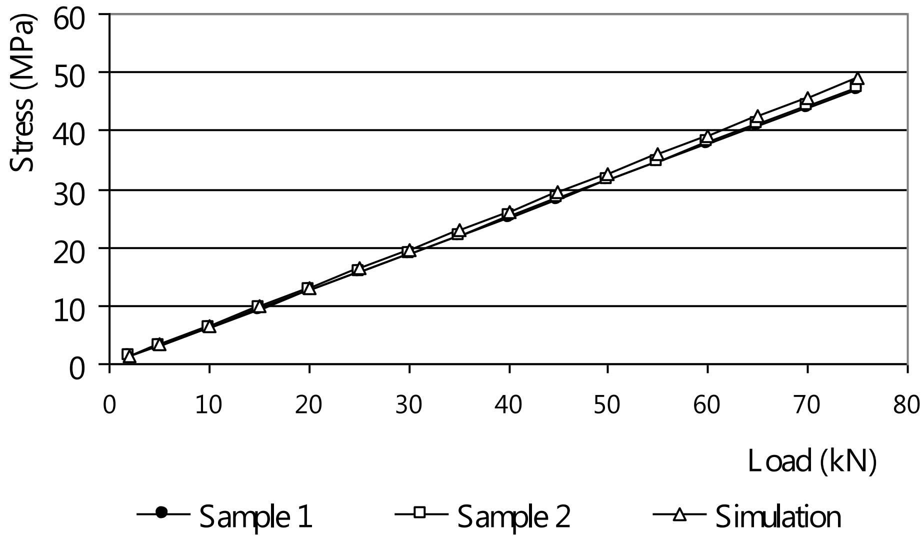

Figure 10: Parallel-to-fiber stress of the two analyzed methods.

4 NUMERICAL MODEL FOR THE COMPOSITE STEEL-WOOD SYSTEM

The proposed combination structure is numerically modeled in three dimensions. The presented results appear in (N/m^2). For this model, 6,624 *Solid64* elements and 8,190 nodes were used. After the modeling, the load Q_c was applied with gravity at 9.8 m/s^2 and the boundary conditions. The movement is restricted to the x and y axes on the left boundary, and only the y axis on the right boundary. Figure 11 shows the grid utilized in the numerical modeling and figure 12, the stress presented by the wooden beam.

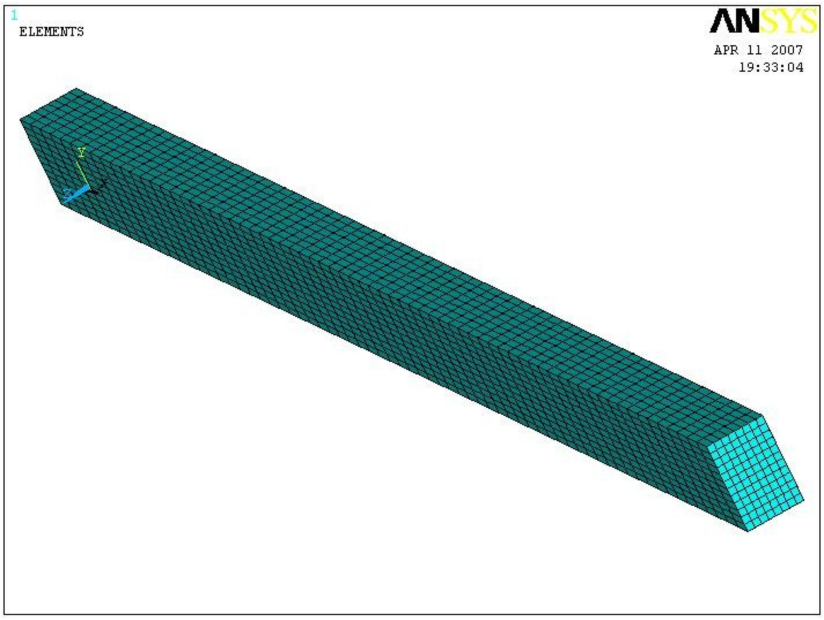

Figure 11: Model of the Candeia-wood beam isolated in finite elements.

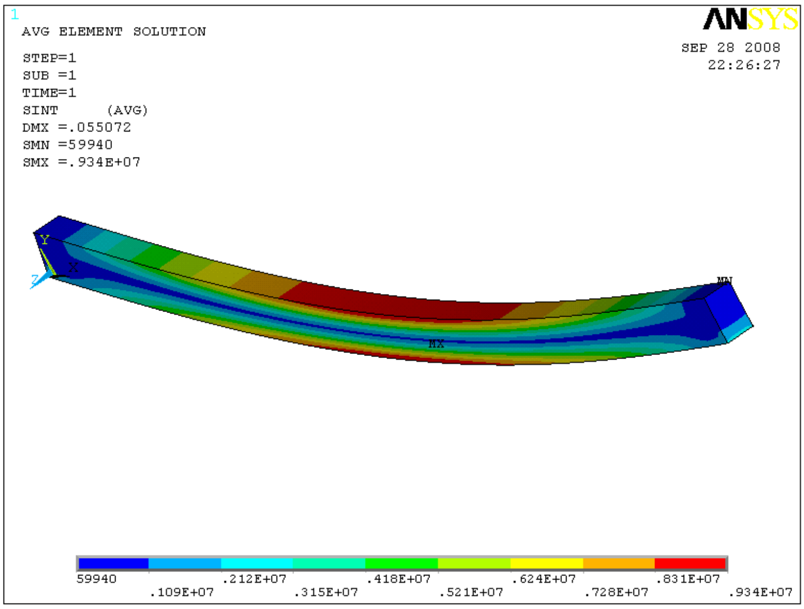

Figure 12: Stress presented by the isolated Candeia-wood beam.

In the numerical modeling of the T section profile inserted into the heart of the wooden beam throughout its length, 6,624 *Solid64 and 828 Shell43* elements were used, giving a total of 7,452 elements and 9,170 nodes. After modeling, load q_d, is applied with the gravity at 9.8 m/s^2 and the boundary conditions. The movement is restricted to the x and y axes on the left boundary and only the y axis on the right boundary. Figures 13 and 14 show the stress presented by the wooden beam and by the metallic profile, with their respective proportions when treated as a composite wood-steel beam.

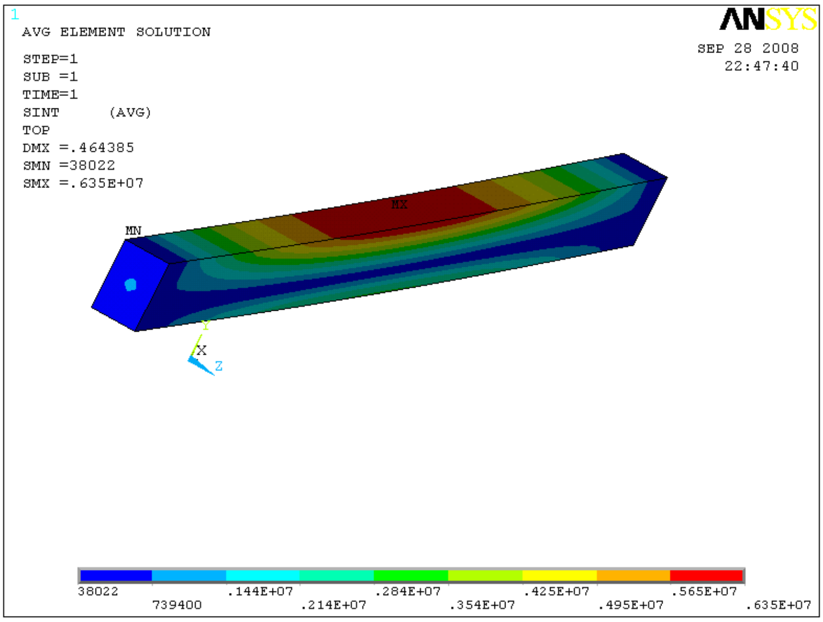

Figure 13: Stress of the wooden beam with a steel T-section profile in relation to the y axis – wooden

section.

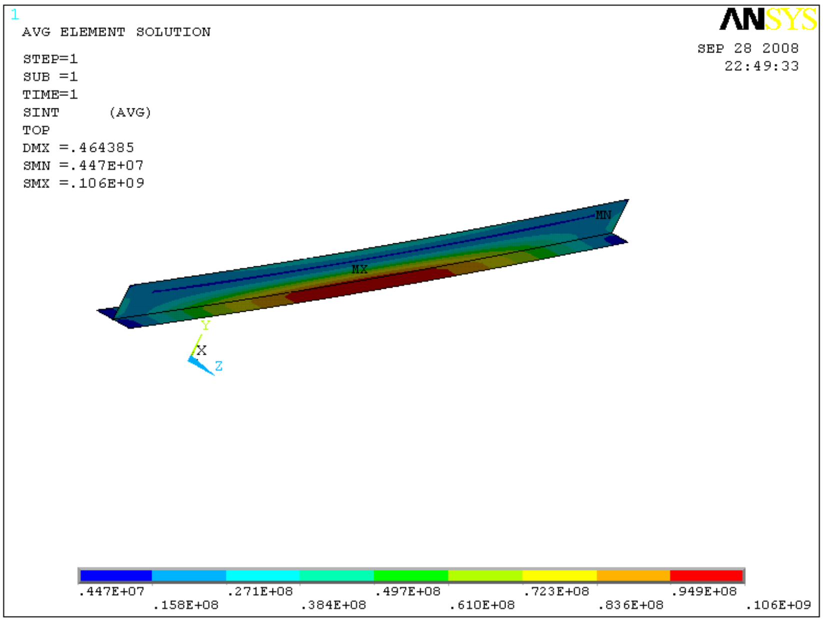

Figure 14: Stress of the wooden beam with a steel T- section profile in relation to the y axis – steel T-section profile.

As a second reinforcement proposal, previously presented, there is a steel plate fixed to the underside of the wooden beam, in the tensile region, fixed by highly adherent adhesives and special bolts. In this way, the fixed plate increases traction strength in the most solicited region, resisting together with the wood the tensile forces provoked by bending.. In this analysis, the physical properties are also applied, as well as the loads, gravitational action and the boundary conditions of the previous example.

In this modeling, 6,624 *Solid64,* 471 Shell43 and 01 *Link8* elements were utilized, totaling 7,096 elements and 8,468 nodes. After the modeling, load q_d was applied at a gravity of 9.8 m/s^2 and the boundary conditions. The movement was restricted on the x and y axes at the left boundary, and only the y axis on the right boundary. Figures 15 and 16 present the stress found on the wooden beam and steel plate, with their respective proportions, as it is a composite wood-steel beam.

Comparing the stress obtained for the composite wood-steel structure, with those obtained for the Candeia wood in the laboratory, already transformed into those acceptable by the NBR 7190 Standard (1997), and the maximum stresses presented by the metallic profiles according to the NBR 8800 Standard (2008) for the type of steel in question, it was noticed that the wooden beam, when placed at the utilized load, presented maximum stresses in the order of 9.34 Mpa, as much at the tractioned extremity (inferior face) as at the compressed extremity (superior face). This value is inferior to the calculated strength of the Candeia wood which is approximately 17 MPa, proving that the beam presents strength to the imposed forces, but with low rigidity, justifying the verification of the proposed reinforcements.

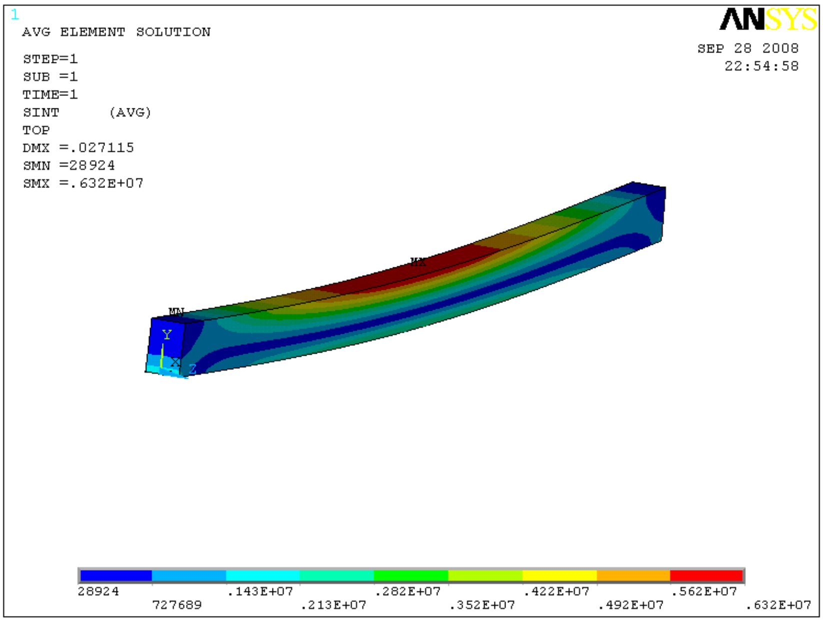

Figure 15: Stress candeia-wood beam with steel plate, wooden section.

As such, when an inverted T section profile is inserted in the heart of the wooden beam, the beam’s carrying capacity is significantly increased, presenting a maximum stresses in the order of 6.3 MPa along its length, exactly where there were no reinforcements. On the other hand, in the reinforced region, the stress did not surpass 3.5 MPa. Comparing these stress values with those presented with the isolated beam, it was found that in the reinforced region, the stress was reduced by more than 62 %. As for the T section profile, it presented a maximum tensile stress in the order of 106 MPa, or less than 50 % of its yield stress limit when using ASTM A36 steel.

When the steel plate is attached to the underside of the beam for its entire length, maximum stresses along its length are in the order of 6.3 MPa, while in the tensile region, they do not surpass 4.2 MPa. Comparing these stress values with those presented by the isolated beam, it can be seen that in the reinforced region, tensile was reduced by more than 55%. As for the steel plate, it presented a maximum tensile stress in the order of 101 MPa, or less than 45% of the yield stress limit for ASTM A36 steel.

The inverted T section profile intervention in the wooden beam is more efficient. However, its constructive process requires specialized labor and greater execution time than the steel plate intervention. As such, it is advisable to reinforce the beam with the steel plate, attached by highly adherent adhesives and special bolts whenever operational speed is the priority. If strength is the priority, then the inverted

T section profile is advisable for reinforcement and plans must include a greater execution time limit, due to the installation difficulties involved.

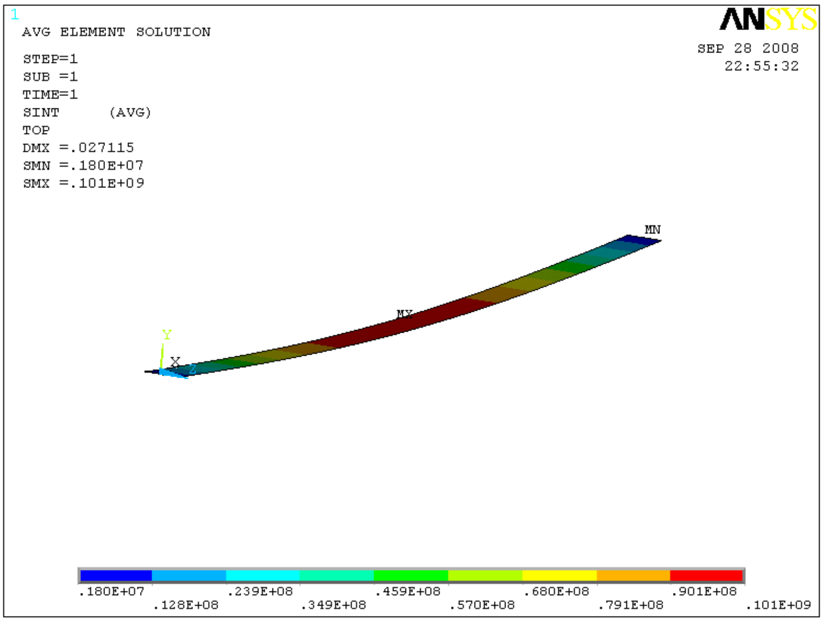

Figure 16: Stress on the Candeia wood beam reinforced with steel plate – steel plate sector.

5 CONCLUSIONS

Herein were presented aspects regarding the intervention in wooden structures with steel profiles and/or metallic plates, whereby the ANSYS software was used for the numerical simulation and analyses. Wood and steel were the structural materials utilized and a composite of the two was proposed to enhance their composition and differences in accordance with their respective standards. When adequately defined, the insertion of light-weight metallic structural elements in wooden structures can provide the required strength, facility the construction process, and still be aesthetical.

According to standard recommendations for the dimensioning of wooden structures, laboratory tests were performed with samples of the same wood with the objective of identifying their physical properties and comparing the results with the numerical model used for validation. The finite element numerical model for the wooden structural element (beam) presented a maximum error for the involved stresses of around 3 % in relation to the experimental value. This error corresponds to an excess in comparison to the parallel-to-fiber compression laboratory test, which makes the finite element model more conservative than the experimental results.

Finally, the intervention as presented herein, makes the process reversible if newer, more efficient and lighter reinforcements are developed. The proposed reinforcements can be removed without compromising the structure, once the beam is properly supported, to avoid damage during the execution of the process.

Acknowledgements

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